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Using laterally compatible cross sections to infer fault growth and linkage models in foreland thrust belts

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ABSTRACT

We investigate changes in shortening, displacement and fold geometry to understand the detailed along-strike structural variation within fold-thrust belts, and infer thrust growth and linkage mechanisms. Field observations from the Vercors in SE France are used to characterise deformation style in the region. Parallel cross sections are constructed, analysed and used to create shortening and thrust displacement profiles from the northern to southern Vercors. Sections show changes in structural style and shortening accommodation from thrust-dominated in the north to fold-dominated in the south. The total shortening distance in the Vercors does not change significantly along strike (3400–4650 m), however displacements along individual thrust zones do vary significantly and displacement profiles show a range in displacement gradients (16–107 m/km). Despite relatively simple shortening patterns in the Vercors, sections show a more complex 3D internal structure of the fold-thrust belt. Thrust displacements and geometries suggest both large-scale thrust zones and small-scale thrusts are soft linked, transferring displacement along strike through transfer zones. Short, soft-linked thrust segments indicate an intermediate stage of thrust growth and linkage, well documented for normal fault systems, which form prior to the formation of thrust branches and hard-linked displacement transfer.

1. Introduction

Dahlstrom (1969) presented a theoretical construction of gradual structural change in the along strike-geometry and displacement of thrust systems. In this he envisaged thrusts relaying displacement through an array (Fig. 1a). Individual thrusts lost displacement and died out laterally in a predicable fashion – giving rise to the so-called "bow and arrow rule" (e.g. Elliott, 1976) where the ratio of thrust map-half-length and maximum displacement is about 10:1. Since then there have been various attempts to quantify the amount of shortening in thrust belts and its along strike variations (e.g. Alvarez-Marron, 1995; Fermor, 1999; Apotria and Wilkerson, 2002; Torres Carbonell et al., 2013). These variations in shortening effect structural style, fold geometry, internal strain, thrust displacement, and other geometric and kinematic aspects of fold-thrust belts (e.g. Pérez-Estaún et al., 1997; Cooley et al., 2011; Torres Carbonell et al., 2013; Qayyum et al., 2015). The underlying causes of along strike variation in fold-thrust belt structure have been attributed to pre-existing basement and basin structure, changes in stratigraphy causing variation in rheological properties and variation in shortening closer to the hinterland in the internal zones (Woodward, 1988; Pérez-Estaún et al., 1997; Cooley et al., 2011; Qayyum et al., 2015; Rocha and Cristallini, 2015; Bhattacharyya and Ahmed, 2016; Cain et al., 2016). Here we develop studies of lateral variation in thrust belt structure using the notion of lateral compatibility to develop an array of mutually-compatible cross-sections and use these to examine lateral changes in displacement.

Despite decades of research on thrust systems, there are few systematic descriptions of variations in shortening and displacement through thrust arrays. This contrasts with research on normal fault systems where there is a well-established fault growth and linkage model (Childs et al., 1995). This model suggests that small faults initiate and, as they grow, the stress perturbations produced by the propagation of their process zones and their strain fields interact so they become soft linked. As displacements increase, fault splays may form, transferring displacement between established fault segments that become hard linked (Fig. 1b; Childs et al., 1995; Davis et al., 2005; Fossen, 2010). Based on this model developed for extensional faults, it would also be expected that

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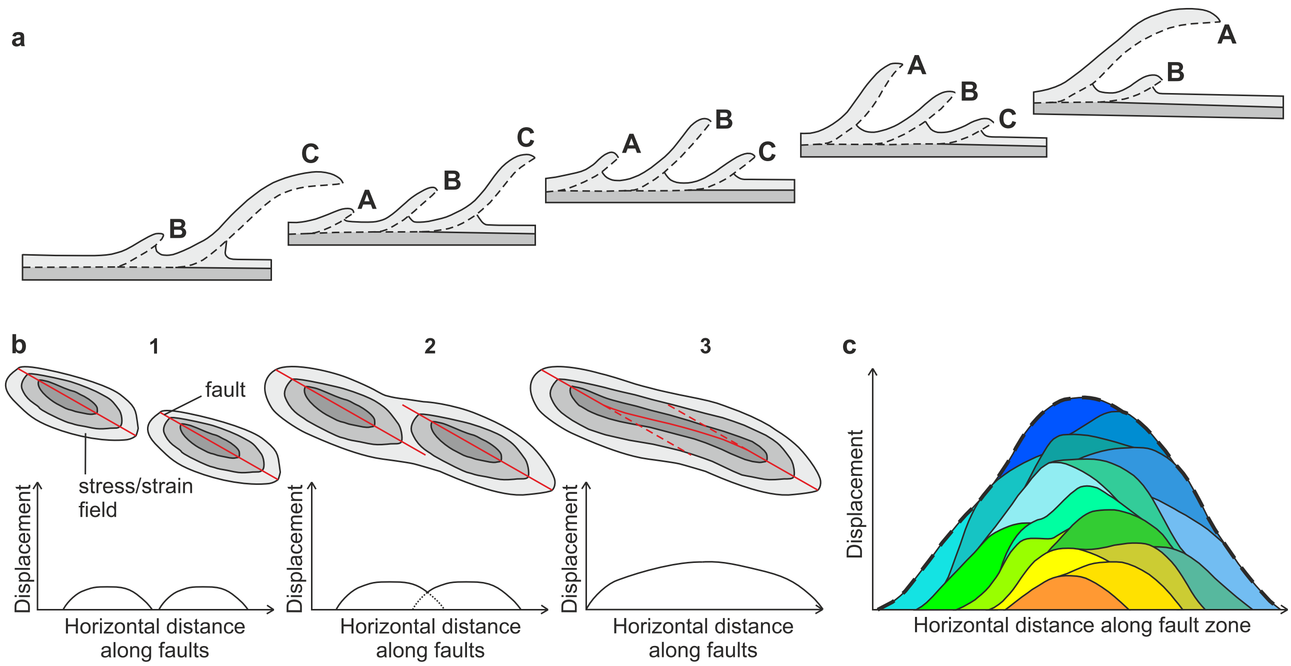

