Petroleum tectonic comparison of fold and thrust belts:
the Zagros of Iraq and Iran, the Pyrenees of Spain, the
Sevier of Western USA and the Beni Sub-Andean of Bolivia

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Abstract: The genetic analysis of fold and thrust belts is facilitated by tracking the evolution of their organic
endowment (petroleum tectonics). Petroleum tectonic analysis of convergent orogenic systems provides an
audit of the processes that control the deformation and kinematics of orogenic belts. The distribution and deformation
paths of the organic endowment intervals are key factors in determining the petroleum system evolution
of fold and thrust belts. This comparison of orogenic systems illustrates the importance of flexural v. dynamic
processes, orogenic wedge taper, mechanical stratigraphy and inherited architecture on the creation, preservation
and destruction of petroleum accumulations. The Zagros, Pyrenees, Sevier and Beni Sub-Andean convergent systems share key characteristics of fold and thrust belts, with major differences in scale, degree of incorporation of organic endowment in evolution of the fold and thrust belt and its foreland, and preservation of fold and thrust belt wedge-top deposits.

The Zagros is an orogen dominated by flexural processes that is a perfect storm for hydrocarbon generation
and preservation. Its multiple stacked sources ensure continuous hydrocarbon generation while stacked detaches
ments foster a low taper and thick wedge-top basins. The Pyrenees is also a flexurally dominated orogen, but the early consumption of its source rocks led to minimal survival of hydrocarbon accumulations during exhumation in a long lasting, high-taper orogenic wedge. The Sevier was initially a flexural orogen that was later dominated by dynamic uplift of the fold and thrust belt and distal foreland subsidence with foreland deformation. The consumption of its pre-orogenic sources during the early low-taper phase indicates a probable robust petroleum system at that time. However, the late high-taper phase exhumed and destroyed much of the early petroleum system. The addition of syntectonic foreland sources to be matured by both local and dynamic subsidence cre-
ated an additional later set of petroleum systems. Post-orogenic events have left only remnants of world-class petroleum systems. The Beni segment of the Sub-Andean Orogen is a flexural system with probable dynamic overprints. Its most robust petroleum system probably occurred during its early low-taper flexural phase, with dynamic subsidence enhancement. Its late high-taper phase with possible dynamic uplift shuts down and stresses the petroleum systems. Comparison of these orogenic systems illustrates the importance of flexural v. dynamic processes, orogenic wedge taper kinematics, mechanical stratigraphy, distribution of source rocks relative to shortening and inherited architecture on the creation, preservation and destruction of petroleum accumulations in fold and thrust belts.

Resource studies show that 14% of world-wide dis-
covered hydrocarbon reserves are within the fold and thrust belts along convergent plate boundaries (Cooper 2007). Oil and gas exploration in fold and thrust belts is risky due to the complexity in tectonic style, structural architecture and petroleum system

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survival potential during the growth of fold and thrust belts. Cooper (2007) presented a statistical compilation of 55 examples of fold and thrust belts, listing a large number of parameters related to both deformation style and petroleum systems worldwide. The results show that fold and thrust belts are rich in traps and the most prolific are rich in organic matter. His analysis indicated that the deformational style has less significance for the hydrocarbon endowment of fold and thrust belts than other elements of the petroleum system. The genetic analysis in our study of four fold and thrust belts indicates that the inherited architecture and details of timing are critical in fold and thrust belt petroleum systems.

The objective of this study is to introduce petroleum tectonic analysis (PTA), as described below, and apply it to document and compare the roles of multiple orogenic processes on the petroleum systems in four fold and thrust belts: Zagros, South Pyrenees, Sevier and Beni Sub-Andean. The thrust belts vary in scale, age, organic endowment and degree of petroleum exploration activity. They occur in different tectonic settings: the Zagros protracted subduction-related continental collision between Eurasia and Arabia; the Pyrenean intracontinental collision between Eurasia and Iberia; the Sevier fold and thrust belt related to the long-lived subduction of the Pacific plate beneath North America; and the Beni Sub-Andean fold and thrust belt related to active subduction of the Pacific plate beneath South America. The Zagros and Pyrenees were formed on the lower plate while the others evolved in the upper plate (Fig. 1).

In this analysis many of the details of these complex orogenic systems are oversimplified for the purpose of comparison. The cross-sections analysed were chosen because they are sequentially restored with sufficient published petroleum system modelling along their lengths to allow high-level integrated analysis. They do not capture all the major elements of the entire fold and thrust belts they represent but are sufficient to illustrate the potential usefulness of the applied analysis. The focus is an integrated high-level petroleum and tectonic genetic analysis of orogens. The tectonic analysis informs the understanding of petroleum potential while the petroleum analysis informs the tectonics understanding. Traditional hydrocarbon analysis of fold and thrust belts like that of Cooper (2007) take a more static approach based on present-day configurations and status. The PTA approach is more dynamic, focusing on the full genetic evolution of the petroleum systems. This analysis provides a method for auditing the role of various competing orogenic processes in fold and thrust belts while providing a context for examining their petroleum potential.

The petroleum tectonic synthesis from this study highlights the impact on the petroleum systems in convergent orogens of: (1) presence and distribution of source rocks; (2) shortening relative to organic distribution; (3) pre-orogenic architecture and the mechanical stratigraphy that impacts orogenic wedge

![Fig. 1. Topographic map (Amante & Eakins 2009) showing location of fold and thrust belts. The boxes show locations of Figures 5–8. The black lines represent the transects addressed and the red lines represent the portions of the fold and thrust belts to which the transects apply.](http://sp.lyellcollection.org/Downloaded from)
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kinematics; and (4) the relative dominance of orogenic processes of flexural basin advancement v. dynamic uplift/subsidence as the pre-orogenic section is incorporated into the orogenic wedge.

Petroleum systems in fold and thrust belts

A petroleum system, as described by Magoon & Dow (1994), is defined as all the essential elements and processes needed to create an oil and gas accumulation. The elements are source, reservoir, seal and overburden. The processes are trap formation and the generation-migration-accumulation of petroleum. In successful petroleum systems all these elements and processes must favourably align in space and time to enable both formation and preservation of hydrocarbon accumulations.

The four fold and thrust belts analysed have indications of all the petroleum-system elements (Table 1). In fold and thrust belts where all elements are present, their progressive deformational histories dictate the generation and destruction of petroleum systems (Roure & Sassi 1995). The occurrence of petroleum accumulations is dependent on a narrow range of deformation pathways (Magoon & Dow 1994). Understanding the limited windows of time when all elements and processes align for hydrocarbon accumulations to form in fold and thrust belts, and the challenges of preservation of those accumulations, is the essence of PTA.

PTA

PTA is the integrated analysis of petroleum-system evolution and tectonic processes. It tracks the transformation of the organic matter relative to hydrocarbon migration and trapping geometries. PTA assesses the potential for and status of petroleum accumulations in a tectonic context. As part of the analysis, indications of hydrocarbons are used to constrain tectonic models. The process of PTA helps identify key unknown variables and the potential petroleum system impacts of the uncertainties. The kinematic and petroleum system appraisal method (Roure & Sassi 1995) is built on by adding a tectonic context. PTA can be applied at a local trap or orogenic scale. Fold and thrust belt petroleum systems are very sensitive to the temporal and spatial alignment of processes, making them excellent candidates for PTA. In this paper PTA is being applied at an orogenic scale to compare and contrast the diverse fold and thrust belts analysed.

PTA of fold and thrust belts begins with a stratigraphic analysis of the pre-orogenic section. What is its shape and mechanical layering? What is the distribution of potential source intervals within the stack? When and how much of the pre-orogenic section has been involved in the deformation? The same analysis is completed for the syntectonic section. A subsidence pattern analysis of the syntectonic section provides a sense of the dominant tectonic processes. Does the depositional centre progressively shift tracking the deformation front, suggesting strong flexural processes; or is it broad and relatively stationary, suggesting a dominance of dynamic processes? Do the subsidence patterns and dominant processes vary through time?

