Syn-kinematic strata influence the structural evolution of emergent fold–thrust belts

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Abstract: Whether thrusts are ramp-dominated and form imbricate fans or run out onto the syn-orogenic surface, forming 'thrust-allochthons', is governed by the activity of secondary 'upper' detachments along the syn-orogenic surface, activations of which are inhibited by syn-kinematic sedimentation at the thrust front. In the northern Apennines, where thrust systems are ramp-dominated and form an emergent imbricate fan, syn-kinematic sedimentation was abundant and accumulated ahead and above each thrust. In the southern Apennines, the far-travelled Lagronegro allochthon achieved its high displacements (>65 km) while the foredeep basin received little sediment. The imbricate fan at the front of the main Himalayan arc developed within a foredeep that experienced high rates of syn-kinematic sedimentation. In contrast, further west, the Salt Range Thrust emerged into a distal, weakly developed foredeep with significantly reduced rates of sediment accumulation. Displacements were strongly localized onto this thrust (c. 25 km displacement) which activated an upper detachment along the syn-orogenic surface. It is an arrested thrust-allochthon. Lateral variations into the adjacent, ramp-dominated but still salt-detached, Jhelum fold-belt are marked by increases in syn-kinematic sedimentation. As sedimentation styles can vary in space and time, individual thrusts and thrust systems can evolve from being allochthon prone to imbricate dominated.

Kinematic explanations of fold–thrust structures are commonly illustrated graphically as developed in stratigraphic templates that are laterally unvarying. Mechanics are monotonous – the layering in the models is shown simply to chart displacements. Over-reliance on these idealized approaches has led to significant problems in the interpretation of natural structures – numerous studies of natural fold–thrust belts have shown that inherited stratigraphic variations and structures, especially pre-existing faults, can play important roles not only in localizing thrust surfaces but also in promoting disharmonic deformation (reviewed by Butler *et al.* 2018). These concepts of structural inheritance, preconditioning deformation, are now well established, and are especially important at low strain states. However, syn-kinematic strata can also influence structural evolution (e.g. Leturmy *et al.* 1995, 2000; Storti & McClay 1999). As such, the integration of stratigraphic information of syn-kinematic deposits may reduce uncertainty in the interpretation of thrust belt structure if these influences can be generally established. The aim of this paper is to explore these influences, specifically the role of sedimentation at the toe of a thrust sheet, on the gross structure of thrust systems. It is illustrated with natural case studies from the Apennines of Italy and the frontal portions of the NW Himalayas.

Thrust trajectories in emergent systems

Emergent thrust systems are those where structures interact directly with the syn-orogenic surface. They contrast with buried systems where thrusts recombine updip. Emergent thrust systems are characterized by imbricate fans, with the direct incorporation of syn-kinematic sediments. Syn-kinematic sediments cannot be incorporated into buried systems such as duplexes because thrusts are entirely enveloped by branch-lines (see Boyer & Elliott 1982). Emergent imbricate fans and duplexes both rely on regionally extensive detachment horizons, such as over-pressured shales or evaporites, to preferentially form floor-thrusts. It is these geometries that, since the work of Cadell (1889), have been widely reproduced in analogue models (reviewed by Graveleau *et al.* 2012), interpreted from seismic sections through accretionary prisms at subduction zones (e.g. Grando & McClay 2007 amongst many others) and used to understand thrust-related sedimentary basins (e.g. Ford 2004). It is the aggregation of the combined displacements across the imbricate fan that allows these types of thrust system to accommodate large horizontal contractional strains. Consider a thrust system forming with only a single detachment horizon (Fig. 1a), without active erosion or deposition. The geometries of imbricate thrusts

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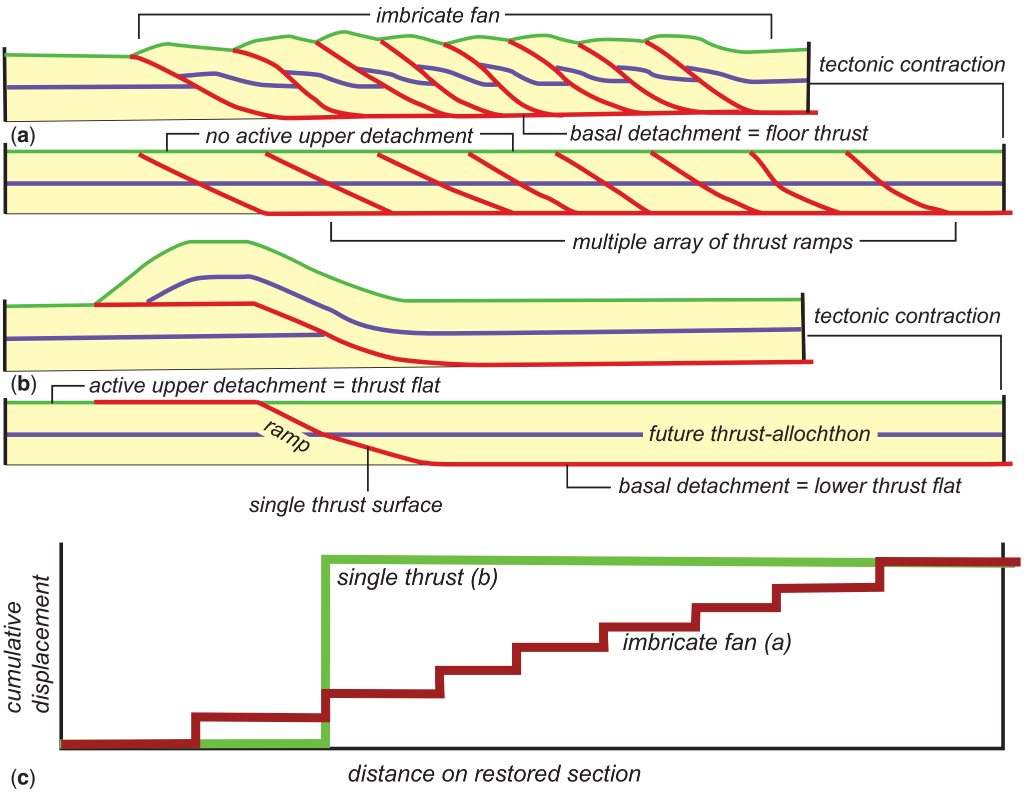

Fig. 1. Contrasting examples of thrust localization. (**a**) A final and undeformed state section where the strata are deformed into an imbricate fan and there is only one detachment surface – which acts as a floor thrust. (**b**) A single thrust sheet carried on a thrust that follows two detachment (flat) levels. It is this geometry that can evolve into a thrust allochthon (far-travelled thrust sheet). These two sections show the same tectonic contraction (so would be compatible with each other within a thrust system). (**c**) The distribution of displacement, referenced to the restored section, for the two scenarios. A similar relationship could apply when considering time-averaged displacement rate.

are ramp-dominated so displacements are significantly less than the thickness of strata involved in the structure. In order to achieve large displacements (Fig. 1b), the thrust must run along a secondary detachment, the upper flat. The thrust trajectory forms a staircase. It is in this manner that large-displacement thrust sheets ('thrust-allochthons') can develop – they need to be detachment (thrust-flat) dominated. Note that the development of large-displacement thrusts is very rarely investigated in analogue models (but see Bonnet *et al.* 2008) and are perhaps under-represented in the catalogue of theoretical thrust system forms.

There is an important proviso to the argument outlined above: that the thrust sheet is not continuously eroded back as it is emplaced. There are natural situations where this erosion happens – including at the Alpine Fault in New Zealand (e.g. Little *et al.* 2005). However, this might be regarded as an extreme case as erosion rates are amongst the fastest on the planet. Apparently, it is erosion that keeps the thrust belt located onto a single structure. In the settings described here, the structures are formed in, and at the margins of, foredeeps: they are foreland fold–thrust belts. Consequently, it is the surface processes of deposition rather than erosion that are likely to be more important.

That syn-kinematic sedimentation should influence the structural evolution of thrust belts (e.g. Ford 2004) is a simple corollary of theories of wedge dynamics, as originally configured by Davis *et al.* (1983). The distribution of sedimentation across and ahead of thrust wedges changes the surface slope that, together with the orientation of the basal detachment and rheology (e.g. cohesion, overpressure) along the detachment and within the translating mass, exerts a control on the mechanical state of the thrust wedge. The consequences of active sedimentation for structural evolution of individual fold–thrust structures has been investigated by numerical models (e.g. Strayer *et al.* 2004; Vidal-Royo *et al.* 2011; Hughes *et al.* 2014). Analogue models show that the spacing and geometry of imbricate thrusts, together with their relative timing and activity, change depending on syn-kinematic sedimentation (Storti & McClay 1999; Bonnet *et al.* 2008; Barrier *et al.* 2013). Elsewhere it is argued that the relative partitioning of sedimentation ahead of the thrust wedge strongly influences the geometry of the thrust belt (Butler *et al.* 2019).

The relationship between sedimentation and the emplacement of allochthons has been described extensively from seismically imaged salt systems (e.g. Hudec & Jackson 2009). These relationships can be applied to tectonic allochthons by considering a simple emergent thrust structure (Fig. 2) climbing stratigraphic section into syn-kinematic strata. If sedimentation is continuous during displacement, the thrust trajectory is largely defined by the lateral pinchout of the syn-kinematic strata onto the thrust sheet. So, if sedimentation rates keep pace with displacement, the thrust follows a ramp trajectory (Fig. 2a). In contrast, if there is little or no sedimentation at the emergent thrust front (Fig. 2b), the thrust follows a low-angle trajectory, forming an upper thrust flat. It is in this situation that individual emergent thrusts can accumulate large displacements and carry thrust allochthons (far-travelled thrust sheets). Thus syn-kinematic sedimentation is expected to exert a strong influence on the trajectory of emergent thrusts.