Fig. 1. a) Dahlstrom (1969) model for soft-linked thrusts; as displacement on one thrust decreases, it must increase on another to maintain a constant shortening distance along the fold-thrust belt. In this case displacement on thrust A increases towards the top, displacement on thrust C decreases towards the top and the maximum displacement on thrust B is on the central section. b) Fault growth and linkage model. At stage 1 the stress and strain fields of two small faults do not interact; the faults are unlinked. At stage 2 the faults have grown and their displacements increased; their stress and strain field begin to interact so they are soft linked. By stage 3 the thrust displacement has increased and a thrust splay has formed, linking the two faults; the faults are now hard linked. b) High displacement thrust fault zones may be expected to be made up of multiple, smaller fault segments. Total thrust zone displacement (dashed line) is made up of slip on individual small fault segments or series of linked fault segments (adapted from Fossen, 2010).

displacement on a large fault is made up of slip on multiple hard-linked smaller fault segments that have branched to form a major fault zone (Fig. 1c). However, in contrast with this understanding from normal faults, much of the early work on the three dimensional structure of thrust systems treated them as fully connected (hard-linked). In this fashion displacement has been interpreted to have transferred simply across branch lines (e.g. Diegel, 1986; Hossack, 1983). While these studies of finite fault patterns show predicable map patterns in restored state (e.g. Butler, 1985; Fermor, 1999), they give little information on how the thrust array developed.

The aim of this paper is to examine a thrust system that shows rather low displacements – focussing on the Vercors segment of the Sub-Alpine thrust belt of SE France. The intention is to establish whether systematic variations of displacement exist through the thrust array that might inform the growth of the system. Field data are used to highlight large-scale structural variation along strike in the fold-thrust belt. Cross sections are used to investigate how shortening varies along strike, and how fold geometry changes within a fold-thrust belt. Thrust zone displacements are also analysed to determine the detailed nature of how shortening may be distributed, how this may vary along strike, and how displacement is transferred within and between fault zones.

2. Vercors field area

The Vercors is a fold-thrust belt forming part of the Sub-Alpine Chains of France, which, along with the Jura, represent the most westward regional-scale deformation structure deformation associated with the Alps. The French Sub-Alpine Chains run for over 200 km from Chamonix in the NE to south of Grenoble in the SW (Fig. 2a) and include the Haute-Giffre, Bornes, Bauges, Chartreuse and Vercors subdivisions (Moss, 1992a; Bellahsen et al., 2014). Thrusting and folding in the Vercors is thought to have occurred in the middle-late Miocene (Roberts, 1994; Bellahsen et al., 2014), between 10 and 6 Ma (Butler, 1987), and represents one of the youngest phases of Alpine deformation. Prior to Alpine mountain building, the external Alps were part of a rift margin where the main extensional phase occurred during the mid-late Jurassic and regional subsidence occurred during the Cretaceous (Lemoine et al., 1986; Rudkiewicz, 1988; Butler, 1989). Although many associated normal faults are present in the Jurassic-Cretaceous succession, they are not thought to have been inverted during Alpine compression (e.g. Butler, 1989).

The Vercors forms a plateau elevated 1000–2300 m above its foreland (regional) level, some 15–20 km across. At outcrop it is dominated by the "Urgonian" limestone (Hauterivian-Barremian) that is the youngest carbonate platform that built out from this part of the European continent towards the Tethyan ocean. The Urgonian is c 250–300 m thick. It is underlain by older Cretaceous and Jurassic strata. These strata comprise of marls, shales, mudstones and competent limestones (Ramsay, 1963; Lemoine et al., 1986; Arnaud-Vanneau and Arnaud, 1990). The Mesozoic strata within the thrust belt form a marked mechanical multilayer, which is likely to have a significant control on present-day fold and thrust geometries. Collectively the stratigraphy achieves thicknesses in excess of 6 km in the east of the Vercors. However, well-data (see Butler, 1987) for the foreland show the equivalent stratigraphy to be less than 3 km thick and dominated by carbonates. Thus the Mesozoic strata formed a broad westward-tapering wedge. During the Miocene this wedge was pushed westwards, along a basal detachment established in Triassic evaporites (Bayer et al., 1987; Mugnier et al., 1987; Roberts, 1991) and lower Jurassic shales, forming a high plateau offset by internal thrusts. The front of the Vercors appears to be pinned by pre-existing normal faults (so-called "faille de l'Isere" Butler, 1987, 1989).