The next step is a structural analysis concentrating on the geometric evolution of the area. Sequential restoration is required. Existing sequential cross-sections can be used but ideally the following steps are involved. The present-day geometry is defined, focusing on levels of erosion and preserved growth sections. Structural analysis begins with the pre-orogenic restoration, which helps define the distribution of pre-orogenic source rocks and constrain their thermal states. Using the orogenic processes indicated by the subsidence analysis as a guide, sequential reconstructions of the fold and thrust belt are generated, focusing on times of possible process and/or taper change. Integration of organic geochemical, thermochronological and geochronologic data with the stratigraphic and structural analysis is used to develop more robust sequential restorations. This analysis enables identification of potential areas and critical time frames for generation and preservation or destruction of hydrocarbon accumulations.

The key step in PTA is auditing the evidence of hydrocarbons relative to the critical time frames defined above in order to infer the potential for preservation or exhumation of accumulations and/or generative areas. This includes analysis of the deformation paths of both accumulations and failed features. Additional sample collection and analysis is often required to define the deformation paths of successful and unsuccessful traps. PTA is presented here as a linear process; however, in practice, PTA is an iterative process as data and understanding evolve.

Integrated petroleum-system thermal modelling is an integral part of auditing fold and thrust belts that is beyond the scope of this comparison paper. Potential generative areas discussed in this paper are identified from referenced publications, or where source intervals are inferred to be buried >2 km and receiving significant additional burial. Where overburden increases to >5 km, a risk of being past peak generative potential is recognized. Detailed sampling, analysis and modelling are required to confirm the potential generative areas.

Orogenic processes and petroleum systems

DeCelles & Giles (1996) define foreland basin systems as having accommodation driven by flexural
load and far-field subsidence due to interactions between the subducted slab and the mantle (Fig. 2). Flexural subsidence progresses systematically with the advancing orogenic load. Flexural forelands are excellent settings for hydrocarbons. The systematic progression of subsidence and uplift converts organic matter to hydrocarbons while creating ideal geometries for accumulations. As the flexural process progresses, it eventually destroys the previously accumulated hydrocarbons. In contrast, dynamic topography, defined by Hager & Richards (1989) as dynamic subsidence and uplift that creates longer...
wavelength (100s–1000s km) effects, is less systematic as it is controlled by deep earth processes. When dynamic uplift and subsidence are superimposed on the flexural system, they can enhance or perturb the petroleum systems of the orogen, depending on the phase and magnitude of the dynamic processes (Painter & Carrapa 2013).

Critical taper and petroleum systems of fold and thrust belts

Petroleum systems in fold and thrust belts are most frequently successful at the extreme leading edge of orogenic wedges. In flexurally controlled basins, the wedge-top zone is the overlap between the orogenic wedge and the foreland basin (Fig. 2). The kinematics of the wedge-top zone is critical to the petroleum tectonics of fold and thrust belts. An important aspect is whether the wedge-top portion of the fold and thrust belt is dominated by erosion or preservation as the deformation progresses. Erosion tends to decapitate the traps and shut down generation in wedge-top basins.

Critical taper (Fig. 3) is the concept that the fronts of orogenic wedges taper toward their undeformed forelands and advance when the sum ($\phi$) of their basal ($\beta$) and upper ($\alpha$) slopes reaches a critical value ($\phi_c$) (Chapple 1978; Davis et al. 1983; DeCelles & Mitra 1995) (Fig. 3). Critical taper is influenced by climate, erosion, mechanical stratigraphy and the quality and distribution of detachment intervals (e.g. Chapple 1978; Davis et al. 1983; DeCelles & Mitra 1995; Van der Pluijm & Marshak 2004; Ford 2004). Critical taper is commonly applied to entire orogens but in this analysis it is applied at a smaller scale to the dynamics at the deformation front with respect to the width of the wedge-top zone.

According to critical taper concept, the angle of the deforming wedge controls the wedge-top zone width and thickness (Chapple 1978; Davis et al. 1983). Erosion of the top of the deforming wedge ($\alpha$) and the mechanical architecture of the section being incorporated into the deformation are important influences on the deformation front (DeCelles & Mitra 1995). Fold and thrust belts tend to advance intermittently, trying to reach an equilibrium angle (DeCelles & Mitra 1995; Van der Pluijm & Marshak 2004; Ford 2004). The width of the wedge-top zone at the front of the deforming orogenic wedge influences the robustness and preservation of petroleum systems within fold and thrust belts. Figure 3 shows that wide wedge-top zones with limited erosion are out of sync with deposition in the foreland portion of the system. Increasing taper tends to erode the wedge-top zone providing sediments to the foreland. At the supercritical point, the thrust front tends to rapidly advance in order to lower the taper (Davis et al. 1983). The presence of good detachment intervals enhances the low-angle step-out, or jump forward, of deformation (DeCelles & Mitra 1995). The jump forward to lower taper with more limited erosion and wider wedge-top zone minimizes exhumation and extends the duration and effectiveness of the associated petroleum systems in the wedge-top portion of the fold and thrust belt (Bordenave 2014). In the analyses below, local palaeotopographic slope is poorly constrained ($\alpha$). Well documented dramatic jumps forward of deformation with preserved growth section, as in the southern Pyrenees (Meigs & Burbank 1997; Vergés et al. 1998), and with both preserved growth section and thermochronological data in the Sevier (Constenius et al. 2003; DeCelles & Coogan 2006; Peyton et al. 2011; Yonkee & Weil 2015) and Zagros (Homke et al. 2004; Emami et al. 2010; Kosnaw et al. 2017), have been used to infer local lowering of taper. The highly successful petroleum system of the middle Zagros fold and thrust belt (Bordenave 2014) analysed below is interpreted to be enhanced by a taper-lowering step-out of deformation on an excellent detachment.
Fig. 3. Critical taper, wedge tectonics and petroleum systems. Fold and thrust belts advance forward as a deforming wedge. The lower angle of the wedge (β) is influenced by the quality and distribution of detachment intervals. The top of the wedge (α₁) is the topographic slope controlled primarily by erosion. The wedge is attempting to get to a balanced state (φₜ) (a). When an imbalance arises possibly due to a drying of climate affecting (α₁) or advancement to the edge of a detachment interval (β) the wedge will internally thicken, through internal thrusting, back-thrusts and duplexing. The deforming wedge will expand to a super-critical state (b). When the wedge crosses a threshold, it will step forward with new thrust slices at the toe (c). If the wedge angle gets sub-critical, too low for the situation, it will return to internally thickening to re-establish the critical angle (φₜ) (d). Fold and thrust belts are continually in a state of imbalance attempting to establish an evolving critical state (orange line). Fold and thrust belt petroleum systems are more successful in lower-taper settings where the tendency for wider wedge-top basins extends the generation opportunities (green polygons) and the traps and migration routes are more direct. Modified from Van der Pluijm & Marshak (2004).
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The more extensive wedge-top basins associated with local lower taper can enable a larger volume of organic matter to remain at temperatures where it can actively generate hydrocarbons. These active wedge-top basins are directly linked to growing structural traps, thus maximizing the potential for the generation and preservation of hydrocarbon accumulations. As described below a wide wedge-top zone with limited erosion is favourable for petroleum systems in fold and thrust belts assuming the additional load does not over-mature the source.

Pre-orogenic architecture and inherited initial $\beta$

The presence and distribution of organic matter in the pre-orogenic sedimentary wedge is a first-order driver of petroleum tectonics. If a source is consumed in an orogen, it is likely to create a petroleum system. A lack of source results in no petroleum system. The distribution of the source dictates the longevity of the petroleum system. The shape of the pre-orogenic depositional wedge and distribution of detachment intervals are significant controls on the early evolution of critical taper (Hughes this volume, in review; Butler et al. this volume, in review) and consequently on the preservation of hydrocarbon systems in the active fold and thrust belt. Pre-orogenic sedimentary wedges with a steep basal surface (high $\beta$ in Fig. 3) have a predisposition to initially have a higher critical taper ($\phi_c$) (DeCelles & Mitra 1995; Meigs & Burbank 1997). Pre-orogenic sedimentary wedges with high aspect ratio (low initial $\beta$) and multiple detachments promote lower taper (DeCelles & Mitra 1995; Meigs & Burbank 1997).