Sibson (2004) amongst others notes the primary importance of fault dip-angle, relative to movement direction, on the propensity for slip. The vertical load acting on the fault plane increasingly outcompetes the shear strength of the fault plane with increasing fault-dips. Steep frontal ramps (dip-slip) are less able to slip than lower-angle thrusts. So,

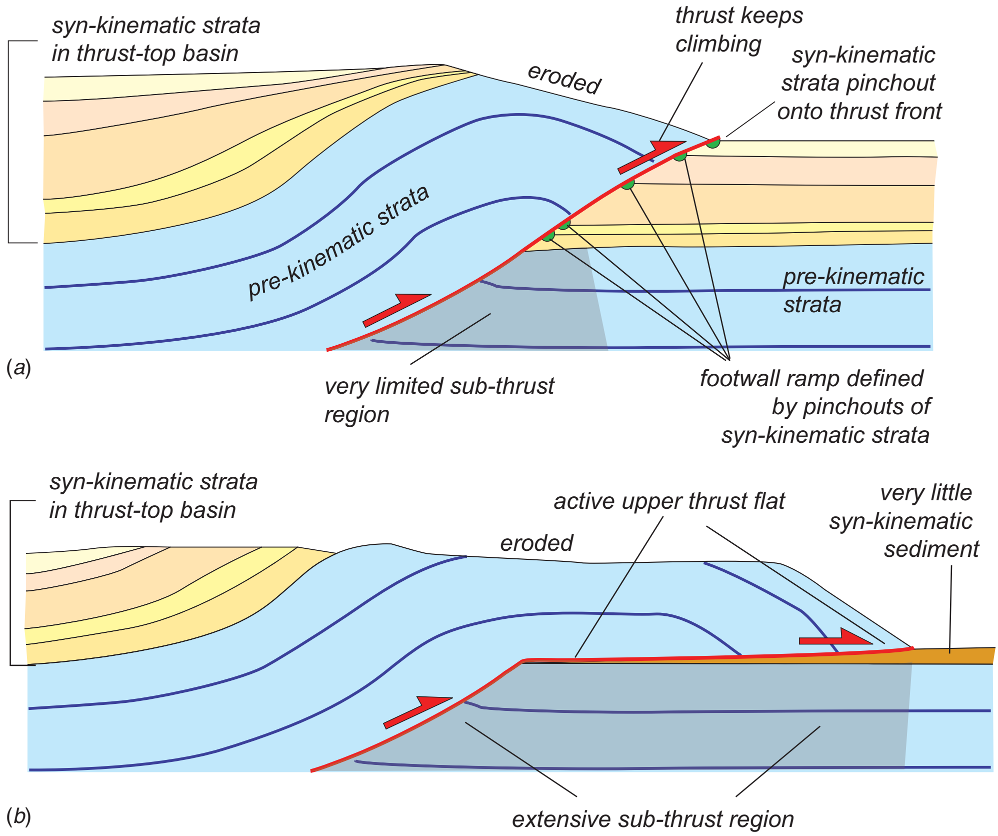

Fig. 2. Concepts relating to emergent thrust faults. (**a**) Aggradation of syn-kinematic strata ahead of the thrust with their lateral pinchout against the thrust sheet progressively forming a footwall ramp. The thrust follows a ramp-dominated, steep trajectory. In a thrust system, this relationship between deformation and deposition is likely to form thrust arrays (Fig. 1a). (**b**) A contrasting case where the thrust front is starved of sediment. Syn-kinematic deposits are illustrated as ponded in the thrust-top basin. The resultant thrust trajectory develops at a low-angle, forming an upper flat. These systems can evolve into thrust-allochthons, as illustrated in Figure 1b.

unless the thrust sheet is continuously eroded during emplacement, ramp-dominated systems are intrinsically less able to slip than their counterparts with low-angle thrust trajectories. Individual thrusts with displacements that are significantly greater than the stratigraphic section through which they have climbed (i.e. have heaves that are considerably greater than their throws) require the activation of a thrust flat at the top of the ramp. By virtue of their relatively large heaves and staircase trajectories, these systems have a greater propensity for creating significant volumes of sub-thrust strata compared with the ramp-dominated systems. These behaviours could be important when assessing the prospectivity of thrust belts that host hydrocarbons.

The relationships between syn-kinematic sedimentation and associated structural geometry is now examined with reference to two case studies. Both are active to recently active and preserve critical relationships that might otherwise be lost by erosion in more ancient thrust belts. The first is from the Apennines of Italy, which includes the natural example used by Storti & McClay (1999) to support the deduction made from their analogue models of thrust belts. The other study here is of the structural evolution of the front ranges of the NW Himalayas.

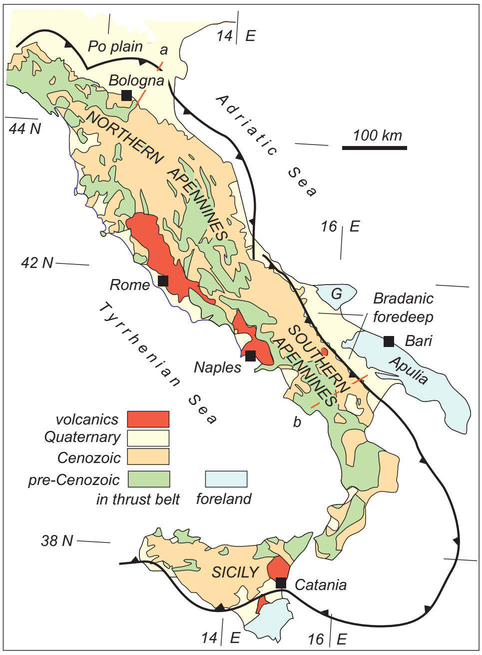

Fig. 3. Simplified map of the Apennine thrust system. The section lines of Figure 4 are indicated. G, Gargano promontory.

Contrasting the northern and southern Apennines

The Apennine chain of the Italian peninsula (Fig. 3) is defined by a broadly NE-vergent thrust system of Neogene age, directed towards an orogenic foreland represented by the floor of the Adriatic sea. The foreland strata are exposed in the Apulian and Gargano promontories (Fig. 3) but are otherwise buried by Plio-Quaternary sediments. The subsurface of the thrust belt is imaged seismically and penetrated by wells, largely acquired for the exploration and production of hydrocarbons (reviewed by Bertello *et al.* 2011). The thrust belt shows important variations in structural style along its length, with an increased propensity for large-displacement thrust sheets towards the south (e.g. Butler *et al.* 2004 and references therein). The increase in displacements from north to south is predicted from the tectonic setting of the Apennines where crustal shortening in peninsular Italy is balanced by lithospheric stretching in the Tyrrhenian Sea and its borderlands (e.g. Faccenna *et al.* 2001, and references therein). However, it is how these displacements are accommodated that is of interest here.

Northern Apennines: Po plain section

The margin of the Northern Apennines with the foredeep basin of the Po plain (Fig. 3) is defined by a thrust belt, the frontal portions of which are buried beneath the Quaternary deposits of the basin. The structure is known from seismic reflection profiles and hydrocarbon exploration wells, initially compiled by Pieri & Groppi (1981). Since then, these structures have become exemplars of thrust-top basins with the now-legacy seismic profiles (e.g. Pieri 1987) widely reproduced. It was here that Storti & McClay (1999) proposed that syn-kinematic sedimentation influenced the spacing of imbricate thrusts. The thrust belt is illustrated by the classic cross-section, modified after Castellarin *et al.* (1985) for the Bologna area (Fig. 4a). Picotti & Pazzaglia (2008) provide further well control. However, the overall architecture has remained largely unmodified since the early seismic interpretations.

The thrust belt is marked by a series of anticlines, cored with early Miocene and older carbonates that represent the pre-kinematic strata for this part of the Apennines. These anticlines are asymmetric, verging generally northeastwards and are generally interpreted to be carried on SW-dipping thrusts. These climb section into upper Miocene and younger strata, chiefly marine sandstones and claystones which represent deposits of the ancestral foredeep of the Po plain. These broadly syn-kinematic strata achieve thicknesses in excess of 10 km but thin dramatically onto the anticlines. Tilted onlap surfaces

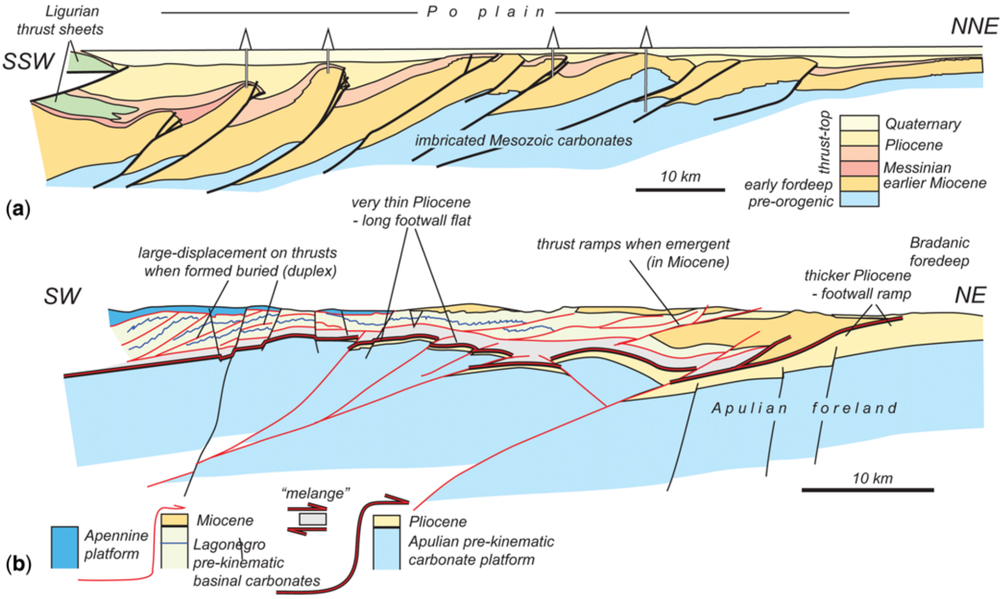

Fig. 4. Cross-sections through the Apennine thrust system (located on Fig. 3). (**a**) Section through the frontal part of the Northern Apennines (modified after Castellarin *et al.* (1985)). (**b**) The transect through the Southern Apennines (modified after Butler *et al.* 2004, fig. 11).

and the general variations of thickness, especially evident in the Plio-Pleistocene successions, indicate that these strata accumulated as the anticlines amplified and therefore while the related thrusts were active. The thrusts show ramp geometries through the syn-kinematic deposits with no significant activation of thrust flats at these stratigraphic levels.

The syn-kinematic strata reveal the relative activity of deformation across the thrust belt. Structures progressively became inactive from hinterland to foreland, apparently implying a 'piggy-back' sequence of thrusting. However, through most of their history, the structures were active together. Deformation is especially obvious in the different thicknesses of Plio-Quaternary strata. Seismic data reveal that the late Pleistocene strata seal the whole system. More recent studies, using additional borehole, geomorphological and geodetic data, indicate that deformation has stepped back into the hinterland (Picotti & Pazzaglia 2008).