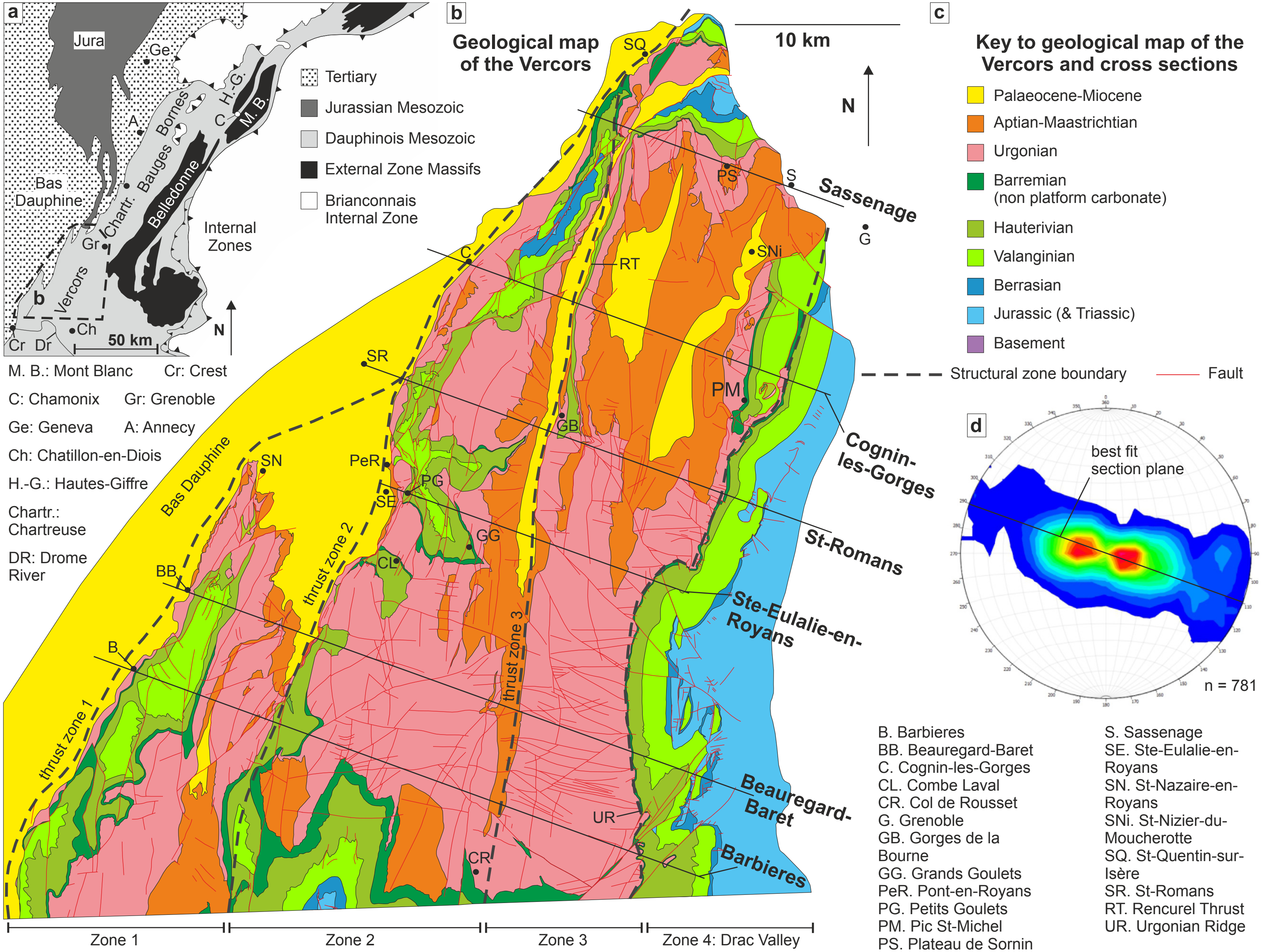

Fig. 2. a) Location map and simplified geological map of the French Sub-Alpine Chains in SE France. Adapted from Moss, 1992a. b) Geological map of the Vercors showing the boundaries of major structural zones (dashed lines) and cross section traces, adapted from B.R.G.M. map sheets 1967, 1968, 1975, 1978, 1983. c) Key to geological map and cross sections (Figs. 6–11). d) Equal area stereonet showing contoured poles to bedding for the Jurassic-Cretaceous succession (using a 0.75% contour interval). The orientation of the best fit section plane is derived by calculating the average bedding dip direction using Move software.