PTA of selected fold and thrust belts

This PTA generalizes and simplifies aspects of the selected fold and thrust belts in order to focus on themes that can constrain and/or can be constrained by analysing the deformation path of organic matter. Specifics of certain areas will naturally vary but we believe the major themes of the approach are broadly applicable and useful in comparing diverse fold and thrust belts. While the four fold and thrust belts analysed have differing scales, tectonic settings and degrees of petroleum exploration, PTA provides an insight into their genetics and a unified method for their comparison and contrast.

Stratigraphic analysis and pre-orogenic architecture

A comparison of the stratigraphic section at the present-day deformation front of each studied fold and thrust belt (Fig. 4) illustrates the amount of consumption of the pre-orogenic sedimentary wedge and key characteristics of the remaining pre-orogenic architecture. Figure 5 shows the pre-orogenic wedge, main detachments, source intervals and the location of the deformation front for each orogen. Table 1 summarizes the distribution of petroleum-system elements and the pre-orogenic architecture of each fold and thrust belt. The Zagros has a thick pre-orogenic section with multiple reservoir, seal, source and detachment intervals (Bordenave 2014; Aqrawi & Badics 2015; English et al. 2015). Less than half of the Zagros pre-orogenic sedimentary wedge has been incorporated into the fold and thrust belt. The Pyrenees, by contrast, incorporated its entire pre-orogenic sedimentary wedge. The characteristics of the southern Pyrenees pre-orogenic section are inferred from the less deformed portions of the related pre-Pyrenean basins (Cámara & Klimowitz 1985; Vergés & García-Senz 2001; Biteau et al. 2006). For this analysis the largely eroded pre-orogenic section of the southern Pyrenees is inferred to have multiple reservoir-seal pairs above a primary source interval. The Sevier has multiple pre-orogenic source, reservoir and seal intervals (Anna et al. 2007). The Sevier has incorporated more than half of its pre-orogenic sedimentary wedge, including Paleozoic sources and reservoir-seal pairs (Burtner & Nigrini 1994). In addition, the Sevier contains multiple syntectonic sources and reservoir-seal pairs. The Beni segment of the Sub-Andean fold and thrust belt has incorporated most of its pre-orogenic sedimentary wedge including most of the known Paleozoic source intervals (Louterbach et al. 2018).

Figure 5 is a vertically exaggerated, same-scale comparison of the pre-orogenic architecture of the four fold and thrust belts based on the pre-orogenic portions of the cross-sections shown in Figures 6–9, which are analysed below. In addition to the obvious scale differences, the variations in shapes of the pre-orogenic sedimentary wedges, distribution of detachments and source intervals are shown. Summaries of the Zagros petroleum systems are in Bordenave (2014) for the Iranian segment and Aqrawi et al. (2010), Aqrawi & Badics (2015) and English et al. (2015) for the Iraqi segment (Table 1). The Zagros, with a low initial $\beta$, thick broad pre-orogenic sedimentary wedge, multiple reservoir-seal pairs and 11 major sources and detachment intervals (Table 1) was predisposed to be a robust petroleum system that favoured a lower taper. The southern Pyrenees, in contrast with the Zagros, has a mostly eroded pre-orogenic sedimentary wedge. The southern Pyrenees is inferred to have a high initial $\beta$ and a thick and narrow pre-orogenic sedimentary wedge (Meigs & Burbank 1997). Using the northern Pyrenean Aquitaine basin (Biteau et al. 2006) as an analogue, the eroded pre-orogenic section of the southern Pyrenees is inferred to contain possible petroleum-system
Fig. 4. Simplified stratigraphic section at present-day thrust front for each fold and thrust belt. (Fig. 5 shows the location of the deformation front relative to the pre-orogenic architecture.) The sections are hung on the pre-orogenic stratigraphy. The thickness of the pre-orogenic section (blue) is indicative of how far the fold and thrust belt has advanced. The Zagros has a c. 10 km-thick pre-orogenic section with multiple source intervals (green ovals) preserved. The Pyrenees has completely consumed its pre-orogenic section and has no remaining source intervals. The mechanical stratigraphy is illustrated by the strong (red-brown) intervals and weaker detachment intervals (pink arrows = evaporite, brown arrows = mudstones). The Zagros has the most dynamic mechanical stratigraphy. The Beni has the least dynamic mechanical stratigraphy. The syntectonic sections (tan) reflect the dominant subsidence processes during the fold and thrust belt deformation.
elements (described below). It has a detachment near its base and a stiff section above (Meigs & Burbank 1997; Grool et al. 2018). This architecture made it predisposed to be a higher-taper system (Meigs & Burbank 1997). The Sevier pre-orogenic section has an inflection point where the sedimentary wedge thins and initial $\beta$ changes from moderate to low. This inflection point coincides with the loss of Paleozoic detachments and source intervals and becomes a focus of orogenic change and petroleum system exhumation. In the Beni Basin, Paleozoic source and detachment in the middle of the pre-orogenic sedimentary wedge may foster a lower-taper step-out at the leading edge of the fold and thrust belt. The near complete incorporation of the Beni system source intervals is a petroleum system preservation concern (Louterbach et al. 2018).

**Orogenic processes and syntectonic section**

Subsidence analysis studies the sedimentary filling of a basin through geologic time and space to understand the basin’s genetics (Xie & Heller 2009; Lee et al. 2019). Subsidence analysis of syntectonic sections is reflective of the subsidence mechanism. Flexural subsidence moves in front of an approaching orogenic load. Subsidence rates accelerate as the load moves into an area (DeCelles & Giles 1996). Dynamic subsidence is over a larger area and does not systematically vary or move. It is believed to be driven by deep lithospheric processes (Painter & Carrapa 2013). Figure 4 shows the syntectonic section at the thrust front of each orogen. The Zagros (Prouz et al. 2017) and southern Pyrenees (Vergès et al. 1998) appear to have flexural basin fill of 4–5 km (Fig. 4). The marine foreland sedimentation in the southern Pyrenees allows high resolution subsidence analysis; Vergès et al. (1998) and Grool et al. (2018) documented the 65 km advance of a 3–5 km deep flexural wave over a c. 30 myr period. The syntectonic section of the Sevier is indicative of a flexural system with a late dynamic subsidence overprint (Painter & Carrapa 2013; Yonkee & Weil 2015). The less constrained, inferred thick
Fig. 6. Sequential reconstructed cross-sections through the Zagros fold and thrust belt based on the restored cross-sections through Lurestan by Vergés et al. (2011) and Alavi (2007) and in Kurdistan by Koshnaw et al. (2017). Vertical exaggeration is 1:1. The pre-Zagros and proto-Zagros had significant potential hydrocarbon generative areas (green lines) (Aqrawi et al. 2010; Bordenave 2014; English et al. 2015). The middle Zagros low-taper system with large wedge-top basins (long blue arrow) was the optimal time for petroleum system formation. The late Zagros increase in taper, most dramatic at the Mountain Front Flexure (MFF), exhumed most of the generative wedge-top area (Bordenave 2014).
The syntectonic section used in this analysis for the Beni Sub-Andean fold and thrust belt is speculated to be a dynamically-enhanced flexural-basin system (Louterbach et al. 2018). Detachment intervals in the syntectonic sections shown in Figures 4 and 5 and noted in Table 1 can promote rapid step-out of the deformation front and potential lowering of local taper (Chapman & DeCelles 2015). This is similar to the impact of detachments in the pre-orogenic architecture discussed above. Syntectonic source intervals greatly expand the petroleum potential of a system as will be seen in the late Sevier system discussed below.