Southern Apennines: Basilicata

The structure of the Southern Apennines differs considerably from the northern part of the chain (e.g. Casero *et al.* 1991). The cross-section displayed here (Fig. 4b) has been modified after Butler *et al.* (2004, fig. 11). Their terminology and interpretations are followed here. Further seismic data are provided by Shiner *et al.* (2004) and Patacca & Scandone (2004). These were acquired during extensive hydrocarbon exploration in the Southern Apennines and, with numerous well penetrations, reveal a major allochthonous thrust sheet largely comprising Mesozoic deep-water successions (the so-called Lagonegro units). This has been emplaced onto platform carbonates of the Apulian foreland (Butler *et al.* 2004 and references therein). At outcrop, the thrust belt is separated from the foreland by a foredeep basin containing Plio-Quaternary sandstones and claystones. The base of the Lagonegro allochthon is marked by a 'melange' of highly sheared, over-pressured Miocene clays and sands (Mazzoli *et al.* 2001), which presumably represent deposits entrained by the allochthon from a now-buried and deformed precursor foredeep. The Apulian foreland carbonates have been located at depth in wells and mapped on seismic data for over 50 km hinterlandward of the thrust front. This indicates that the Lagonegro allochthon has been emplaced on a low-angle thrust following a broadly flat-detachment. The geometry of this thrust at depth to the west remains obscure, but could have localized on a normal fault that originally bounded the Lagonegro basin.

Separating the Lagonegro allochthon and its entrained mélange from the Apulian platform is a thin veneer of highly sheared Pliocene claystones and marls that represent the lower parts of the modern foredeep. These rocks and their Apulian substrate are cut by thrusts. Some of these roof into the base of the Lagonegro allochthon to form a duplex while others breach through it.

The thrust front lies in the modern foredeep where it is buried within Plio-Pleistocene sediments (e.g. Palladino 2011). These achieve thicknesses in excess of 4 km. Seismic data (reviewed by Butler *et al.* 2004, see also Shiner *et al.* 2004) illustrate that the frontal thrust climbs section into these thick foredeep sediments. The change in thrust geometry apparently relates to differences in the depositional thickness of the foredeep sediments into which the thrust sheet is emplaced.

The Lagonegro allochthon contains numerous imbricate thrusts that restack the deepwater Mesozoic carbonates. Some of these have large displacements that branch up onto the base of another thrust sheet (carrying the so-called Apennine platform; Fig. 4b). Others climb into Miocene deep-water sandstones and claystones that are broadly syn-kinematic. Where thrusts cut these syn-kinematic strata they generally climb ramps. More detailed analysis is unjustified as the preservation of these Miocene deposits upon the allochthon is very limited. Low-temperature thermochronological data (Mazzoli *et al.* 2008; Corrado *et al.* 2010) indicate that exhumation and thinning of the Lagonegro allochthon were partly coeval with its emplacement.

Variations

The two cross-sections (Fig. 4) display varying controls by pre-existing faults and inherited variations in the pre-kinematic strata. However, the fundamental differences in structural style, between spaced imbricate thrusts and a major tectonic allochthon, coincide with significantly different depositional and subsidence patterns in the foredeep basins within which the thrust systems emerged. Where sedimentation swamps the thrust structures, as in the Northern Apennines entering the foredeep of the Po Plain, these structures are well spaced. Individually displacements only amount to a few kilometres, but the thrusts were largely active together. Therefore, it is the aggradation of displacements and their timing that provide estimates of orogenic contraction and of bulk shortening rate (Fig. 1a). In the southern Apennines, the Lagonegro allochthon accommodated substantial shortening by localizing slip onto its basal detachment. This detachment glides on a thin syn-kinematic succession of lower Pliocene rocks that have become highly sheared. When the thrust front entered the modern foredeep, in late Pliocene–early Pleistocene time, it encountered a basin area experiencing faster rates of sediment accumulation. The modern thrust front has therefore evolved from a footwall flat, with large displacements, into a footwall ramp, with rather low displacements.

Structural styles in the Apennines appear to be influenced by the magnitudes of syn-kinematic sedimentation around the emergent thrusts. However, the account above is rather qualitative because it is difficult to compare absolute estimates of shortening, and therefore rates of thrusting, from different parts of the chain. As noted above, the Apennine system shows significant variations in bulk shortening along its length, as deduced from corresponding differences in the amount of coeval lithospheric stretching in the orogenic hinterland. Consequently, it is appropriate to study a system where structural styles and the magnitudes of syn-kinematic sedimentation vary within the same geodynamic context.

Lateral structural variations and syn-kinematic sedimentation in the NW Himalayas

The frontal structures of the Himalayas emerge into the foredeep developed on the Indian continent (Fig. 5). Regional subsidence patterns in the foredeep vary, with stratigraphic thicknesses exceeding 6–7 km along the mountain front (summarized by Burbank *et al.* 1996; Fig. 5a). These deposits provide exceptional stratigraphic records of syn-kinematic subsidence, drainage evolution and the timing of structural evolution in a continental thrust belt. Pioneering magnetostratigraphic studies (e.g. Johnson *et al.* 1979, 1986; reviewed by Burbank *et al.* 1996) provide control on sediment aggradation rates from which fold–thrust activity can be resolved. Much of this work has centered on the well-exposed, semi-arid areas of the NW Himalayas, and it is this setting that provides the second case study here. The region is also an important hydrocarbon province, as reviewed by Craig *et al.* (2018).

Within the NW Himalayas, there is significant variation in structural style as the arcuate, broadly radially vergent main Himalayan thrust system sweeps into the Hazara syntaxis (Fig. 5). Further west, the Himalayan thrust system changes geometry. The arcuate system is replaced by the castellated map-pattern of the Salt Range (Fig. 5b). This forms the thrust front and it is separated from the topographic mountain front (broadly the trace of the Main Boundary Thrust on Fig. 5b) by a gently elevated part of the foredeep, termed the Potwar plateau. Variations in structural style, not only between the main Himalayan arc and its western continuation, but also along the Salt Range front, have been documented by various studies (e.g. Butler *et al.* 1987; Powers *et al.* 1998; Jadoon *et al.* 2015; Qayyum *et al.* 2015). The variations in the map-pattern of the front ranges are apparently manifest in changes not only in the patterns of thrusting in the subsurface but also in the thicknesses of foredeep strata.

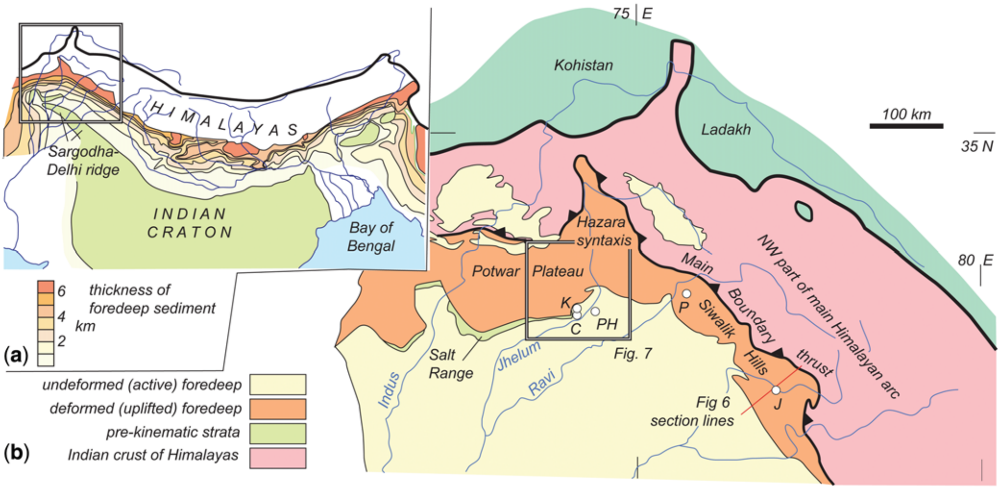

Fig. 5. Tectono-stratigraphic setting of the Himalayan thrust belt. (**a**) Large-scale setting and variations in sediment thickness in the Himalayan foredeep, modified after Burbank *et al.* (1996) and Garzanti (2019). (**b**) Simplified map of the NW Himalayas (boxed area in Fig. 5a), modified after Garzanti (2019). The boxed area a is the location of Figure 7. The section lines of Figure 6 in the NW Himalayan arc are shown together with the location of selected stratigraphic sections of Burbank *et al.* (1996) and reported in Figure 12 (C, Chambal Ridge; K, Kotal Kund; P, Pabbi Hills; P, Parmandal; J, Jawalamukhi).

Active deformation in the Himalayan thrust belt, evidenced by seismicity (Chingtham *et al.* 2016 and references therein), geodetic data and very young tectonic geomorphology (e.g. Thakur 2013), is the youngest part of a tectonic history that stretches back into the Miocene. Prehistoric activity is recorded by strata of the foredeep and satellite basins. The oldest part of the foredeep megasequence is the Rawalpindi Group. This succession is dominated by red mudstones and sandstones that collectively represent relatively distal fluvial and local lacustrine units. It passes up into increasingly more proximal strata represented by the Siwalik Group, the youngest foredeep fill that accumulated from rivers draining the ancestral Himalayan chain. It consists of interbedded sandstones and local gravels, representing river channels, together with red claystones, siltstones and fine sands, inferred to represent overbank, flood plain deposits. The transition between the Rawalpindi to Siwalik groups is diachronous, reflecting the migration of the foredeep basin through time, and is dated in the study area at 12–14 Ma (Burbank *et al.* 1996). Burbank *et al.* (1996) use variations in the sandstone character, interpreted to represent deposition from different river systems through the evolution of the ancestral foredeep, to divide the Siwalik Group into distinct lithostratigraphic formations; the upper, middle and lower Siwaliks. It is the Siwalkik Group that provides a critical chronometer of deformation in the frontal part of the NW Himalayas, calibrated by pioneering magnetostratigraphic studies reported in the late 1970s and early 1980s (Johnson *et al.* 1979, 1982, 1986; Opdyke *et al.* 1982; summarized by Burbank *et al.* 1996).

The foredeep megasequence lies unconformably upon a succession of pre-orogenic strata that span much of the Phanerozoic, with important unconformities. These older rocks include the Eocambrian Salt Range Formation, a major evaporitic unit. The overlying strata show significant lateral variations in thickness and facies, but overall appear to behave, within the front ranges of the NW Himalayas, as a single mechanical unit (the ‘carapace’ of Butler *et al.* 1987; see also Grelaud *et al.* 2002). The youngest part of the supra-salt carapace comprises Eocene carbonates upon which the Rawalpindi Group lies unconformably.

In most studies, it is the behaviour and distribution of the Salt Range Formation that controls variations in the structure of the mountain front in the NW Himalayas (e.g. Butler *et al.* 1987; Lillie *et al.* 1987; Jaumé & Lillie 1988; Yeats & Lillie 1991; Burbank *et al.* 1996; Cotton & Koyi 2000). These evaporites underlie the Potwar region and thrust belt to the west of the Jhelum River (Fig. 5b). They appear to be absent beneath the foredeep of the main Himalayan arc. The aim of the next section is to describe the structure of the frontal Himalayan thrust belt and to discuss the importance of the salt along the basal thrust detachment relative to the variations in thickness of syn-kinematic sediments in the development of lateral variations in structure.