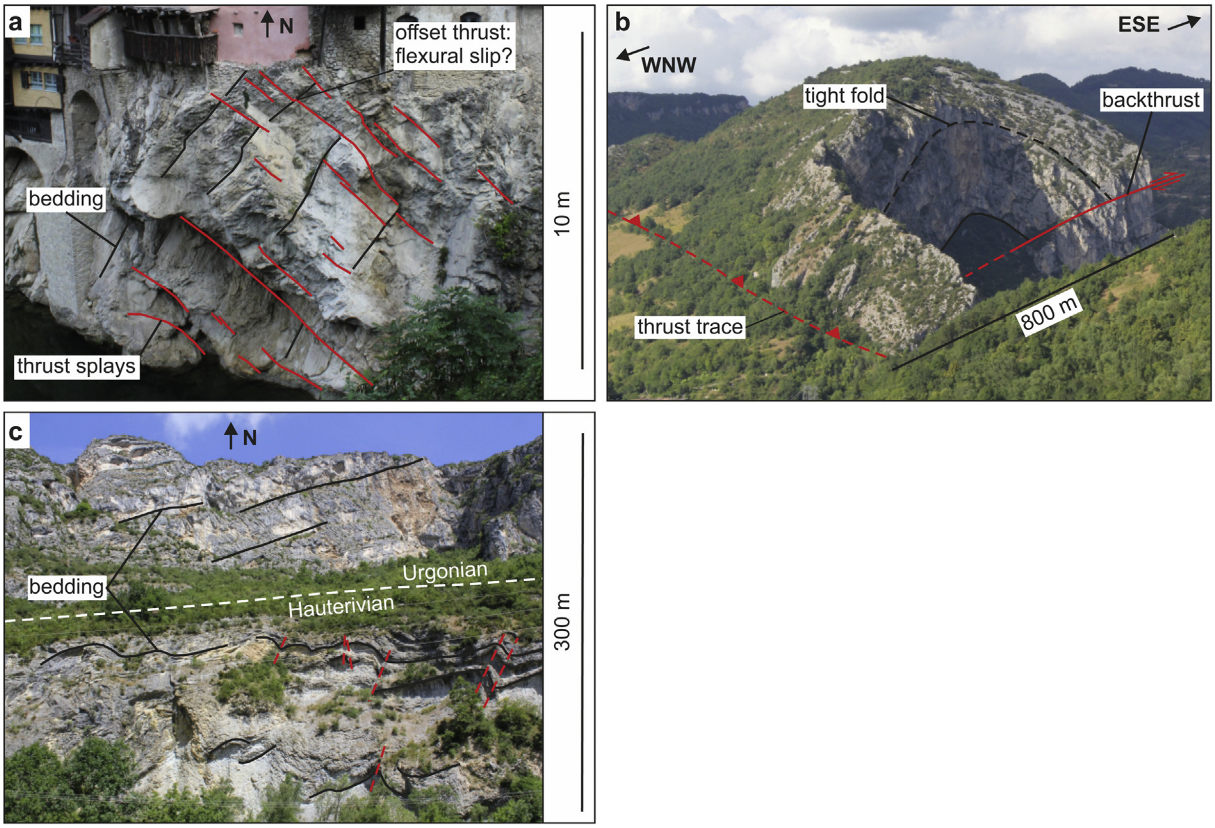

Fig. 3. a) Looking north onto eastward dipping thrust splays in the forelimb of the fold at Pont-en-Royans. b) Looking NNE from Ste-Eulalie-en-Royans to the tight Urgonian fold at Pont-en-Royans, possibly caused by the presence of west-dipping backthrusts causing a pop-up structure. c) Looking north into the fold core at Pont-en-Royans. Small-scale folding in the Hauterivian is probably caused by compression within the fold core. See Fig. 2 for locations.

This study builds upon previous analyses of the Vercors. Butler (1987) presents a single balanced cross-section through the Vercors that established that plateau uplift and its internal thrusting resulted from about 10 km of shortening, with an additional 15 km of displacement being accommodated on a large backthrust that emerges to the east of the Drac Valley. Deville and Sassi (2005) presented a cross section through the Vercors, as part of a larger study on structural variation and thermal evolution of the Sub-Alpine Chains. As part of their regional study of the Subalps, Gratier et al. (1989) presented four cross-sections through the Vercors and demonstrated the southward decline in net displacement across the system. This is in contrast to the much higher displacements interpreted further north in the external Alpine thrust belt, where hard-linked interpretations have been applied (Butler, 1985; Deville et al., 1994; Affolter et al., 2008; Bellahsen et al., 2012, 2014). The position of the Vercors, at the southern end of this declining chain, is ideal for testing the thrust linkage model proposed by Dahlstrom (1969), and the fault growth and linkage model originally established for normal fault systems (Fig. 1b, Childs et al., 1995).

3. Field observations

Field observations, photographs, sketches and bedding orientation data were collected in the field. We now describe some field relationships and fold geometries from different structural zones throughout the fold-thrust belt, which have been influential in regional cross section construction. The Vercors was divided into four main structural zones (see Fig. 2b), which were chosen based on the positions of major thrusts, well-developed fold forelimbs marking the edge of large fold structures, or topographical features.