Zagros fold and thrust belt

The Zagros Orogen contains the most successful fold and thrust belt petroleum systems on the globe, with c. one-fifth of global proved reserves (Cooper 2007; BP plc 2018) (Fig. 1). The Zagros fold and thrust belt is a young, active taper-building flexural system that has consumed approximately half of its pre-orogenic sedimentary wedge (e.g. Mouthereau et al. 2012; Saura et al. 2015) (Figs 5 & 6). Its exceptional organic endowment and favourable architecture for robust wedge-top petroleum systems, and its relatively early phase in the incorporation of its organic

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**Fig. 7.** Sequential reconstructed cross-sections through the southern Pyrenees. Vertical exaggeration is 1:1. The optimal hydrocarbon generative time was at the initiation of the orogen. The source rocks, primarily near the base of the pre-orogenic section just above the basal detachment, would have shut down early. Any accumulations would have had to survive the exhumation and disruption of a high-taper orogenic wedge. Modified from Beaumont et al. (2000).
endowment in the orogen, contribute to its exceptional success (Bordenave & Hegre 2010). Its inherited architecture, with abundant source and detachment intervals, and dominance by flexural processes fostered phases of extensive wedge-top basins that created and preserved robust fold and thrust belt petroleum systems. Based on the analysis below, the Zagros was probably even more successful from a petroleum-systems standpoint before the most recent, mostly destructive phase of its evolution.

Summaries of the Zagros petroleum systems are in Aqrawi et al. (2010), Bordenave (2014) and Aqrawi & Badics (2015) for the Iranian segment, and in Aqrawi et al. (2010) and English et al. (2015) for the Iraqi segment (Table 1).

Pre-Zagros. The pre-orogenic architecture (Turonian at c. 90 Ma) is a thick and broad sedimentary wedge with multiple source and detachment intervals (Fig. 5 and Table 1). The broad sedimentary wedge and abundant detachments favour rapid
step-outs of deformation and lower-taper orogenic wedge phases. The sedimentary wedge is as much as 10 km thick, which would have driven the deeper source intervals into, and possibly through, their generative phases before any major shortening took place (Bordenave 2014). Green lines in Figure 6 define the potential generative areas by Bordenave (2014).

Proto-Zagros. The proto-Zagros obduction event (c. 70–40? Ma) created a local narrow, thick foreland system (Homke et al. 2009; Saura et al. 2011; Koshnaw et al. 2017), from 2 km to as much as 4 km thick in NE Kurdistan. This event, which formed the Amiran Basin in Iran, is distinct from the primary Zagros event discussed below. The tectonic and foredeep loads would have driven additional pre-orogenic source intervals through their main generative potential by this time. The broad activation of foreland structures (Abdollahie Fard et al. 2006; Saura et al. 2011) at this time created traps for the hydrocarbons that migrated west from the fold and thrust belt (Fig. 6). Several of the structurally trapped foreland accumulations shown on the map in Figure 6 were initiated at this time.

Bordenave (2014) describes the petroleum systems in the Iranian Zagros segment. A significant portion of the orogen’s organic endowment probably was driven through its major hydrocarbon generative potential before the Zagros flexural system started. The proto-Zagros petroleum systems can be audited in the proto-Zagros foreland traps shown on the map in Figure 6. Evidence of modified early hydrocarbon accumulations is recorded in altered and tilted hydrocarbon rims at some of the older accumulations in foreland traps. Dukhan Field of Qatar has a record of these early petroleum systems (Fig. 6). An integrated structural and geochemical analysis of the Dukhan structure (Norlund et al. 2009) shows folded degraded oil rims that restore back to horizontal when the Zagros growth section is unfolded. The implication is that proto-Zagros oil was trapped,
altered and then during the Zagros event was involved in additional folding. The orogen-perpendicular axis of the Dukhan Field also acts as an 80 km-long spirit level, tracking the flexural tilt of the structure into the fold and thrust belt foreland basin.

Some of the proto-Zagros foreland traps have a second life as they are later caught up in the fold and thrust belt (Bordenave 2014). The presence in the Fars salient of presumably pre-Zagros generated Paleozoic source hydrocarbons in post-generation Zagros traps implies a ‘hotelling’ of hydrocarbons in foreland traps to be re-migrated and trapped again when the fold and thrust belt incorporates the accumulations (for example, the gas accumulations in the fold and thrust belt on the extension of the Qatar Arch shown near the label ‘Fars’ on the map in Fig. 6). The presence of proto-Zagros foreland structural traps is another aspect that makes the Zagros an exceptional petroleum province.

Early to middle Zagros. The main Zagros flexural foreland system begins in Early Miocene time although older recognized folds in Lurestan started at about early-Middle Miocene time (Vergés et al. 2019). The subsidence analysis of Zagros deformation is dominated by a progressive flexural wave (Homke et al. 2004; Pirouz et al. 2017; Vergés et al. 2019). Early to middle Zagros (Middle Miocene to late Miocene–Pliocene boundary) deformation was dominated by low taper, utilizing numerous high-efficiency detachments. The middle Zagros orogenic wedge jumped out to its present-day deformation front by c. 5 Ma (see long blue arrow of Fig. 6) (Emami et al. 2010). Homke et al. (2004) document 8.1–7.2 Ma early growth at the present-day thrust front in Lurestan including folding and uplift above what will become the Mountain Front Flexure (MFF). Koshnaw et al. (2017) observe the same events in the Iraqi Kurdistan segment of the Zagros with a c. 8 Ma growth section at the present-day thrust front.

This low-taper system with a wide wedge-top zone was the most robust petroleum system of the Zagros fold and thrust belt. The maximum volume of source interval was driven to its generative depth during this phase (Bordenave 2014). The thick wedge-top basin sediments drove active generation while preserving the fold and thrust belt traps from exhumation. The surviving portions of the low-taper wedge-top basins in the Dezful and Iraqi Kurdistan embayments of the fold and thrust belt (see map, Fig. 6) have a very high success rate for petroleum accumulations in structural traps (Pitman et al. 2004; Bordenave 2014; English et al. 2015).

Late Zagros. The late Zagros stage of deformation (c. 5–0 Ma) involves an internal thickening of the orogenic wedge, with the basal detachment stepping deeper into the basement and an increase in elevation. The MFF (see map, Fig. 6) is the surface expression of the increasing taper (Emami et al. 2010; Gines et al. this volume, in press). In Lurestan the MFF is at the deformation front and has been documented to be active 3–2 Ma (Homke et al. 2004). Figure 6 shows the late Zagros deformation front (ZDF) in Lurestan does not advance much (short blue arrow) while the slope (α) increases. Additionally, to the north in Iraqi Kurdistan, Koshnaw et al. (2017) and Tozer et al. (2019) have documented a c. 5 Ma activation of the MFF, c. 80–100 km behind the low-taper deformation front. Furthermore, drainage reorganization and changes in the channel fill characteristics have likely been created by the increasing taper (Vergés 2007; Mouthereau et al. 2012). The detrital zircon record shows the loss of a distinct hinterland signal in relation to this youngest deformational phase. The rising mountain front likely creates a barrier that diverts and/or traps the hinterland detritus (Koshnaw et al. 2017).

This increasing taper exhumed the wedge-top basins, shut down most of the fold and thrust belt petroleum systems and destroyed existing accumulations. Behind the MFF, the petroleum systems degrade from active to survival mode (Bordenave 2014). The destruction is most extreme where the MFF is at the deformation front. Success rates change from very high in front of the MFF to very low behind the MFF. Abundant seeps, exhumed giant palaeo-accumulations (Goff et al. 2004) and a few successfully reconfigured accumulations from deeper petroleum systems behind the MFF (Bordenave 2014) are evidence of the former richness of the exhumed wedge-top zone (Fig. 6).

The Zagros orogenic system has consumed at least half of its hydrocarbon endowment. It was at its peak petroleum systems effectiveness during the early low-taper phase but is still outstanding, even after losing more than half of its wedge-top basins to exhumation. The organic endowment and the predisposition of the Zagros to be a low-taper fold and thrust belt system are major contributors to its successful petroleum systems.

Southern Pyrenees fold and thrust belt

This analysis specifically addresses the southern Pyrenees as reconstructed in the critical taper wedge models of Meigs & Burbank (1997) and Beaumont et al. (2000). This cross-section along the central part of the South-Central Unit (Grool et al. 2018) is analysed because it has multiple sequential steps and is focused on taper evolution (Fig. 7). Variations of the significant themes identified can be extrapolated to the other portions of the southern Pyrenees to different degrees. The southern Pyrenees is a small, classic, well-documented systematic advance...
of a flexural foreland basin system (Muñoz 1992; Vergés et al. 1998; Beaumont et al. 2000; Grool et al. 2018). Its pre-orogenic sedimentary section along this cross-section is inferred to have similarities to the less deformed Aquitaine Basin on the opposite side of the of the Pyrenean Orogeny (see map in Fig. 7).