NW Himalayan arc

The frontal structures of the main Himalayan arc are represented at outcrop by anticlines cored by strata of the Siwalik Group. Sparse seismic and wells, chiefly located on these anticlines, provide subsurface control. The structure is illustrated here using the Kangra transect in NW India (Fig. 6). Three published versions are shown to reflect uncertainty in subsurface interpretations given the limitations of imaging.

Burbank *et al.* (1996, fig. 9.3c) interpret the thrust belt to be developed above a detachment along the base of the foredeep deposits. They show these strata to onlap directly the crystalline basement of the Indian crust, relationships that are inferred from wells that bottom in basement in the SW of their profile (Adampur and Hoshiapur wells, Fig. 6a). The anticlines are spaced at c 10 km apart and interpreted by Burbank *et al.* (1996) to be associated with thrusts that splay from the basal detachment. The section is ramp-dominated: Burbank *et al.* (1996) propose that the thrust spacing reflects the thickness of foredeep sediments. These reach values greater than 8 km in the NE end of the section, closest to the main Himalayan chain. These foredeep strata thin and pinch out onto the underlying basement towards the foreland (SW). Most of the Siwalik Group strata, together with those of the underlying Rawalpindi Group, show long-range thickness changes that reflect the regional differences in subsidence across the foredeep. They predate local thrust structures and are therefore pre-kinematic with respect to individual folds and thrusts in the line of section. Only the uppermost Siwalik strata are locally syn-kinematic, showing thickness changes associated with folds.

Detachment along the base of the foredeep strata is also a feature of the interpretation of Powers *et al.* (1998, their fig. 6; Fig. 6b). Their cross-section has been constructed using strict angular relationships (following the methods of Suppe & Medwedeff 1990 and others) which create ramp-flat geometries in the subsurface. Note the contrasting levels of structural complexity, for example around the Jawalamukhi well, compared with that invoked by Burbank *et al.* (1996). However, in both sections the thrusts cut up through the full foredeep succession.

Both Burbank *et al.* (1996) and Powers *et al.* (1998) infer basal detachment beneath the frontal folds of the NW Himalayas. However, other workers suggest that the outcropping folds are associated with thrusts that cut up from basement. This type of alternative geometry is shown in Figure 6c, using the version compiled by Craig *et al.* (2018; modified after Karunakaran & Rao 1979). Offsets of the basement are substantially less than the equivalents in shallower stratigraphic levels. This could imply reactivation of pre-existing normal faults, which, according to this section, would have controlled thickness variations in the Rawalpindi Group. Although aspects of the structural interpretation in Figure 6c might be modified in the light of more recent well penetrations and seismic data, the

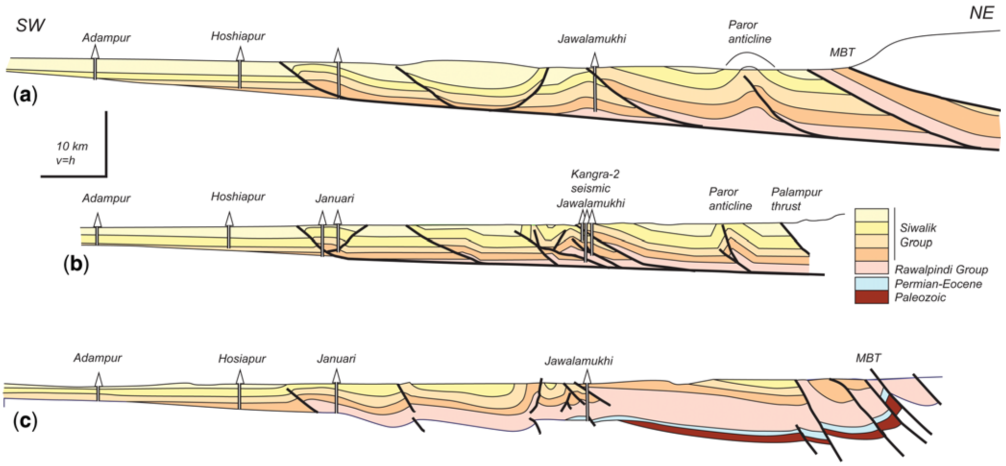

Fig. 6. Interpretations of the structure of the thrust belt in the NW Himalaya (Kangra transect), located on Figure 5b and scaled equally. (**a**) The thrust belt as a simple emergent imbricate fan, dominated by ramps climbing from a basal detachment along the base of the foredeep sediments (after Burbank *et al.* 1996). (**b**) A similar detachment-dominated interpretation by Powers *et al.* (1998) showing complex fold–thrust relationships. (**c**) For Craig *et al.* (2018) the surface structures link back to weak basement faulting at depth. Note that all sections show a similar stratigraphic motif, with foredeep sediments thinning out towards the foreland (southwestwards), also for the pre-orogenic (Eocene and older strata), by Craig *et al.* (2018).

deeper structure and role of basement at depth remains conjectural.

Regardless of the interpretation adopted for the NW Himalayan foothills illustrated by the Kangra transect (Fig. 6), all show thrusts that climb across the Siwalik foredeep sediments as relatively simple ramps. In this regard, the structural geometry is equivalent to that in the Northern Apennines, described above (Fig. 4a). The system is ramp dominated, without the activation of an upper thrust detachment. Therefore, individual thrusts show rather low displacements, relative to the thickness of the strata they cut. It is the aggregation of these displacements and their time-averaged rates that inform estimates of shortening and tectonic convergence rates across this part of the Himalayan mountain front.

The Eastern Salt Range and Potwar Plateau

Thrust structures to the west of the main Himalayan arc, in the vicinity of the Salt Range of Pakistan, contrast radically with those shown in Figure 6, in terms of not only their trend but also their overall structure. The outcrop geology of the Salt Range was mapped by Gee (1980), with these maps extensively interpreted by Butler *et al.* (1987), who provide a comprehensive account of the structure and stratigraphy of the Salt Range. (see also Gee & Gee 1989). These outcrop-based descriptions predate seismic data published by Grelaud *et al.* (2002) and Qayyum *et al.* (2015), which provide significant subsurface control. Figure 7 is a simplified geological map of the eastern part of the Pakistan thrust system embracing the eastern Salt Range and Potwar plateau. Although the main Himalayan thrust system is radial to the trend of the arc, and so is SW-directed in the NW Himalayas, on the west side of the Jhelum river, thrust transport is SSE-directed. The taper of the thrust system in the Kangra transect is 5–7° while, for the Salt Range and Potwar, the taper angle is <3° (Burbank *et al.* 1996). Yeats & Lillie (1991) argue that these differences reflect the different properties of the basal detachment to the thrust belt between the two regions.

Lillie *et al.* (1987) and Butler *et al.* (1987) independently established that the separation of the thrust front in the Salt Range from the main Himalayan chain was caused by thrust detachment along the Eocambrian evaporites of the Salt Range Formation. The central part of the Salt Range is interpreted to be a simple fault-bend fold formed by the basal thrust climbing a ramp currently located beneath the monocline that defines the northern outcrop limits of pre-orogenic strata (Figs 7 and 8a). The thrust ramp is proven by the Kallah Kahar, Dhariala and Hayal-1 wells (located on Fig. 7; Qayyum *et al.* 2015). Lillie *et al.* (1987), using legacy seismic data, illustrate that the footwall ramp is located at a north-dipping step in the top of the underlying basement, interpreted to be a pre-orogenic normal fault (Fig. 8a).

Application of salt-based thrust wedge concepts (Davis & Engelder 1985), qualitatively by Butler *et al.* (1987) and quantitatively by Jaumé & Lillie (1988), imply that the thrust wedge north of the Salt Range front can only maintain a low critical taper. Therefore, variations in the position of the thrust front should betray the subcrop of salt beneath the thrust belt (Butler *et al.* 1987; Cotton & Koyi 2000). However, studies associated with gravitationally collapsing sedimentary prisms on passive continental margins (see review by Rowan *et al.* 2004) now suggest that surface slope is less important than sedimentary loading in driving lateral motion in salt-based systems (see Ford 2004). This premise underpins the following discussion where alternative controls are considered.

The thrust system in northern Pakistan shows significant lateral variations in structure, evident in map pattern (Fig. 7). Although the outcrop of the eastern Potwar plateau is dominated by foredeep strata, the internal stratigraphy of the Siwalik Group, together with bedding dips, picks out structures (Fig. 8). Below these structures are referred to as the Jhelum fold belt, named after the eponymous river. Butler *et al.* (1987) argued that the lateral transition, from simple thrusting with its associated fault-bend fold in the central Salt Range, into the Jhelum fold belt reflected a change in the level of the basal detachment. However, their assumption that the detachment climbed into the Siwaliks below the eastern fold belt was disproven by Pennock *et al.* (1989). They present seismic data that show the continuity of Eocambrian salt at depth and detachment at this level throughout the two areas.

Qayyum *et al.* (2015) and Grelaud *et al.* (2002) provide interpreted seismic sections that collectively illustrate the variety of structural styles in the Salt Range and Potwar Plateau area (Fig. 8). These reveal significant faulting of the top-basement horizon which may have controlled the original thickness of Eocambrian salt. However, it appears that, apart from that structure that localized the frontal ramp on the Salt Range Thrust, these early normal faults do not appear to have controlled thrust–fold development elsewhere. Alternative explanations must be sought for the lateral variations in Himalayan structures in the region.