3.1. Pont-en-Royans: thrust zone splays, backthrusts and disharmonic folding (structural zone 2)

The frontal thrust of structural zone 2 (see Fig. 2b) can be observed in the village of Pont-en-Royans where, instead of a single thrust surface, several thrust splays can be seen cutting up through folded Upper Cretaceous units (Fig. 3a), defining a distributed thrust zone. From the outcrop, it is unclear how these thrusts link at depth. The fold geometry at Pont-en-Royans is also of particular interest due to its very short wavelength. Fig. 3b shows a very tight fold to the east of the village; we have interpreted this as being caused by backthrusts branching off the main foreland-directed thrust at depth. Backthrusts can be seen elsewhere throughout the Vercors at a range of scales. The presence of backthrusts, particularly in fold forelimbs, have a significant control on resulting fold geometry and potentially damage distribution.

The tight fold geometry at Pont-en-Royans is associated with high density fracturing in the Urgonian Limestone, and small-scale, disharmonic folding in the Hauterivian shales below (Fig. 3c). Disharmony in weak underlying layers (Hauterivian shales) appears to have allowed the Urgonian limestone to fold tightly, resulting in the geometry seen on Fig. 3c. This difference in deformation style between more competent units such as the Urgonian and Upper Valanginian, and more incompetent units such as the Lower Valanginian and Hauterivian can be seen throughout the Vercors at a range of structural positions. The Pont-en-Royans structure is a good example of the relationship between deformation distribution in strong versus weak units in the Vercors, caused

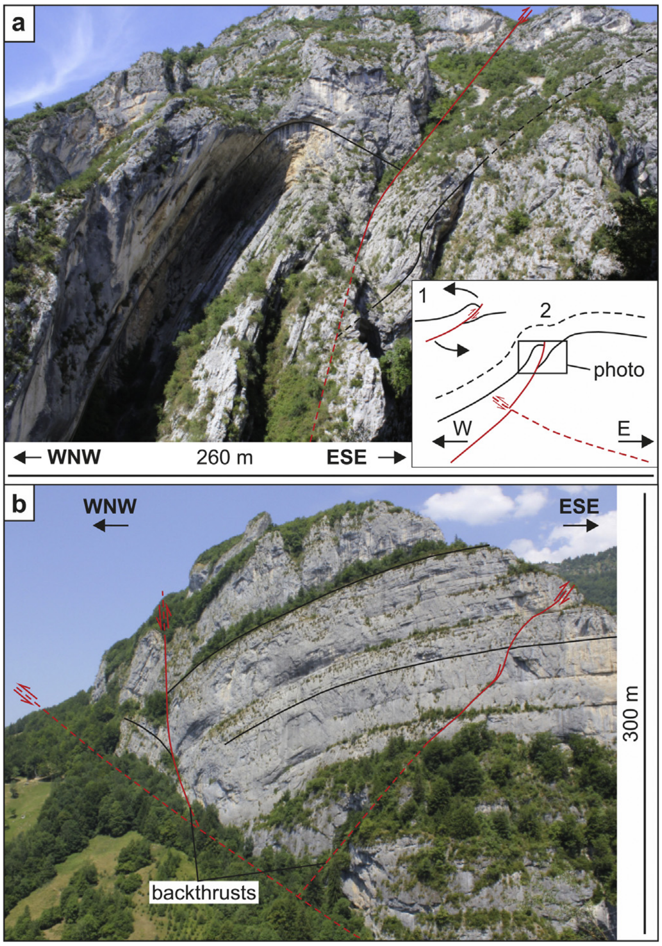

Fig. 4. a) Looking north from Petits Goulets; a steep, west-dipping backthrust probably formed early during Vercors deformation, and was later rotated as the larger fold forelimb developed. Inset: suggested evolution of the Petits Goulets structure: stage 1: backthrusting followed by rotation of the resultant fold due to folding above a larger, eastward-dipping thrust at depth; stage 2: eastward-dipping thrust offsets the older backthrust. b) The Urgonian fold forelimb above the Rencurel Thrust in the Gorges de la Bourne; backthrusts are seen cutting through the fold but they do not alter fold geometry significantly. See Fig. 2 for location.

by rheological differences. The competent Urgonian Limestone defines the large-scale fold geometry, and much smaller scale folds form in the incompetent Hauterivian below in response to compression in the fold core.

3.2. Petits Goulets: pre-existing structure in fold forelimbs (structural zone 2)

The forelimb structure at Petits Goulets (see Fig. 2b for location) is another example of the importance of backthrusts in fold-thrust belts. This forelimb exposure has a very different geometry to at Pont-en-Royans, despite being located just 1.5 km along strike to the south. In this example a prominent fault can be seen in cross section in the forelimb of the fold (Fig. 4a). We have interpreted this as a westward dipping backthrust that pre-dates the main folding and thrusting phase, based on the fold geometry and steep fault angle observed in the field. However Butler (1987) suggests the backthrust formed late and offsets the main eastward-dipping thrust. Initially the dip of this feature would have been much shallower, but it has since been rotated within the forelimb of a larger fold-thrust structure (see inset Fig. 4a). The presence of this backthrust has created small-scale folding within the fold forelimb, which causes structural complexity and could potentially affect the strain distribution within this region.

3.3. Rencurel Thrust (structural zone 3)

The Rencurel Thrust zone marks the western edge of structural zone 3 (Fig. 2b). Above the thrust is a well-developed forelimb of the Rencurel structure. It is best exposed in the Gorges de la Bourne (Fig. 2b) where a gently westward-dipping forelimb can be seen in the Urgonian (Fig. 4b). Minor backthrusting, associated with the Rencurel Thrust appears to have developed at this locality, but in this case the backthrust displacement is minimal meaning it does not have a significant impact on the fold geometry, unlike at Pont-en-Royans (Fig. 3b).