_Aquitaine Basin, early southern Pyrenees analogue._ The Aquitaine Basin (2562 mmboe; Cooper 2007) is a significant preserved petroleum system in the Pyrenees Orogen (Bourrouilh et al. 1995; Biteau et al. 2006). The Aquitaine Basin is a foreland basin in the northern Pyrenees on the opposing upper plate of the doubly vergent Pyrenees Orogen (Bourrouilh et al. 1995; Biteau et al. 2006; Rougier et al. 2016; Teixell et al. 2018). The Aquitaine Basin and southern Pyrenees share a similar rift history (Grool et al. 2018). However, the southern Pyrenees rift section is mostly exhumed (Grool et al. 2018) while the Aquitaine Basin is only mildly deformed and exhumed (Vergés & García-Senz 2001; Biteau et al. 2006). The relatively abrupt lateral variation of the rift structure, as observed on the map in Figure 7 from the western Basque-Cantabrian zone to the easternmost Pyrenees, constrains the variations of the petroleum systems (Vergés & García-Senz 2001) (Fig. 7).

_Pre-Pyrenees._ The pre-orogenic architecture influenced the petroleum and tectonic evolution of the southern Pyrenees. The thick and narrow geometry of the pre-orogenic depositional wedge, with an excellent Upper Triassic detachment near the base of the thick stiff sequence (Grool et al. 2018), encouraged the involvement of the entire pre-orogenic wedge early in the orogen. This led to a relatively high-taper orogenic wedge (Meigs & Burbank 1997). The inferred concentration of organic matter at the base of the Mesozoic syn- and post-rift pre-orogenic section focuses the petroleum potential to the earliest phases of deformation (Table 1). Pre-50 Ma the 5–6 km thickness (Meigs & Burbank 1997; Vergés et al. 2002) of the sequence was sufficient to convert much of the organic matter to hydrocarbons even before the orogen had begun. Traps are commonly the missing element in late-rift and post-rift petroleum systems with deep source intervals.

_Early Pyrenees._ The earliest Pyrenees deformation around c. 50 Ma (Grool et al. 2018), when traps formed but the deep sources were not yet exhumed, was probably the most robust phase of the southern Pyrenees petroleum system, assuming it was similar to the Aquitaine Basin petroleum system. Discovery of tar sands and/or hydrocarbon fluid inclusions in the erosional remnants of this system would indicate a petroleum system that was once working. The location of both a possible source (inferred) and an excellent detachment (Grool et al. 2018) at the base of the pre-orogenic section would tend to make this a short-lived petroleum system.

_Middle to late Pyrenees._ By middle Pyrenees (30 Ma), the inferred pre-orogenic organic endowment was being exhumed, as were any palaeo-accumulations. Any accumulations would have had to survive the 65 km of deformation front advance with limited chance for recharge. The taper is generally high at 4–5° (Meigs & Burbank 1997). During the mid to late Pyrenees (long blue arrow in Fig. 7) there is a rapid advance of the deformation front, facilitated by syntectonic detachments with a slight lowering of the taper (Meigs & Burbank 1997). This occurs after consumption of the pre-orogenic source rocks. A small preserved petroleum system in the southern Pyrenees corresponds to early Eocene syntectonic source rocks locally deposited during the early Pyrenees stages of the marine foreland basin. This sourced a small unique productive gas field (e.g. Alvarez 1994). The lack of an extensive syntectonic source, like that in the Sevier Orogeny (below), precludes the development of late robust petroleum systems. The southern Pyrenees petroleum potential is thus in preserved remnants of an early petroleum system or in local anomalies.

_Sevier fold and thrust belt._ The Sevier Orogen (Fig. 1) is a composite fold and thrust belt with an early flexural wave that is overwhelmed by dynamic subsidence and uplift processes (DeCelles 2004; Painter & Carrapa 2013; Yonkee & Weil 2015). The dynamically driven, exceptionally broad and thick foreland sets the Sevier apart from the previously mentioned orogens. Schematic cross-sections (Fig. 8), based on the sequential restorations of Constenius et al. (2003), DeCelles & Coogan (2006) and Yonkee & Weil (2015) and on the foreland stratigraphy of DeCelles (2004) and Painter & Carrapa (2013), attempt to capture the interplay of the flexural v. dynamic processes. The consumption of the pre-orogenic source intervals and involvement of significant syntectonic source intervals created a world-class petroleum system (Campbell & Ritzma 1979). Exhumation driven by post-orogenic events has left only tar sand remnants of this giant petroleum system (Campbell & Ritzma 1979).

_Early Sevier._ Early Sevier (c. 155 to c. 85 Ma) is characterized by a progression of flexural basins and relatively low-taper system (DeCelles & Mitra 1995). Isopachs track this progression of sediment accumulation (Burtner & Nigrini 1994; DeCelles 2004; Painter & Carrapa 2013). DeCelles (2004), Painter & Carrapa (2013) and Yonkee & Weil...
probably consumed during this early phase (Burtner 1994). Most of the pre-orogenic source rocks were thought to have been exhumed by the increasing taper (Burtner & Nigrini 1994), which was likely the most robust phase for fold and thrust belt petroleum systems. The surviving fold and thrust belt accumulations are associated with the best-preserved wedge-top basins in northern Utah and southern Wyoming. Pre-orogenic sources probably generated hydrocarbons during this period (Burtner & Nigrini 1994); however, unlike in the Zagros Orogen, there were few foreland traps to catch hydrocarbons migrating out of the Sevier fold and thrust belt during this phase.

**Middle Sevier.** During the middle Sevier (c. 85–70 Ma), the deformation front stopped advancing (short blue arrow of middle and late Sevier in Fig. 8) as the orogen built taper (DeCelles & Mitra 1995; Constenius et al. 2003; DeCelles & Coogan 2006), creating a number of structural culminations. Dynamic uplift of the fold and thrust belt and dynamic subsidence of the distal foreland began to dominate during this period of taper increase (DeCelles 2004; Painter & Carrapa 2013; Yonkee & Weil 2015). The middle Sevier cross-section (Fig. 8) shows limited sediment accumulation at the deformation front, with maximum accumulation shifting 200 km east into the distal foreland. By the end of this phase most of the fold and thrust belt petroleum systems were shutting down and being exhumed by the increasing taper (Burtner & Nigrini 1994). Few foreland structures existed to trap the hydrocarbons generated during the middle Sevier phase. The Moxa Arch (Fig. 8, red arrow on map) is an exception. It is interpreted to be a basement-cored Laramide style foreland uplift in a subsiding foreland basin (Becker & Lynds 2012). The Moxa Arch is probably too small (c. 20 × 70 km) (Becker & Lynds 2012) to be driven by geodynamic unloading processes in the subsiding foreland. The Moxa Arch hosts the most successful surviving foreland petroleum accumulations of the Sevier foreland and the world’s largest CO₂ accumulation. It contains early traps able to catch hydrocarbons generated in the fold and thrust belt, with minor late reactivation aiding preservation. This scenario is similar to the successful Zagros foreland.

**Late Sevier.** Late Sevier (c. 70–50 Ma) tectonics are characterized by limited advance of the deformation front, enhanced dominance of dynamic processes and the addition of multiple high-relief basement-cored Laramide style uplifts in the foreland. These local uplifts, illustrated on the late Sevier c. 66 Ma cross-section in Figure 8, complicate the subsidence pattern, adding local flexural subsidence to the long wavelength dynamic subsidence (Yonkee & Weil 2015). There was very little sediment accumulation at the deformation front at this time, as the centre of accommodation shifted to 400 km east of the deformation front.

Exhumation of the fold and thrust belt continued to shut down and destroy its petroleum systems (Burtner & Nigrini 1994) while local flexurally-enhanced dynamic subsidence of the foreland drove some of the syntectonic source intervals to hydrocarbon generation (Anna et al. 2007). One challenge for the foreland uplifts is breaching of the foreland traps as a result of structural relief and exhumation (Fig. 8; Fan & Carrapa 2014).