Most of the interpreted sections based on seismic profiles (Fig. 8) are constrained with well data so that the stratigraphic contact between the Rawalpindi and Siwalik groups can be tied to reflectors. However, this is not possible for the central Salt Range profile (Fig. 8a) of Qayyum *et al.* (2015) as there are no appropriate well penetrations into the footwall of the Salt Range Thrust. The Lilla well (Fig. 7; Yeats &

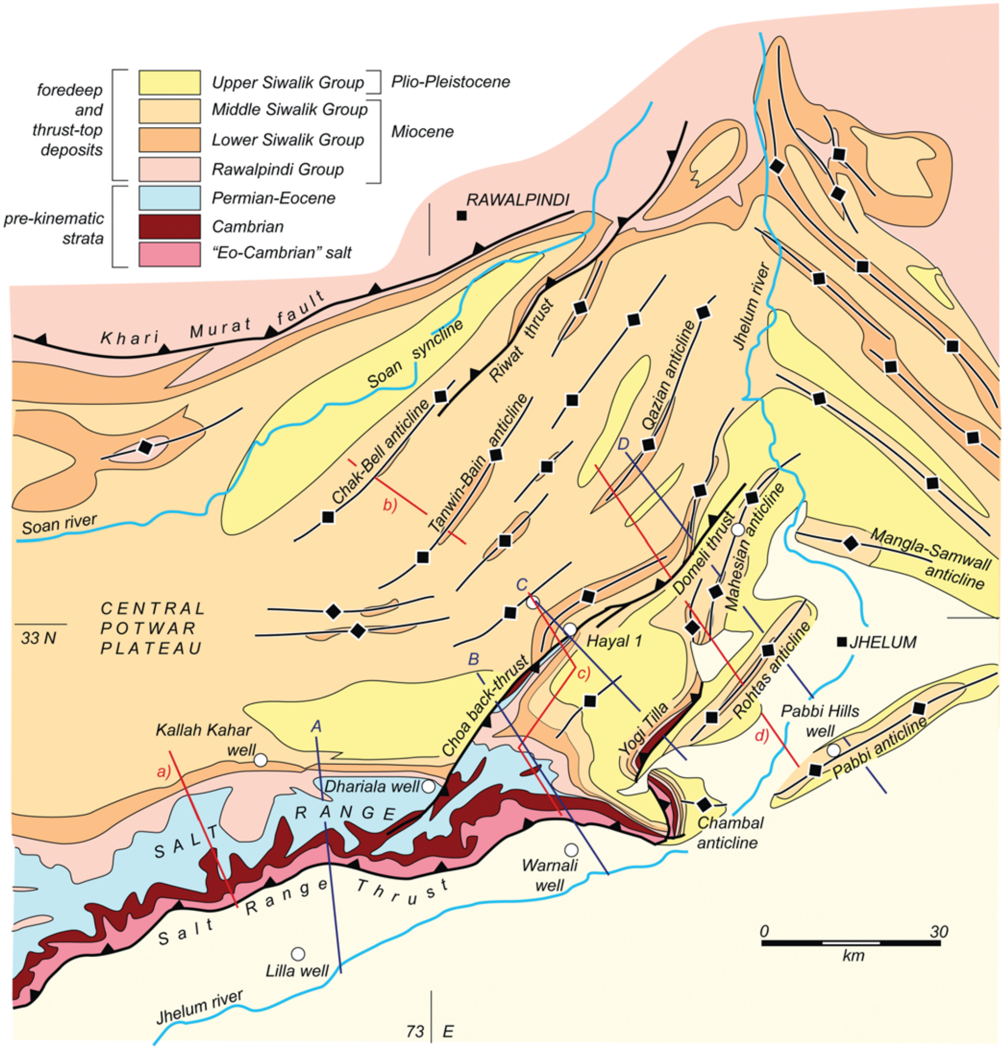

Fig. 7. Simplified geological map of the eastern Salt Range and Potwar districts, modified after Grelaud *et al.* (2002) and located on Figure 6b. The section lines of Figure 8 (red lines, a–d) and Figure 9 (blue lines A–D) are shown together with selected wells.

Thakur 2008) provides some constraint, suggesting the bulk of these footwall strata are Siwalik Group, the uppermost part of which is late Pleistocene in age. Using the seismic velocities for the Siwaliks of Qayyum *et al.* (2015; 3000–3150 m s^{-1}) suggests that the panel of foredeep sediments in the footwall to the Salt Range Thrust on this profile (750 ms; Fig. 8a) is just 1125–1220 m thick. A similar low-angle thrust trajectory on the footwall of the Salt Range Thrust is evident on the profile provided by Grelaud *et al.* (2002; Fig. 8c), although the profile line is jagged and generally oblique to the thrusting direction.

The Lilla exploration well contains <1500 m of Siwaliks that rest unconformably upon a thin sequence (<250 m) of pre-orogenic strata including Salt Range Formation evaporites that rest in turn on crystalline basement (Qayyum *et al.* 2015). These low thicknesses coincide with a basement high in the foreland, termed the Sargoda–Delhi ridge (Burbank *et al.* 1996). This ridge is an ancient structure marked by thin pre-orogenic Phanerozoic successions as well as the reduced foredeep subsidence record.

The structures within the Potwar Plateau (e.g. Fig. 8b) and in the Jhelum fold belt (Fig. 8d) form

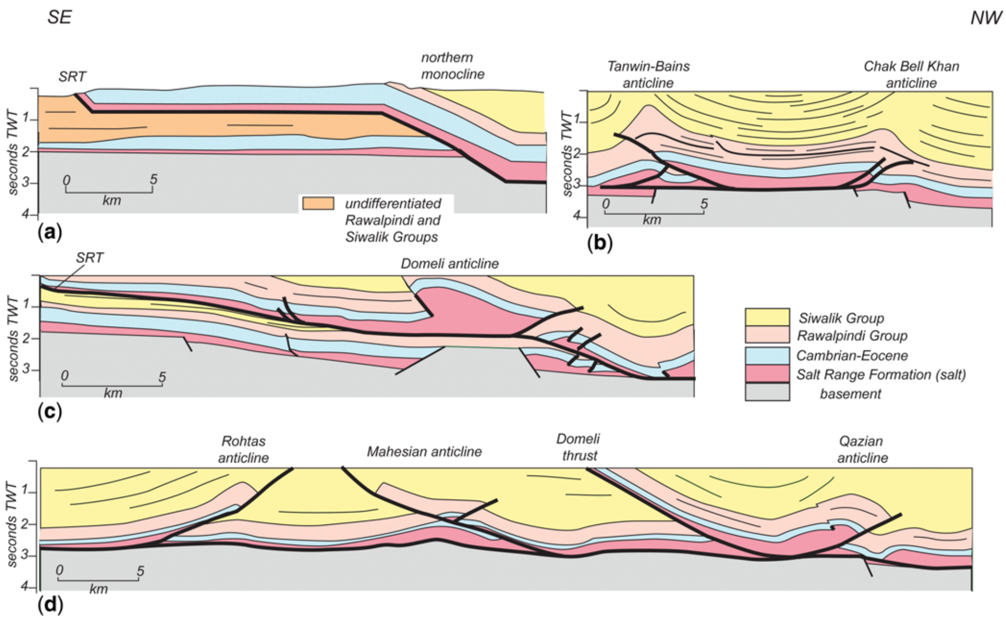

Fig. 8. Illustrations of published structural-stratigraphic relationships as interpreted from 2D seismic sections. The vertical scales are in seismic two-way-time. Section lines are shown on Figure 7. SRT, Salt Range Thrust. (**a**) The oft-cited interpretation of the central Salt Range (Qayyum *et al.* 2015, fig 6), showing the footwall ramp located on a pre-existing normal fault (as proposed by Lillie *et al.* 1987). (**b**) The complex fold–thrust structures on the central-northern Potwar, where thicknesses of foredeep sediments exceed 5 km (from Grelaud *et al.* 2002, fig. 4b). (**c**) The low-angle Salt Range Thrust duplicating the pre-orogenic strata in the eastern Salt Range. Salt thicknesses are highly variable, reaching a maximum within the Domeli anticline. The deep distribution of salt is influenced by pre-orogenic normal faults which create relief on the top of basement. Note that the section line is kinked (see Fig. 7). (**d**) Qayyum *et al.*'s (2015) interpretation of the subsurface structure of the eastern Potwar fold belt (see Pennock *et al.* 1989). Note that the thicknesses of foredeep exceed 7 km (assuming seismic velocities >3 km s^{-1}, Qayyum *et al.* 2015).

beneath sequences of Siwalik Group that are substantially thicker than are represented ahead of the Salt Range Thrust. Rather than show a simple foreland-ward vergence, thrusts are bi-directional, creating arrays of pop-up structures. These structures detach on Eocambrian salt.

Serial sections

The lateral transition between the fold-dominated, pop-ups of the Jhelum fold belt (Fig. 8d) and the simple fault-bend fold of the central Salt Range has been interpreted invoking a NNW–SSE-trending compartmental fault (e.g. Jadoon *et al.* 2015). In this manner the two structural styles are restricted to distinctly different domains in the fold–thrust belt. However, the outcrop trace of stratigraphic boundaries in the patterns of Siwalik units is unbroken by any such fault and therefore prohibits this interpretation. A more complex fault-linkage model is proposed by Drewes (1995) and incorporated into the study of Qayyum *et al.* (2015). In this, thrusts carrying the anticlines of the Jhelum fold belt are inferred to form a full branching network and have continuity to outcrop. However, Butler *et al.* (1987, working from the original work of Gee 1980) showed that thrusts terminate laterally in folds, an interpretation supported subsequently by seismic from the Lilla anticline (Yeats & Thakur 2008). Therefore, the interpretation favoured here is that the change in structural style, from the fault-bend fold on the Salt Range Thrust to the Jhelum fold belt, is gradational.

The change in structural style is represented here by comparing four serial sections (Fig. 9). As proposed by Baker *et al.* (1988), the central Salt Range section (Fig. 9a) shows a simple emergent thrust sheet that nucleated along a pre-orogenic normal fault that underlies the northern flank of the range and essentially conforms to Qayyum *et al.*'s (2015; Fig. 8a) seismic interpretation. On this section line, Cambrian strata of the supra-salt carapace form a frontal hanging wall ramp that constrains the original southward extent of the Salt Range to lie only just ahead of the modern range front. The section

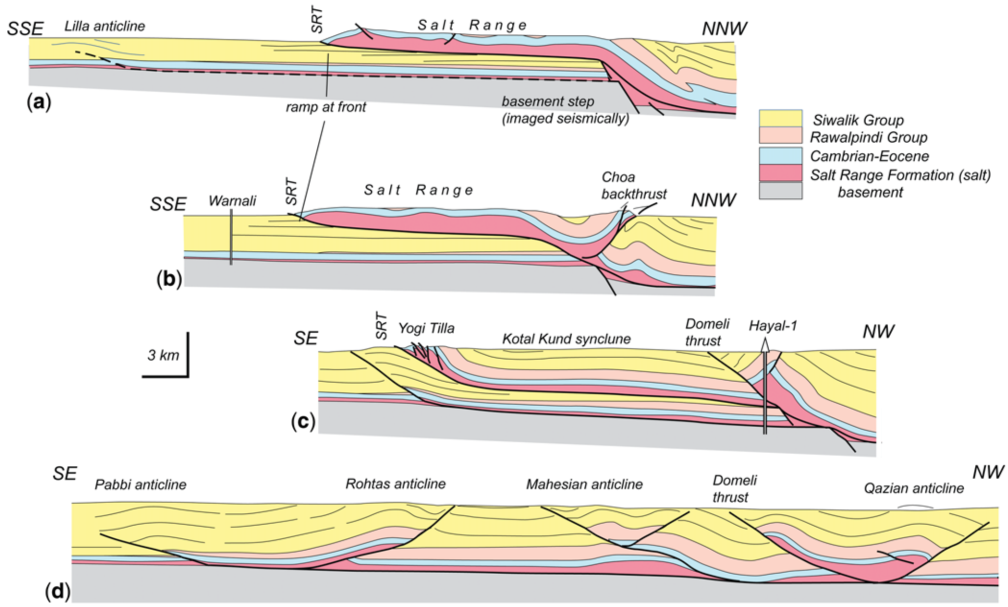

Fig. 9. Serial cross-sections through the eastern Salt Range and the continuation into the eastern Potwar fold belt, located on Figure 7. SRT, Salt Range Thrust. (**a**) Section line A: shows the relationship between thrusting beneath the Salt Range and the recent Lilla anticline (Yeats & Thakur 2008). (**b**) Section line B: interprets the structure at the eastern edge of the main Salt Range where the northern margin is marked by a back-thrust. (**c**) Section line C: uses the seismic data (e.g. Grelaud *et al.* 2002; Qayyum *et al.* 2015; Fig. 8c) beneath the Siwaliks of the composite Kotal Kund syncline to locate the footwall ramp to the SRT beneath the Domeli Thrust (which has very limited surface expression). (**d**) Section D: illustrates the structure of the eastern Potwar fold belt. Note the variable thickness of salt, thicker beneath the Qazian and Mahesian anticlines, suggesting that these structures initiated from salt pillows developed earlier within the foredeep basin.