3.4. Plateau de Sornin (structural zone 3)

At the northern tip of the Vercors the Urgonian rises sharply from NW of Sassenage, where it is exposed in the Isere Valley, to the Plateau de Sornin, 1300 m above (see Fig. 2b for location). The Urgonian flattens on the plateau before being cut by the Rencurel Thrust Zone 5.5 km further west (Fig. 5a). This geometry is quite different from anything seen further south in the Vercors and suggests a more complex thrust geometry at depth. Unlike further south where exposure of Urgonian Limestone suggest smooth, curved fold profiles, the Urgonian above Sassenage appears to have a kinked geometry with distinct hinge zones.

3.5. Urgonian plateau and the Drac Valley (structural zones 3 and 4)

The eastern edge of the Vercors is marked by the Urgonian plateau and ridge that runs continuously for over 50 km from St-Nizier-du-Moucherotte in the north to Chatillon-en-Diois at the southern edge of the Vercors (Fig. 2). Urgonian bedding on the ridge dips moderately to the west, probably due to the presence of an underlying backthrust. The presence of such a continuous, high-elevation ridge suggests this backthrust must be a continuous feature, with relatively high displacement. The Drac Valley to the east of the ridge exposes multiple ridges of Jurassic sediments (Fig. 5b), all dipping to the west. These ridges are also likely to have formed due to eastward vergent backthrusts. The backthrusts forming the Drac Valley structures and the Urgonian ridge probably splay off the large-displacement backthrust bounding the eastern edge of the Drac Valley, suggested by Butler (1989).

4. Cross sections through the Vercors

To analyse structural variation along strike, a series of 6 parallel, regional-scale cross sections were constructed through the Vercors, from the Bas Dauphine in the west to the Drac Valley in the east (see Fig. 2b). The orientations of the cross sections are ESE-WNW (110–290°). This orientation was chosen by calculating the average dip direction of surface bedding data (see Fig. 2d), which is parallel to the thrust transport direction (Philippe et al., 1998). The six cross section lines were chosen in locations where exposure is good enough to analyse fold geometry in cross section, for example along WNW-ESE oriented gorges. The bedding data used to construct the cross sections was made up of our own field data, along with data from published geological maps of the Vercors (B.R.G.M. map sheets 1967, 1968, 1975, 1978, 1983). Lithological unit boundaries and fault positions on the published maps (B.R.G.M. map sheets 1967, 1968, 1975, 1978, 1983) were also used for cross section construction. Bedding data was projected from between 1500 and 2000 m either side of each section line; the projection