The post-orogenic events extended, uplifted, tilted and eroded the fold and thrust belt province (Constenius et al. 2003; DeCelles & Coogan 2006; Yonkee & Weil 2015) while exhuming 1–2 km of section from the foreland (Lazear et al. 2013). Only complicated erosional remnants (e.g. Chidsey et al. 2007), containing 3167 mmboe of economic hydrocarbon accumulations (Cooper 2007) remain of what probably were world-class petroleum systems (Fig. 8). Some 29 000 mmboe of uneconomic heavy oil accumulations (Campbell & Ritzma 1979), which occur as small remnants on the flanks of deeply eroded foreland highs, provide evidence of major foreland petroleum systems that have been exhumed. The situation would be similar if 2 km of overburden were eroded from the Zagros system.

**Beni Sub-Andean fold and thrust belt**

The Beni fold and thrust belt segment of the northern Bolivian Sub-Andean (Fig. 1) is poorly constrained due to sparse data in a difficult-to-date non-marine syntectonic section. It has been included in this discussion to demonstrate the applicability of PTA techniques to fold and thrust belts that have not yet been extensively investigated. In general, PTA of an under-constrained interpretation highlights the uncertainties and offers potential ways to add constraints.

Roeder (1988), Baby et al. (1995, 1997) and McQuarrie et al. (2008) interpreted the Beni fold and thrust belt as a thin-skinned system. The analysis presented here tracks the organic endowment utilizing sequential restorations generated by Louterbach et al. (2018) involving both thin-skinned thrusts...
and high angle basement faults. As discussed in the stratigraphic analysis and in Table 1, all the elements for petroleum accumulations are present in the Beni fold and thrust belt; the primary uncertainty is when the overburden was applied and removed. Louterbach et al. (2018) interpreted an early history of a step-out at the deformation front with a thick wedge top, followed by internal deformation and erosion of the fold and thrust belt. In this context, the greatest probability of a robust petroleum system occurred in the early phase and accumulations would need to have survived the later exhumation phase to be preserved.

Pre-orogenic Beni. The pre-orogenic Beni (40 Ma) consists of a Paleozoic to Early Cenozoic narrow thin pre-orogenic sedimentary wedge (in cross-section view) described in the stratigraphic analysis discussion above and in Table 1. Upper Paleozoic source and detachment intervals are both in the upper half of the pre-orogenic sedimentary wedge (Fig. 5), geometry favourable for a robust low-taper wedge-top petroleum system. Petroleum system modelling by Baby et al. (1995) indicates that deeper Paleozoic source intervals are in a generative phase before initiation of the fold and thrust belt deformation (green lines in Fig. 9). As in the Zagros and Sevier PTAs above, any inferred pre-orogenic generative phases could be audited in pre-orogenic traps in the modern Beni foreland basin.

Early Beni. The early (40–16 Ma?) evolution of the Beni involved the step-out of the thrust front to near the edge of the Paleozoic detachment (long blue dashed arrow of early Beni in Fig. 9). The timing is consistent with that proposed by Rak et al. (2017). This is interpreted as a low-taper wedge with 5 to possibly 8 km thick wedge-top deposits (Louterbach et al. 2018). This step-out is analogous to the middle Zagros step-out, discussed above, which created its most robust wedge-top petroleum system. There is a clear early Miocene flexural subsidence signal with subsidence accelerating through time (Louterbach et al. 2018). A comparison to the Sevier orogenic system implies that there could be additional processes active at this time. The interpreted very thick wedge top could be due to dynamic subsidence enhancement. To identify an overprinting dynamic subsidence process, detailed age control and area-wide subsidence analyses showing a progressing flexural signal, similar to that in the Pyrenees but with excess regional subsidence, is required.

Deformation was initiated by the Early Miocene when Paleozoic source rocks received additional overburden, resulting in a second phase of hydrocarbon generation (Baby et al. 1995), as indicated by the green lines in Figure 9. As interpreted, the deformation front has jumped out to near its furthest extent, with its maximum wedge-top section at this time. This is the most favourable time for a robust hydrocarbon system in the Beni fold and thrust belt. The broad generative areas and simple traps of the early Beni fold and thrust belt are analogous to the Zagros wedge-top basins. The thick wedge top keeps generation going on and precludes exhumation of the traps, but there is a potential risk of over-maturation of source rocks and degradation of reservoir quality. Identifying the processes controlling the possible extra thickness is important for distributing this potential risk of over-maturity. The sub-economic Candamo accumulation, located c. 200 km to the NW in the Sub-Andean zone of the southern Peruvian Madre de Dios fold and thrust belt, is characterized by high maturity gas/condensate with marginal reservoir quality (McGroder et al. 2015) and may be a survivor of a similar overburden scenario.

Middle Beni. It is speculated that around 16–8 Ma the orogenic wedge began building taper by an increase of the internal deformation, modifying and developing new structures in the orogenic wedge while not significantly advancing (short blue arrow of middle Beni in Fig. 9). The internally thickening orogenic wedge complicates traps, reducing some generative areas while potentially over-maturing others. Integration of thermochronological, geochemical, magnetostratigraphy and detrital zircon data would provide tighter constraints on the sequencing of deformation. It is inferred that this phase would disrupt potential generative areas (shortened green lines in Fig. 9).

Late Beni. In the late phase (8–0 Ma), the front of the orogenic wedge did not significantly advance (short blue arrow of late Beni in Fig. 9) but continued building taper, while the dynamic influence may have reversed from dynamic subsidence to dynamic uplift in the fold and thrust belt. This interpreted regional uplift is based on the highly eroded aspect of the fold and thrust belt and on the projection of thermochronology results from the Madre de Dios Basin in southern Peru, c. 200 km to the NW (Louterbach et al. 2014, 2018), which show a Plio-Pleistocene period of broad uplift of both the eastern side of the Eastern Cordillera and the Sub-Andean zone. The interpreted lack of a foredeep for the late Beni fold and thrust belt may indicate a dynamic uplift, similar to the late Sevier (Fig. 9). Taper increases with the involvement of a deep basement level detachment similar to the MFF of the late Zagros phase discussed above. The late erosion could be driven by dynamic uplift and/or the basement related faults. Higher density thermochronological uplift analysis, as in the Sevier, is required to constrain the dominant driving mechanism and areal extent of the exhumation with more certainty. From a petroleum
systems context the inferred broad uplift would shut down potential generative areas. Integrated studies like that of the Dukhan Field (Nørlund et al. 2009) in the Zagros foreland could document this shut down and identify modified palaeo-accumulations, further constraining the possible interpretations. A PTA of the dominantly thin-skinned interpretations (Roeder 1988; Baby et al. 1995, 1997; McQuarrie et al. 2008) of this portion of the Beni fold and thrust belt has different petroleum system implications. A continuous break-forward sequence with a narrow wedge top would have more limited hydrocarbon opportunities: for example, the frontal trap in a break-forward thin-skinned sequence would be the youngest, with limited to no connections to generative areas, while in the analysis presented above the frontal traps are among the oldest in the fold and thrust belt and had access to long-lived generative areas. The broad range of uncertainties in the Beni fold and thrust belt highlights the importance of well constrained geochronologic, thermo-chronological and integrated geochemical data.

The limited data in the Beni precludes definitive identification of the dominant processes (flexural vs. dynamic) through time, but the PTA puts the Beni fold and thrust belt in a global context that enhances our understanding of its tectonic evolution and provides perspective for where new data could have the most significant impact.

Recognizing the uncertainties, the Beni fold and thrust belt’s pre-orogenic architecture and possible thick syntectonic load indicate an orogenic system that was more favourable for hydrocarbon accumulations in its early development. The Beni fold and thrust belt is under-explored, with only 3 mmboe of discovered reserves (Cooper 2007). A focus on defining the dominant tectonic processes is required. In the present day, the Beni appears to be in exhuming mode with the best chance for survival of petroleum accumulations in areas that are exceptions to the general tectonic trends, similar to the preserved wedge-top basins of the Sevier Orogen.