projects south to include the Lilla anticline. Following Yeats & Thakur (2008), this is shown detaching on evaporites of the Salt Range Formation and therefore the original footwall ramp to the Salt Range Thrust must be offset, as shown. The tectonic contraction represented by the section, using a line-length restoration of the pre-orogenic carapace, is 24 km. In essence, the Salt Range on this transect behaves as a thrust allochthon (Fig. 1b).

The fault-bend fold geometry is evident for the cross-section through the easternmost Salt Range (Fig. 9b), as implied by the seismic interpretations of Grelaud *et al.* (2002; Fig. 8c) and their cross-section. As with Figure 9a, the positions of the footwall and hanging wall ramps through the supra-salt carapace along the Salt Range Thrust are well constrained in the subsurface and at outcrop, respectively. However, on the section line here, the northern flank of the Salt Range is marked by the Choa back-thrust. This structure was originally interpreted by Butler *et al.* (1987) from Gee's (1980) mapping and can be traced to converge with the Salt Range Thrust to the west of the section line. The back thrust is an example of displacement transferring away from the Salt Range Thrust moving to the east. Nevertheless, a simple line-length restoration of the carapace on this section line reveals a total shortening of 24 km, within error of the value obtained further west.

Further east again and the strata of the supra-salt carapace of the Salt Range plunge beneath a tract of foredeep sediments within the broad Kotal Kund syncline (between the Choa back-thrust and the Yogi Tilla structure on Fig. 7), as shown on seismic profiles presented by Qayyum *et al.* (2015). The footwall ramp on the Salt Range Thrust is shown to lie beneath the northern anticline in the section line (Fig. 9c), as it was encountered in the Hayal-1 well. The Salt Range Thrust merges at the SE flank of the Yogi Tilla structure, a composite thrust stack formed of imbricated Salt Range Formation and Cambrian strata (Butler *et al.* 1987). The outcrop trace of the Salt Range Thrust (Fig. 7) shows a dramatic northward jog from the Salt Range to Yogi Tilla, interpreted by Qayyum *et al.* (2015) as a manifestation of a lateral ramp in the subsurface. However, the hanging wall to this thrust, as it passes across the Kotal Kund syncline, is not cut by cross-faults. Note that the Choa back-thrust, evident on Figure 9b, is replaced by the southward directed Domeli Thrust on Figure 9c. Overall, the structural style on this section line retains the central element of a thrust allochthon (Fig. 1a). The line-length restoration of the supra-salt carapace reveals a total shortening on this section line of 33 km, significantly greater than for the section lines further west. This displacement discrepancy is currently unexplained.

Structural styles vary further east into the Jhelum fold belt, but the Domeli Thrust provides a link into the cross-section, represented here as Figure 9d. Other structures can be traced between these section lines (Fig. 7). The Salt Range Thrust at Yogi Tilla (Fig. 9c) is brought up and tilted northwards by the Rohtas anticline (Pennock *et al.* 1989). The Salt Range Thrust loses stratigraphic separation, moving northeastwards so that, in the Jhelum fold belt, the outcrop is exclusively Siwalik Group. The trace of the Salt Range Thrust can be correlated with a thrust that carries the Mahesian anticline. However, the displacements represented by offsets on the Salt Range Thrust in the Salt Range are dispersed not only onto the thrust beneath the Mahesian anticline but also onto structures within the Rohtas anticline and the Domeli Thrust with its associated folds. The outlying Pabbi anticline may be directly comparable with the incipient Lilla anticline that lies to the west. In comparison with the transects further west (Fig. 9a–c), which approximate to thrust allochthon behaviour, the Jhelum fold belt is the equivalent to an emergent imbricate fan (Fig. 1a). A line-length restoration of the supra-salt carapace on Figure 9d implies a total shortening of 26.5 km.

Comparisons

The serial sections illustrate lateral variations in structural geometry along the thrust front. As noted above, the contrast from a simple emergent fault-bend fold in the central Salt Range (Fig. 9a) to the dispersed structures of the Jhelum fold belt (Fig. 9d) was recognized by Butler *et al.* (1987) and attributed to the lateral climb from west to east, of the basal detachment from the Salt Range Formation up into the foredeep strata. This explanation was falsified by Pennock *et al.* (1989), who provided seismic evidence for detachment on salt beneath the Jhelum fold-belt. Indeed, the entire system appears to be salt-floored (Qayyum *et al.* 2015). Therefore, variations in structural style are unlikely to be caused by variations in the properties of the basal detachment. Normal faults such as that localized at the thrust ramp beneath the main Salt Range have not been imaged beneath the Jhelum fold belt. The supposition, investigated below, is that these structural variations have formed in response to differences in the thickness of syn-kinematic overburden.

Timing, sediment accumulation rates and structural styles

Although there are no seismically recognizable growth architectures, such as fanning reflector patterns or progressive unconformities (as noted by Grelaud *et al.* 2002), the outcropping Siwalik succession provides exceptional control on the timing of structures. There are three complementary approaches: variations in sediment accumulation rate through time, the evolution of palaeodrainage patterns and the appearance of substrate clasts that chart uplift and erosion of the floor of the foreland basin.

Unrivalled magnetostratigraphically calibrated sections, pioneered by Johnson and others (e.g. Johnson *et al.* 1979) and compiled by Burbank *et al.* (1996), provide exceptional control on sedimentation accumulation rates. Where these increase from older to younger strata, the rates are consistent with flexural subsidence in the foreland basin owing to the advancing orogenic load. As Burbank *et al.* (1996) notes, stratigraphic sections in the Siwaliks are not decompacted so the approach, especially for charting changes in the early parts of basin subsidence, is open to doubt. However, decreasing sediment accumulation rates with time in younger, less buried sections, cannot be explained by failing to decompact stratigraphic thicknesses. Decreasing rates up-section imply that regional subsidence owing to flexural loading is in competition with local uplift owing to fold amplification. Thus fold-initiation can be detected in sediment accumulation curves (Johnson *et al.* 1986).

Two other approaches yield information on the timing of deformation. As Burbank *et al.* (1996) note, the courses of the major trunk rivers in the Potwar region can be traced through time in the architecture of sand-bodies, linked with their palaeoflow indicators, within the Siwaliks. The changes in the courses of these major rivers not only chart the large-scale capture of drainage flowing into the Ganges system (i.e. southeastwards) by the modern lower Indus valley (southwards) but also the rise of intrabasinal high ground, through anticline amplification. Additionally, the generation of eroding substrate within the foredeep area can be charted by the early arrival of substrate clasts in the Siwalik record.

Integrating the various lines of evidence noted above, Burbank *et al.* (1996) argue that the main phase of Salt Range uplift, and displacement on its eponymous thrust, occurred over the past 3.5 Ma. However, they note an earlier period of uplift at around 6.3 Ma, during which clasts were shed from substrate that outcrops in the Salt Range into the southern Potwar, followed by a period of quiescence (Burbank & Beck 1989). Likewise, local drainage systems became northward-directed into the Potwar at 6.3 Ma. Thus, the Salt Range experienced two distinct phases of uplift. Similar patterns are deduced by Blisniuk *et al.* (1998). It is this protracted timing that was used by Grelaud *et al.* (2002) for petroleum system modelling of the eastern Salt Range. Invoking significant thrusting in the Salt Range prior to 3.5 Ma creates problems of lateral strain compatibility into the Jhelum fold belt. Differential sediment accumulation rates originally compiled by Johnson *et al.* (1979; reviewed by Butler *et al.* 1987) indicate that folding on this transect (Fig. 9d) is younger than 3 Ma, meaning that any early deformation in the Salt Range would have been kinematically isolated.

An alternative explanation for early deformation in the Salt Range (c 6.3 Ma), rather than invoke horizontal compression, is that the range was uplifted above a salt pillow (Fig. 10). Lateral migration of salt, driven by sediment accumulation beneath the modern Potwar plateau, should be expected when the setting is compared with other salt-floored systems (e.g. Provencal Alps, Graham *et al.* 2012; Pyrenees, Rougier *et al.* 2016). In this mode, salt flows from beneath areas of thick overburden to sites of relatively low overburden, which in foredeep basins will be towards the foreland (see Rowan 2019, for review and conundrums). The extruding salt can then pool against pre-existing normal faults – forming a composite pillow structure beneath the carapace of Phanerozoic strata. It is the uplift of this carapace by salt inflation below that forms a barrier to drainage in the southern Potwar and a source of clasts into the Siwaliks. Only later does this area need to become involved in tectonically coupled thrusting. Early developed salt tectonics may explain some of the discrepancies in estimates of shortening between cross-sections noted earlier. More work is needed to resolve these issues.

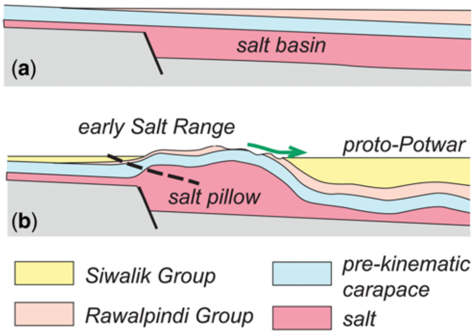

Fig. 10. A model for the early uplift of the Salt Range area within the Himalayan foredeep by the lateral migration of salt (a–b in time). This provides an explanation for the erosion of substrate clasts from the Salt Range and their deposition within the foredeep (green arrow) before the initiation of the thrust belt in the area (trajectory of future Salt Range Thrust dashes in b).