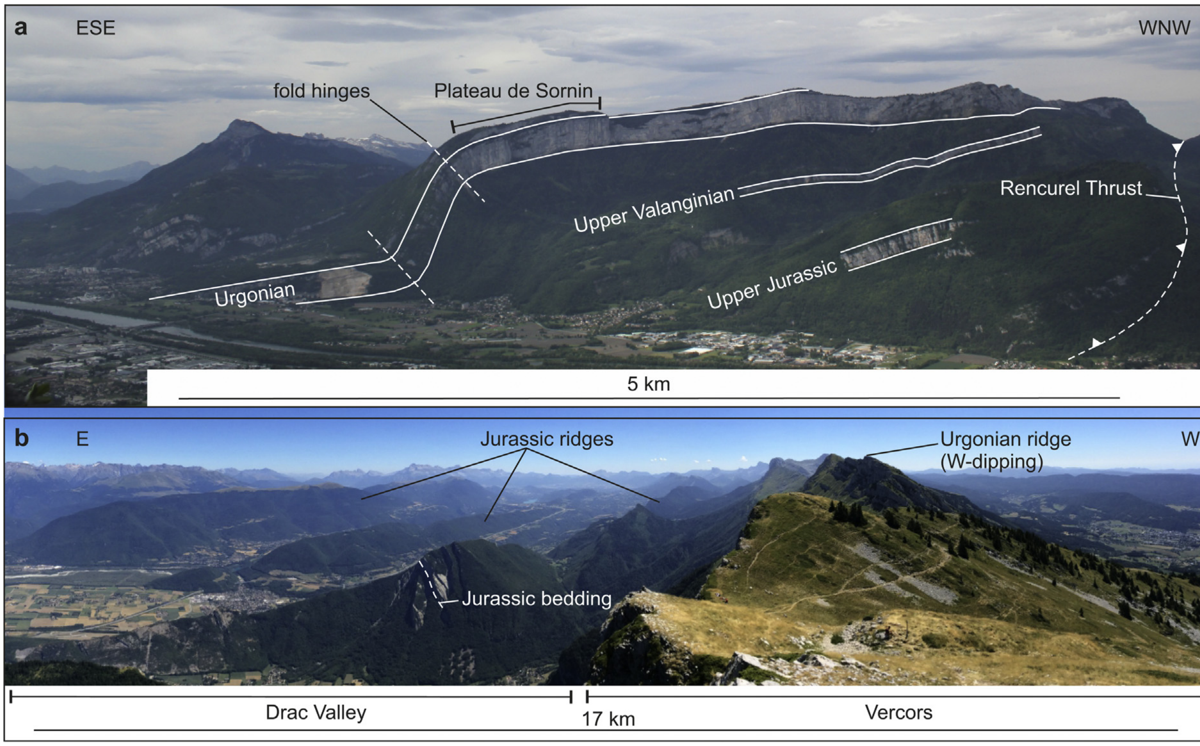

Fig. 5. a) Looking south from the southern Chartreuse onto the northern Vercors. The Urgonian shows a clear kinked geometry as it rises from the Valley bottom to the Plateau de Sornin, possible due to a kinked thrust geometry at depth. b) Looking SE from Pic St-Michel to the Drac Valley. Forested ridges represent the dip panels of Jurassic folds, probably caused by west-dipping backthrusts at depth. See Fig. 2 for locations.

distance was chosen to ensure high enough data density on each cross section.

Field observations have shown the variation in deformation style in different units must be taken into account when constructing a regional-scale cross section. In weaker units, such as the Hauterivian, the bedding orientation may relate either to large scale fold geometry, and therefore parallel stronger unit horizons, or to much smaller scale folds which are not representative of regional scale structure (e.g. Fig. 3c). For this reason, where discrepancies between bedding data in competent and incompetent units are found, the data from the more competent unit is assumed to be more representative of larger scale structure, and is therefore used for cross section construction. Horizons (top Jurassic-Aptian/Maastrichtian) were restored using line-length restoration with a fixed pin at the WNW end of each cross section (e.g. Dahlstrom, 1969) to ensure they balanced and had realistic fault geometries.

4.1. Barbieres cross section (Fig. 6)

The Barbieres cross section is the most southerly section presented here. It runs through the south-central Vercors, across the wide Urgonian plateaus. The cross section features two high-displacement thrusts, both of which are towards the western end of the section (thrust zones 1 & 2, Fig. 2b). Backthrusts splaying off eastward-dipping thrusts are also a key feature of this section; some are emergent and some have been interpreted at depth due to asymmetric folding at the surface. Structural zone 3 is bounded by the Rencurel Thrust Zone (thrust zone 3) which, in this section, is non emergent and instead is inferred at depth due to the presence of a well-developed, steeply dipping forelimb at the surface. The section also includes a large number of out-of-zone thrusts (i.e. thrusts located outside of the main thrust zones 1–3).

4.2. Beauregard-Baret cross section (Fig. 7)

The Beauregard-Baret section is 5.8 km north, along strike of the Barbieres section. It also features the two high-displacement thrusts at the western end, bounding structural zones 1 and 2, as well as the well-developed forelimb above the non-emergent Rencurel thrust at the western edge of structural zone 3. Thrusting in this section is mainly foreland-directed, but there are some minor backthrust splays inferred in structural zone 1. The section contains a few out-of-zone thrusts, as well as minor folding in larger-scale fold backlimbs.

4.3. Ste-Eulalie-en-Royans cross section (Fig. 8)

The Ste-Eulalie-en-Royans section is located 10 km north, along strike of the Beauregard-Baret section. There is no surface evidence for the main thrust controlling the development of the frontal structure (zone 1) seen on the Barbieres and Beauregard-Baret sections therefore it is assumed that displacement has decreased and this structure no longer exists as far north as the Ste-Eulalie-en-Royans line. The most striking feature of this section is the complication in the forelimb of the frontal structure (zone 2). This is the oversteepened backthrust described at Petits Goulets in section 3.2 (Fig. 4a); based on the steep thrust dip this is interpreted as an older thrust with an eastward transport direction that has later been oversteepened by the formation of a larger forelimb. The presence of this backthrust structure has been attributed to a buttressing effect (as suggested by Butler, 1987) due to the presence of a basement-involved normal fault at the level of the regional detachment. The buttressing effect has been described by Welbon (1988) and Butler (1989), where a rigid obstacle at depth (i.e. the basement fault scarp) acts as a buffer, inhibiting propagation of a regional detachment layer towards the foreland. In response to this a hinterland-directed thrust is inferred to have propagated up from this buffering obstacle at depth. Alternatively this feature could be a ‘rabbit-ear’ structure, in which the hinterland-dipping thrust and the backthrust are coeval; the backthrust ramps out of a bedding slip surface, forming asymmetrical fault-propagations folds within the foreland-dipping fold forelimb (Neely and Erslev, 2008). Since the major eastward-dipping thrust is not exposed it is not possible to distinguish between the two interpretations. The Ste-Eulalie section also reflects the tight fold geometry above thrust zone 2 seen at Pont-en-Royans (Fig. 3b). The other key feature of the St-Eulalie section is the Rencurel Thrust zone which marks the western end of structural zone 3. On this section it is an emergent feature with several major thrust splays and no significant fold forelimb development.