**Discussion**

Petroleum-systems evolution of fold and thrust belts provides a perspective for the genetic analysis of orogenic systems. The distribution of organic matter and its deformation pathway during orogeny determine the realization of hydrocarbon potential and preservation of petroleum accumulations. Common petroleum system basin modelling in the industry is one- or two-dimensional, stacking stratigraphy or maps based on present day geometries (Magoon & Dow 1994; Al-Hajeri et al. 2009; Peters 2009). This approach is a good proxy in areas of simple vertical motion but breaks down completely when there is significant horizontal displacement. This is especially the case in fold and thrust belts where there can be significant shortening of potential source intervals. More sophisticated kinematic and petroleum system appraisal (e.g. Burtnet & Nigrini 1994; Roure & Sassi 1995; Calderón et al. 2017) can be enhanced with the integration of a genetic tectonic context incorporated into PTA. PTA attempts to be more of a four-dimensional proxy for the evolution of petroleum systems in fold and thrust belts, potentially providing a more rigorous analysis.

Tectonic analyses do not commonly fully utilize the constraints on tectonic evolution that can come from an integrated petroleum system analysis. A web search of ‘fold and thrust belt tectonics’ publications yields over 145 000 publications. Of these only c. 5000 have any mention of ‘petroleum systems’. When an organic-rich interval has been incorporated into a fold and thrust belt the presence and/or remains of petroleum systems can provide powerful constraints on the processes involved in the fold belt’s evolution. PTA is another tool that can assist in investigating fold and thrust belt genetics.

**Orogen comparison and contrast**

Figure 10 is a side-by-side overview of the interplay of tectonic processes with their petroleum system impacts through time for each orogen analysed. It identifies times most favourable for accumulation of hydrocarbons (dark green polygons) and the times with greater risk for their destruction (red polygons).

The Zagros is a flexural orogen that has a fortuitous alignment of elements and processes for hydrocarbon generation and preservation (Fig. 10). Its multiple stacked sources ensure continuous hydrocarbon generation while stacked detachments foster a low taper and wide wedge-top basins. A pre-orogenic, gently deformed foreland catches hydrocarbons as early traps are incorporated into the fold and thrust belt.

The Pyrenees is also a flexurally dominated orogen, but the early consumption of its source rocks means few accumulations survived exhumation in a long lasting, relatively high-taper orogenic wedge.

The Sevier is a flexural system that was later dominated by dynamic uplift of the fold and thrust belt and distal foreland subsidence with foreland deformation. The late high-taper phase exhumed much of an earlier more robust lower taper fold and thrust belt petroleum system. The addition of syntectonic foreland sources to be matured by dynamic subsidence with contemporaneous traps added a second optimum time for hydrocarbon accumulations in the Sevier foreland. Post-orogenic uplift

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and exhumation have left only remnants of what were once world-class petroleum systems.

The Beni segment of the Sub-Andean Orogen is similar to the Sevier, with a pre-orogenic source that is expected to have had high thermal exposure. It probably had its most robust petroleum system during its early low-taper flexural phase with dynamic subsidence enhancement. Its late high-taper system with possible dynamic uplift shut down and stressed the petroleum systems. The lack of significant syntectonic sources and foreland traps like those in the Sevier and Zagros limits the Beni’s

![Fig. 10. PTA summary chart. The vertical axis is time stretched to the length of time investigated. Note each orogen has a different time scale. Blue dashed horizontal lines correspond to restored cross-sections in Figures 6–9. The first two columns track the interplay of flexural and dynamic subsidence. Dynamic subsidence is light grey. Dynamic uplift is black. The taper and wedge-top columns track the evolution of the frontal orogenic wedge. The exhumation column (magenta) tracks whether the net result of the orogenic system is dominated by erosion of the wedge top or by the preservation of the petroleum-system elements. The width of the sixth column (light green polygons) tracks the potential for active hydrocarbon generation and is labelled with the dominant source area: pre-orogenic, syntectonic, or foreland. When the source has been completely incorporated into the fold and thrust and subjected to extensive exhumation its generative polygon terminates and it is labelled ‘exhausted’. This is an indication of shortening relative to the source distribution. The traps formed (green lines) and traps destroyed (red lines) columns track the formation of traps and their destruction in the foreland (when present) and in the fold and thrust belt; the width of the line indicates which is dominant. The last column with dark green polygons highlights optimum petroleum system timing in the fold and thrust belt and in the foreland. The Zagros foreland, with pre-existing traps and no exhumation, is always optimum (long dark green polygon). The Zagros fold and thrust belt was optimum during the low-taper phase with wide wedge-top basins (shorter dark green polygon). The southern Pyrenees is inferred to have an early optimal hydrocarbon time (short dark green polygon) long before it went through a long destructive phase. The Sevier fold and thrust belt petroleum system is interpreted to have been optimal before c. 85 Ma (first long dark green polygon) after which it had to survive high-taper and probably eventually dynamically driven exhumation. The Sevier has a second optimum petroleum system (second long dark green polygon) driven by dynamic subsidence in its foreland. The Beni fold and thrust belt has greater uncertainty but the early low-taper phase with possible dynamic enhancement was probably its optimum petroleum system (short dark green polygon).]
hydrocarbon potential to early accumulations that survived later exhumation.

The broadly deformed forelands of the Zagros and Sevier create a set of traps in addition to the fold and thrust belt traps (Fig. 10). These foreland traps complete exceptional foreland petroleum systems that complement the fold and thrust belt petroleum systems. The controls on foreland deformation are unclear but they appear to be in part related to reactivation of inherited zones of weakness. In the foreland, as in the fold and thrust belt, the inherited architecture is important. The Zagros and Sevier foreland traps capture hydrocarbons escaping from the fold and thrust belts and record the history of the fold and thrust belts, as is seen in the Dukhan Field of the Zagros and the Moxa Arch of the Sevier. In addition, foreland traps can act as hotels for hydrocarbons that can be re-migrated and trapped again when they are incorporated into the fold and thrust belt, as appears to happen in the Paleozoic petroleum system of the Fars segment of the Zagros.

The interplay of flexural and dynamic processes in the evolving deformation front strongly influences the success and/or failure of hydrocarbon systems. Dynamic subsidence provides an opportunity for the deposition of more overburden, whereas dynamic uplift induces exhumation of petroleum systems. The Zagros and Pyrenees do not appear to record a strong dynamic overprint. In the late Sevier the dynamic processes overwhelmed the flexural processes, stressing the fold and thrust belt petroleum systems, while in the early Beni dynamic processes may have enhanced and/or overmatured the petroleum systems. In addition, the late Sevier has strong dynamic subsidence far into its foreland, creating a major foreland generative region that the other fold and thrust belt systems addressed lacked.

**Upper plate v. lower plate processes**

It is interesting to note that the dynamic influences appear more pronounced on the Sevier and Beni Sub-Andean orogenic systems, which are both on the upper plate of convergent orogenic margins. The Zagros and southern Pyrenees are on the lower plate and do not appear to have been as significantly influenced by dynamic processes. Ziegler et al. (2002) argued that the lower plate foreland subsidence is exclusively controlled by the topographic load exerted by the orogenic wedge whereas the upper plate foreland has an additional load exerted by the pull of the down-going slab. This might be expected given the upper plate is subjected to various influences from the lower plate it is overriding. Upper plate responses to lower plate changes in convergence, slab angle and slab coupling have been proposed for the Andes (Ramos & Folguera 2009; Horton 2018) and the Sevier (DeCelles 2004; Lazear et al. 2013; Painter & Carrapa 2013; Yonkee & Weil 2015). Heller & Liu (2016) see a consistency between late Sevier subsidence patterns and a geodynamic inverse convection model for the passing lower plate. Petroleum system evolution has been significantly impacted by these overprinting deep processes.