Contrasting thrust trajectories

Grelaud *et al.* (2002) infer that the entire passage of the Salt Range Thrust across the Siwaliks in the footwall was syn-depositional. However, this interpretation is not followed here, not least because it implies continuous displacement for at least 8 myr, which is inconsistent with the Siwalik stratigraphy reported by Burbank *et al.* (1996), as re-interpreted here. Consequently, the lower part of the Siwalik succession in the footwall to the Salt Range Thrust is inferred to be pre-kinematic with respect to this thrust. Only later does the thrust cut gradually across the Siwalik strata (Fig. 11a). The serial sections (Figs 9a–c), show the footwall of the Salt Range Thrust climbs gradually up-section into the younger Siwalik strata until just below the modern thrust front. At this point the thrust climbs more steeply to the surface. The implication is that sedimentation rates have increased in the Siwaliks and the thrust trajectory has steepened in response (Fig. 11b). The proposal here is that this steeper thrust trajectory had a reduced slip-tendency and so could not accommodate the tectonic displacements being transferred to the thrust front along the regional salt detachment. Therefore, deformation was dispersed away from the Salt Range Thrust and onto folding, both in its hanging wall (southern Potwar) and footwall (e.g. Lilla anticline). The Salt Range began to form as a thrust allochthon and was carried for *c.* 25 km, but its further development was arrested by sedimentation rates increasing at its front and deformation consequently was dispersed onto new additional structures.

Lateral variations

Well data from ahead of the deformation front of the Salt Range chart differential accumulation of foredeep sediments from west to east (Fig. 12a). In the Lilla well that lies ahead of the thrust front in the central Salt Range (Fig. 7), the total thickness of foredeep strata, overlying the supra-salt carapace, is 1433 m. These strata are 2429 m thick in the Warnali well, to the east (Qayyum *et al.* 2015). The well on the Pabbi Hills encountered over 3 km of foredeep strata (Yeats & Thakur 2008). The well contents, as published (Qayyum *et al.* 2015) do not differentiate between the various components of foredeep strata. However, the outcropping section on the Chambal anticline (Fig. 7) illustrates that the greatest thicknesses are represented by the upper Siwalik

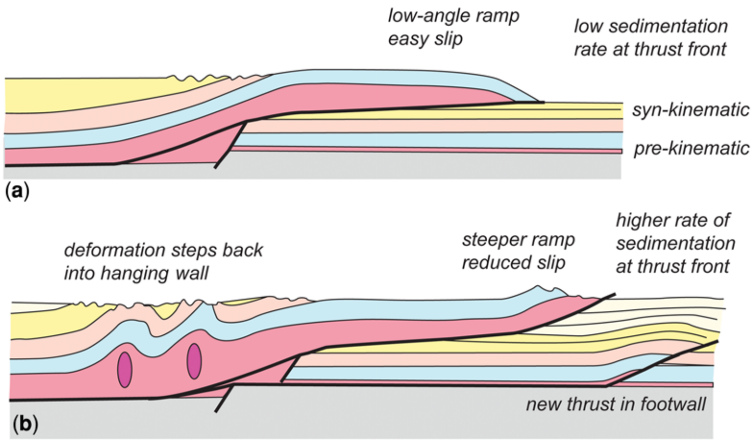

Fig. 11. A model for the control on structural evolution of the Himalayan Thrust Belt in the vicinity of the eastern Salt Range. (**a**) Displacement strongly located onto a single emergent thrust climbing at a low angle across a syn-kinematic succession that accumulated slowly. This behaviour is envisaged for the central Salt Range area. (**b**) A change in behaviour when sedimentation rates increase, increasing in turn the dip of the main thrust, reducing its propensity for slip and promoting deformation both in its hanging wall and in its footwall.

strata. Outcrop-based magnetostratigraphic studies by Johnson *et al.* (1979, 1986; summarized by Burbank *et al.* 1996) show the long-term sedimentation rates for the Siwaliks (Fig. 12b). Neglecting decompaction, the slope of these plots is proportional to the sediment accumulation rate. These increase eastwards from the eastern Salt Range to the Pabbi Hills. The west-to-east increase in thickness of Siwalik successions is evident on the serial sections (Fig. 9). The change from simple thrusting (Fig. 9a) to folding in the Jhelum fold belt (Fig. 9d) coincides with an increase in the thickness of foredeep sediments. It is possible that these changes may also amplify differences in early formed halokinetic deformation structures or in patterns of basement faulting – subjects that may be fruitful for further research. However, it is the variation in syn-kinematic sedimentation that is proposed here to have promoted the changes in structural style illustrated on Figure 9.

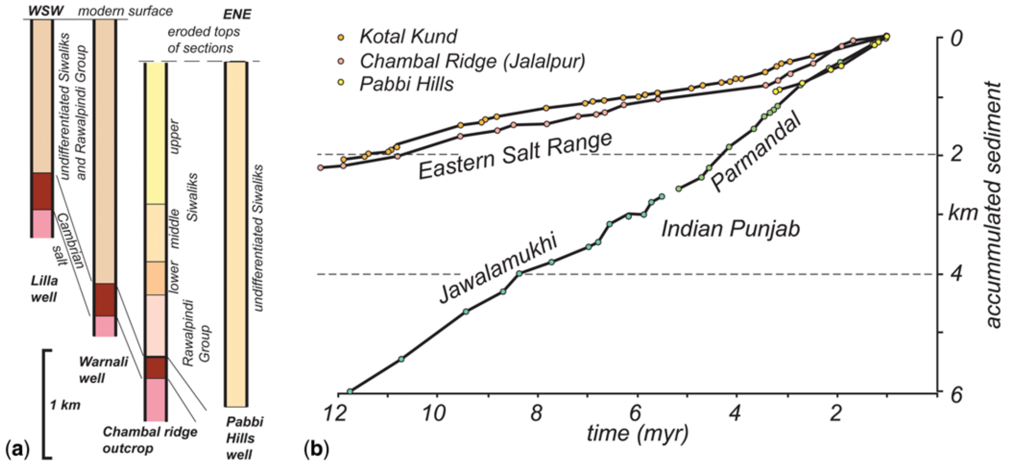

Fig. 12. Sediment accumulation variations across the eastern Salt Range and foreland, contrasted with the NW Himalayas. (**a**) Thickness of foredeep sediments in wells (Qayyum *et al.* 2015) and outcrop (constructed using mapping by Gee 1980), increasing from west to east (left to right). (**b**) Selected sediment accumulation histories, replotted from Burbank *et al.* (1996) that contrast the pattern from the eastern Salt Range with a composite record from the main Himalayan thrust belt. See Figure 5 for locations.

Comparisons with the main Himalayan arc

As noted above, the main Himalayan foredeep contains substantially greater sediment thicknesses (Fig. 5a) compared with the foredeep in the Pakistan sector of the thrust belt, to the west of the Jhelum river. Sedimentation rates in the main Himalayan foredeep are substantially greater too, as noted by Burbank *et al.* (1996). The challenge is to create a sediment-accumulation profile for a single site. The older parts of the foredeep section do outcrop in thrust structures that uplift deeper parts of the foredeep (e.g. at Jawalamukhi, Fig. 6b). However, the younger parts of the foredeep succession have been eroded from these sites. Consequently, the sediment-accumulation profile displayed on Figure 12b is composite, using two distinct sites (Jawalamukhi and Parmandal, Fig. 6b) reported by Burbank *et al.* (1996). This, together with the lack of allowance for burial-related compaction (as noted above), undoubtedly will generate some uncertainty. However, the Himalayan composite profile shows substantially faster rates of sediment accumulation than those from the Pakistan sector and is consistent with the different total thicknesses in foredeep sediment between these sectors.

So, thrust structures in the main Himalayan system are ramp-dominated and collectively form an imbricate fan. This behaviour, associated with the high rate of syn-kinematic sedimentation, matches the expectation of Figure 2a. The implication is that individual thrusts in the main Himalayan system cannot accumulate high, long-term rates of displacement and that in order to accommodate the tectonically required rates of shortening, displacement activity must be dispersed across the imbricate fan, equivalent to the structural style of Figure 1a. Complex thrust activity, consistent with this model, has been documented in this system and reviewed by Mukherjee (2015).

Himalayan foredeep vs Salt Range thrusting

While the Salt Range and Jhelum fold belt are part of the SSE-directed thrust system of the Pakistan Himalayas, they are being encroached by the SW-migrating foredeep relating to the main Himalayan arc. This behaviour is manifest in the evolution of the river systems over the past 10 myr (Burbank *et al.* 1996). The effect is to subject the eastern part of the Pakistan thrust system to increasing rates of basin subsidence and associated sediment accumulation. These are evident in the sediment accumulation record of the Pabbi Hills (Fig. 12b), a site that is being encroached by subsidence from the advancing main Himalayan thrust system. Therefore, the transition from low-angle displacements, that characterize the low rates of syn-kinematic sediment accumulation at the active thrust front, to ramp-dominated thrusting and distributed folding that characterize high rates of sediment accumulation, is expected to have migrated laterally with time. If so, the structural style of the Jhelum fold belt (emergent imbricate fan, Fig. 1a) should be gradually migrating and replacing the simple localized displacement (thrust allochthon, Fig. 1b) along the emergent Salt Range Thrust. This is partly supported by the elevation of the Salt Range Thrust at Yogi Tilla by the amplifying Rohtas structure – relationships suggest that the thrust has been abandoned and deformation is now distributed into its footwall. Further establishing that this behaviour may be migrating westwards with time requires seismic reflection data to straddle the thrust front along the southern edge of the Salt Range. However, the model also suggests that individual folds, such as the Pabbi anticline, are growing westwards with time. Testing this prediction requires a substantially greater suite of magnetostratigraphically calibrated sedimentation rate profiles along individual structures, data that have yet to be acquired.

Discussion

The case studies developed here for the Apennines and NW Himalayas can be generalized to consider structural evolution in emergent thrust systems more widely. These systems show varieties of structural geometry, from dispersed deformation across imbricate fans to highly localized displacements on thrust allochthons.

Development of emergent thrust-allochthons

In the Himalayan thrust belt of Pakistan, the suprasalt carapace in the hanging wall to the Salt Range Thrust starts its history as a thrust allochthon. This behaviour is however terminated in the eastern Salt Range by sedimentation rates apparently increasing at the thrust front, causing the footwall to the Salt Range Thrust to evolve from a flat to a ramp. The inferred consequence of this geometric change is to reduce the propensity for slip on the Salt Range Thrust so that tectonic shortening is distributed more widely into its hanging wall and footwall. Thus, on a single transect, the thrust allochthon evolves into an emergent imbricate fan. Similar behaviour is inferred for the Lagronegro allochthon in the southern Apennines (Fig. 4b), albeit after this structure had acquired substantially more displacement than had the Salt Range Thrust. The emergent Lagonegro allthochton eventually climbed a footwall ramp into the modern foredeep as sedimentation rates increased in the Pleistocene.

Emergent thrust-allochthons are recognized in other orogens. In the western Alps, examples include the Prealpine thrust sheets, now preserved in the Chablais klippen (e.g. Escher *et al.* 1993, and references therein), and the Embrunnais–Ubaye thrust sheets of SE France (Fry 1989, and references therein). Both emerge into their ancestral foredeep. The inference drawn here is that, during their main periods of emplacement, the foredeep was, at these locations, receiving very little sediment. These behaviours are investigated by the analogue models of Bonnet *et al.* (2008). Thrust allochthons are described more widely still, including from the Hellenides (e.g. Robertson & Shallo 2000, and references and therein), the Lycean allochthon of SW Turkey (e.g. Collins & Robertson 1998) and Hawasina-Semail thrust sheets of northern Oman (e.g. Béchennec *et al.* 1990). Perhaps these systems show similar interactions between sediment supply to the active thrust front and the geometry of the thrust belt (Fig. 2b). Butler *et al.* (2019) explore these controls with reference to the Gela nappe and the allochthons (or otherwise) of the Sicilian thrust belt.

The recognition of thrust-allochthons is important for assessing the hydrocarbon prospectivity of thrust systems. Such far-travelled thrust sheets (Fig. 1b) are important for driving thermal maturation of source rocks through tectonic burial. They can also be important for carrying low-permeability strata over reservoirs and therefore create subthrust plays, as in the southern Apennines (Fig. 4b). When thrust systems are swamped by syn-kinematic sedimentation (Fig. 4a), the propensity for thrust-allochthons is greatly reduced. These contrasting behaviours may exert first-order controls on the prospectivity of thrust belts that otherwise contain the necessary components for a viable petroleum system.

Thrust activity, not sequences

The notion of foreland-directed thrust sequences is embedded in idealized views of foreland thrust belts (e.g. Boyer & Elliott 1982). Invariably these ideas derive from structural relationships interpreted from outcrops of ancient thrust systems that either developed as buried systems (e.g. duplexes) or have been denuded of their syn-kinematic strata (e.g. Butler 1987, and references therein). Yet how applicable are these to emergent systems? Simply assuming that there is a foreland-ward migration of deformation may carry unrecognized risks of the relative timing of trap formation and hydrocarbon charge, for example.

The notion that structures form in a strict sequence, and therefore ‘out-of-sequence’ behaviour is unusual, has been used to modify assessments of seismogenic faulting in active thrust belts, such as the Himalayas (e.g. Mukherjee 2015). However, the Apennine and Himalayan case studies outlined above suggest that structural evolution of fold–thrust belts tune to the distribution of syn-kinematic sedimentation accumulating above and ahead of them. The activity of folds and thrusts is likely to overlap in time and potentially show complex cycling between efficient slip on single structures for some protracted periods (e.g. in the central Salt Range for much of the past 3 myr), and deformation dispersed across multiple structures at other times (e.g. the Jhelum fold belt). Simply considering emergent thrust systems as forming in a particular sequence (or lack-thereof) obscures these variations. Surely it is better to expect that emergent fold–thrust structures tend to be active in parallel and to calibrate these activities using the syn-kinematic deposits.

Lateral variations in thrust belt evolution

In over-filled foredeeps (in the sense discussed by Sinclair 1997), the switch in behaviour (Fig. 1) from efficient thrust detachment (thrust-allochthon behaviour) to emergent imbricate fan is expected to relate to the rate of thrusting at this front relative to the rate of foredeep migration. These need not be the same, depending on how the orogenic load and its lithospheric support mechanisms vary through time. In cases where load-migration outpaces the rate of thrusting then sedimentation rates will increase with time. In this way, an active thrust-allochthon could be inhibited, leading to deformation dispersing away from the single, active thrust as discussed above. In areas such as the Himalayan syntaxes, the interplay between loads and thrust motion need not be in the same plane. Therefore, the same thrust front could evolve along its length, as seen in the eastern Salt Range. A similar relationship exists in the Apennines, even though these structures formed in under-filled foredeeps. The northern sector where thrusts are active in parallel and follow ramp-dominated trajectories through the syn-kinematic deposits is forming in a foredeep that experienced rapid rates of sediment accumulation chiefly shed from the adjacent Alpine orogen. The southern Apennines, during the Plio-Pleistocene, largely removed from efficient sediment sources (or where sedimentation is ponded on the thrust system), developed as a thrust-allochthon.

Lateral variations in sediment supply are characteristic of many submarine systems, for example in subduction–accretion complexes impinged on locally by large submarine fans. The impact of sedimentation on the overall shape of the accretionary wedge has been explored (e.g. Ford 2004 and references therein). There appears to be scope to progress these studies by examining the thrust geometry and activity within accretionary complexes.

Conclusions

The trajectory taken by thrusts as they intersect the syn-orogenic surface is critically controlled by the rate of syn-kinematic sedimentation relative to thrust displacement rate (Fig. 13). It is this interplay that governs the inclination of the emergent thrust and therefore its propensity for slip. Far-travelled thrust allochthons, such as the Lagonegro sheet in the southern Apennines (also the Prealpine and Embrunnais–Ubaye thrust sheets of the Alps) are inferred to have been emplaced into foredeeps that, at the time, were receiving very little sedimentation. The central part of the Salt Range Thrust in the Pakistan Himalayas displays a similar behaviour for much of its history. Initially, it behaves as a thrust allochthon, accumulating *c.* 25 km of displacement. However, when sedimentation rates relative to thrusting rates increase with time, or a perpetually high (as in the along-strike Jhelum fold belt), imbricate systems develop with ramp-dominated geometries. As individual thrusts cannot then accumulate substantial displacements, total shortening must be distributed across multiple structures that, over their life-time, have been active together.

Thrust systems can develop fundamentally different structural styles with contrasting histories of thrust activity and localization of deformation if contrasting patterns of syn-kinematic sedimentation are maintained for much of the history of a thrust system (Fig. 13). In this manner, the contrasts in thrust system geometry between the northern and southern Apeninnes of Italy may reflect differences in the depositional patterns of syn-orogenic sediment. Likewise, the greater sedimentation rates ahead of the main Himalayan arc may explain the difference in structural style between its ramp-dominated emergent thrusts and the localization of displacement onto the single Salt Range Thrust of neighbouring Pakistan, where sedimentation rates have been much lower. The lateral migration of the Himalayan foredeep increasingly buried the eastern parts of Pakistan thrust system. This migration of thick syn-kinematic sedimentation may explain the lateral change in structural style in the eastern Salt Range, from a single thrust where relatively sediment-starved to a dispersed tract of folding a bi-directional thrusting when swamped. These variations have developed even though all parts of the Pakistan thrust system have formed above a regionally extensive salt detachment.

If sedimentation rates increase at the toe of a thrust sheet, as at the front of the eastern Salt Range, the structural style can evolve in response (Fig. 13). The examples here illustrate that increasing sedimentation ahead of a thrust can cause it to

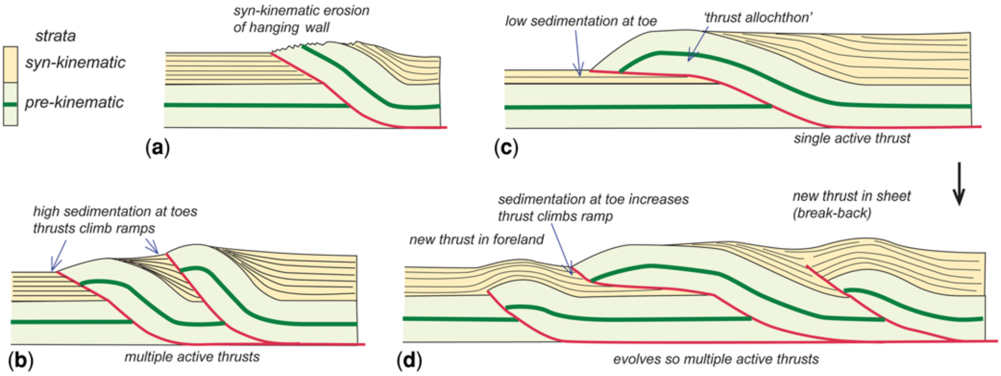

Fig. 13. Summary tectono-stratigraphic models for the evolution of emergent thrust systems. (**a**) A single emergent thrust with high sedimentation at the toe creating a syn-kinematic ramp, accompanied by efficient erosion of the hanging wall. This situation may pertain to settings such as the Alpine Fault in New Zealand but is not discussed here. (**b**) Emergent thrusts with high sedimentation at their toes. This promotes active displacements on multiple thrusts simultaneously and is exemplified here by thrust systems in the northern Apennines (Italy) where structures emerge into the rapidly filling foredeep basin beneath the Po plain. (**c**) The contrasting case where sedimentation rates at the toe of the thrust sheet are relatively low, permitting the activation of the upper thrust flat and the development of a thrust allochthon. This behaviour is exemplified here by the early parts of the emplacement both of the Lagonegro thrust sheet in the southern Apennines (Italy) and the Salt Range thrust sheet of the NW Himalayas. (**d**) How a thrust allochthon (as in c) may evolve as sedimentation rates increase at its toe. This extra sedimentation causes the emergent thrust to climb, thereby reducing its slip efficiency and promoting the development of new thrusts, here shown to form both in the footwall (apparently in conventional 'piggy-back' fashion) and in the hanging wall (in 'break-back' fashion). Note that the system here has evolved so that displacements are accommodated on multiple thrusts simultaneously, as inferred to have occurred here in the eastern Salt Range of the NW Himalayas as the main Himalayan foredeep basin encroached upon this part of the thrust belt.

climb a ramp. This in turn reduces its propensity for slip and, in the case of the eastern Salt Range, causes new structures to develop both ahead and behind the previously active, single thrust. In this manner, emergent thrust systems in general might be expected to show complex deformation activities when viewed across arrays of structures and simple thrust sequences should not be expected.

The study here suggests that emergent thrust systems are critically tuned by sedimentation. Reconstructing patterns of syn-kinematic sedimentation and regional subsidence patterns, as proposed for example by Bonnet *et al.* (2008), may inform understanding of thrust system evolution and provide additional opportunities for testing large-scale structural interpretations.

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Author contributions RWHB: Conceptualization (Lead), Data curation (Lead), Funding acquisition (Lead), Investigation (Lead), Methodology (Lead), Supervision (Lead), Validation (Lead), Visualization (Lead), Writing – Original Draft (Lead), Writing – Review & Editing (Lead).

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