The lower plate Southern Pyrenees (Iberian microplate) and Zagros (Arabian plate) do not appear to have a major geodynamic overprint. The proto-Zagros (c. 70 Ma) foreland’s subtle reactivation of features indicates some stresses are being transmitted far into the foreland during that time frame. The Aquitaine basin, discussed as possibly sharing a rift history with the analysed southern Pyrenees, is on the upper plate side of the Pyrenean orogenic system. A PTA comparison of the southern Pyrenean and Aquitaine systems would be informative. Ziegler et al. (2002) identified the Ouachita–Marathon orogenic system of North America as a potential upper plate system with anomalous uplifts and subsidence over 1500 km into its foreland. The multiple petroleum systems in the Ouachita–Marathon foreland would lend themselves to an interesting PTA effort. PTA offers another avenue for investigation of additional orogenic systems.

**Orogenic processes and fold and thrust belt petroleum systems**

Flexural processes create and destroy petroleum systems as they advance. The most favorable tectonic circumstance for hydrocarbon accumulations is when the frontal orogenic wedge is at a relatively low-taper phase after a rapid advance. In these conditions the maximum amount of source interval can be preserved from exhumation in generative conditions while directly adjacent to preserved traps. The present day Dezful and Kirkuk embayments in the Zagros, the early Zagros, the end of the early Sevier and the early Beni Sub-Andean are robust low-taper thick wedge-top petroleum systems. In the Pyrenees, the lowering of taper associated with a step-out of the deformation front along a syntectonic detachment at c. 29 Ma had the most expansive wedge top but the lack of a well-developed syntectonic source interval precluded an extensive petroleum system.

A taper-building phase trends toward destruction and exhumation of petroleum systems. The Lurestan and Fars salients of the Zagros, the southern Pyrenees, the late Sevier and the late Beni Sub-Andean are high-taper phases that destroy petroleum systems. Petroleum system preservation in high-taper systems is most likely in areas that diverge from the dominant theme of exhumation. The preserved accumulations associated with remnants of
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an eroding wedge-top cover in the Sevier and in the Fars and Lurestan portions of the Zagros are examples of effective accumulation survival scenarios. The exploration potential for the Beni Sub-Andean fold and thrust belt as analysed is best in areas that are exceptions to its interpreted strong exhumation theme.

The pre-orogenic architecture, including the shape of the pre-orogenic sedimentary wedge and its mechanical stratigraphy, heavily influence the evolution of fold and thrust belts. The fold and thrust belt kinematics are regulated by the presence or absence of mechanically weak and strong layers within the orogenic wedge. The Zagros, with a thick broad pre-orogenic depositional wedge and multiple detachments in both pre-orogenic and syntectonic sections, favours lower taper and a robust wedge-top basin. The thick narrow Pyrenees pre-orogenic depositional wedge, with a dominant basal detachment, favours a high taper. Both the pre-orogenic detachments in the thick portion of the Sevier pre-orogenic sedimentary wedge and the syntectonic detachments above the thin portion, favour an early low taper. However, the termination of the pre-orogenic detachments as the depositional wedge thins favour a later high taper. The Beni Sub-Andean has a pre-orogenic sedimentary wedge shape similar to the Pyrenees but a good detachment in the upper half of the wedge makes it favourable to have an early low taper phase.

The distribution of source rocks sets the framework for the evolution of petroleum systems in fold and thrust belts. The Zagros has stacked multiple source rocks, making it the best fold and thrust belt petroleum province in the world. The Pyrenees is challenged because the best source is at the bottom of the section. The Sevier has sources in the thick portion of the pre-orogenic depositional wedge and the addition of excellent syntectonic source rocks. The Beni Sub-Andean, with its best-known source in the upper half of the pre-orogenic sedimentary wedge, is less challenged than the Pyrenees.

**Shortening relative to source length**

The amount of shortening relative to the length of source intervals is a key control on the realization of the petroleum potential of a fold and thrust belt (Table 1). The further back into the orogenic wedge a source interval is incorporated, the more likely its petroleum systems are to be consumed. The red arrow in Figure 5 indicates the present-day deformation front of the fold and thrust belt relative to the pre-orogenic architecture and source distribution. The southern Pyrenees has completely consumed its pre-orogenic sedimentary wedge and source intervals, leaving a challenged petroleum system. The Beni Sub-Andean has consumed most of its pre-orogenic sedimentary wedge and source intervals. It is less challenged. The Sevier has consumed more than half of its pre-orogenic sedimentary wedge and source intervals but adds syntectonic source intervals, resulting in more robust petroleum systems. The Zagros has consumed only half of its pre-orogenic sedimentary wedge and adds an additional syntectonic source interval. The Zagros has very robust petroleum systems.

In the context of the fold and thrust belts analysed above, the presence and distribution of source intervals sets the stage for the evolution of the petroleum systems in the fold and thrust belt. The amount of shortening relative to the source intervals is a major control on how the petroleum potential is realized and preserved. The pre-orogenic architecture and mechanical stratigraphy as they impact the deforming orogenic wedge modulate the petroleum systems, affecting their robustness and preservation. The dominance of flexural v. dynamic processes also modulates the petroleum systems. Where and when the flexural and dynamic processes are active impacts the distribution, robustness and preservation of the petroleum systems.

PTA is an effective way to examine the major processes of an orogenic system. Tracking the narrow range of deformation pathways for the generation and preservation of hydrocarbon accumulation provides an audit of the dominant processes in an orogen. The Zagros is an organic-rich flexurally dominated orogen, the Pyrenees is an organic-poor flexurally dominated orogen, the pre-orogenic and syntectonic sources of the Sevier orogen had optimal conditions for petroleum systems in the fold and thrust belt during its early, flexurally dominated phase and in the foreland during its later, dynamically dominated phase, and the Beni Sub-Andean is an organically challenged flexural system with possible dynamic overprints.

**Conclusions**

**PTA**

PTA is an effective way to investigate the genetic evolution of a fold and thrust belt that has organic-rich intervals. Tracking the petroleum system evolution is an audit of the dominant processes in an orogen. How the pre-orogenic architecture interacts with competing orogenic processes is reflected in the creation and destruction of petroleum systems.

**Analysed fold and thrust belts**

The nature of the rocks that are incorporated into a fold and thrust belt can be tracked in its petroleum system evolution. The distribution of source rocks and the pre-orogenic architecture, including the
shape of the pre-orogenic sedimentary wedge and its mechanical stratigraphy, greatly influence the evolution of petroleum systems within the analysed fold and thrust belts. The amount of shortening relative to source distribution controls the realization and preservation of the petroleum potential. The Zagros fold and thrust belt, with its limited relative shortening and generous endowment of organic and detachment intervals, had the best set-up for petroleum systems; in contrast, the Pyrenees, with relatively extreme shortening and both limited and deep organic and detachment intervals, had the worst set-up for petroleum systems.

Competing orogenic processes interact with the pre-orogenic architecture of a fold and thrust belt to determine its petroleum system evolution. The interplay of flexural and dynamic processes in the evolving deformation front strongly influences the success and/or failure of petroleum systems. As a flexural foreland system advances, dynamic subsidence, as seen in the Sevier foreland and as inferred for the Beni uplift, provides additional overburden, whereas dynamic uplift induces exhumation, as seen in the late Sevier and as inferred for the late Beni Sub-Andean fold and thrust belts.

The most favourable tectonic circumstance for hydrocarbon accumulations in the fold and thrust belts analysed is when the deformation front maximizes wedge-top basins. This can happen when the orogenic wedge front steps out to a local relatively low-taper phase. The maximum amount of source interval can be preserved at optimum generative conditions while directly adjacent to preserved traps.

The Dezful and Kirkuk embayments in the Zagros and the early Zagros, the early Sevier and the inferred early Beni Sub-Andean are local relatively low-taper wedge-top phases favouring the formation and preservation of petroleum systems. Local higher-taper wedges can lead to destruction and exhumation of petroleum systems. The Lurestan and Fars salients of the Zagros, the southern Pyrenees, the late Sevier and the late Beni Sub-Andean are local high-taper phases that destroy petroleum systems.

Petroleum system preservation in high-taper systems is most likely in areas that diverge from the dominant theme of exhumation. The preserved accumulations associated with remnants of an eroding wedge-top cover in the Sevier and in the Lurestan and Fars salients of the Zagros are examples of effective accumulation preservation scenarios.

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