4.4. St-Romans cross section (Fig. 9)

6.7 km north along strike from the Ste-Eulalie-en-Royans section line is the St-Romans cross section. There is little field evidence for backthrusting in the forelimb of the frontal structure, as seen on the Ste-Eulalie-en-Royans section; instead a simpler, steeply dipping forelimb is seen on the St-Romans section. The Rencurel Thrust zone (thrust zone 3) on the western edge of structural zone 3 is again emergent on this cross section, with both foreland and hinterland directed thrust splays. A major feature of this cross section is a high-displacement, westward-dipping backthrust at the eastern end of the section. This thrust is probably associated with the westward dip of bedding on the Urgonian Plateau.

4.5. Cognin-les-Gorges cross section (Fig. 10)

The Cognin-les-Gorges cross section lies 7.8 km north, along strike from the St-Romans section. This cross section features rotated and steepened backthrusts in the forelimb of the frontal structure, similar to that seen at Petits Goulets (Fig. 4a) and on the St-Eulalie cross section (Fig. 8). The deep structure of this feature has been interpreted in the same way as further south, initiating at a basement fault scarp at depth. The Rencurel thrust zone (thrust zone 3) in this cross section is represented as a single structure rather than fault splays, unlike further south. The eastern edge of the Vercors is again marked by a high-displacement, westward-dipping backthrust below the Urgonian Plateau, presumably associated with backthrusting in the Drac Valley (structural zone 4).

4.6. Sassenage cross section (Fig. 11)

The Sassenage cross section is the most northerly of the six regional sections presented, and is located 11 km along strike, to the north of the Cognin-les-Gorges section. It runs through the narrow northern tip of the Vercors, and is therefore a relatively short section. The most prominent feature of the Sassenage section is the large displacement Rencurel thrust zone (thrust zone 3) that emplaces the Hauterivian and Valanginian on top of Miocene rocks. Another distinctive feature of this cross section has already been described in section 3.4; the Urgonian limestone of Plateau de Sornin, which rises sharply from the Valley bottom (Fig. 5a). This geometry has been interpreted in the cross section as being associated with a flat-ramp-flat thrust geometry at depth. Further east towards the hinterland a series of closely spaced thrusts that splay off a major thrust at depth can be seen. These low displacement thrusts are associated with well-developed forelimbs, unlike the large-displacement thrust further west, which has no significant fold forelimb developed.

4.7. Deep structure, the Drac Valley and pre-existing, Mesozoic normal faults

On each of the cross sections presented (Figs. 6–11), a large scale (>1 km displacement) normal fault is shown to offset the top basement horizon; this is the Faille de L'Isere fault. Butler (1987, 1989) interpreted this fault as the main control on the position of the frontal thrust, suggesting that the lower detachment of the fold-thrust belt was unable to propagate westwards from the Triassic evaporites in the Faille de L'Isere hangingwall through to the much stronger basement in the footwall. Instead the detachment deflected upwards over the basement fault scarp of the Faille de L'Isere and emerged as the frontal thrust at the surface, on the western margin of the Vercors. This interpretation has been used in this paper to infer a simple model for the deep structure. Pre-existing literature has also been used to infer the structure to the east of the cross sections; beyond the main field area. Bedding data from the Urgonian limestone to the west of the Drac Valley shows a moderate dip to the west, suggesting a backthrust may be present at depth.

In the Drac Valley a series of westward-dipping dip panels in Jurassic units can be seen (Fig. 5b), also indicating westward dipping backthrusts at depth. These are probably linked to the large displacement backthrust suggested by Butler (1987). Backthrusting in the Drac Valley has been represented as a single, large fault on the Sassenage cross section (Fig. 11) although in reality the structure is probably more complex, with multiple thrust splays.

The other main structural feature of the cross sections is normal faults. Each of the cross sections contains several eastward or westward-dipping normal faults, most of which are thought to predate thrusting and probably relate to Mesozoic rifting during opening of the Tethys Ocean. The normal faults on the cross section are shown to be offset by younger thrusts, and none are shown to have been reactivated or inverted. This is because there is little field evidence along the lines of section to suggest the pre-existing normal faults significantly influence fold-thrust structure; instead they appear to have behaved passively during thrusting. Other authors report localised interaction between pre-existing normal faults and younger thrusts in the Vercors, for example Butler (1987, 1989) shows an example where a normal fault has juxtaposed the strong, competent Urgonian limestone alongside weaker, incompetent Hauterivian shales. This horizontal change in lithology meant that a thrust could not easily propagate from the weak shales into the strong limestones, so instead, intense, localised folding occurred, with potential reactivation of the normal fault in the hangingwall of the newly formed thrust, a phenomenon termed buttressing (Welbon, 1988). Although evidence for buttressing is seen in Mesozoic rocks in the Vercors, it appears to be quite rare and is therefore not represented on the cross sections.

5. Along strike variation

5.1. Shortening and total thrust displacement

Regional cross sections were analysed to determine changes in fold geometry, thrust displacement and shortening. Displacements on each thrust were measured at the top Urgonian horizon for the six regional cross sections (Figs. 6–11), along with total shortening distance and shortening percentage. Fig. 12 shows how these estimates for shortening, along with the total thrust displacement for each cross section, varies along strike. The graph patterns for total thrust displacement and shortening distance are quite similar (Fig. 12a), indicating that, overall, the majority of shortening is accommodated by thrusting and brittle deformation rather than folding. Both the total thrust displacement and shortening distance

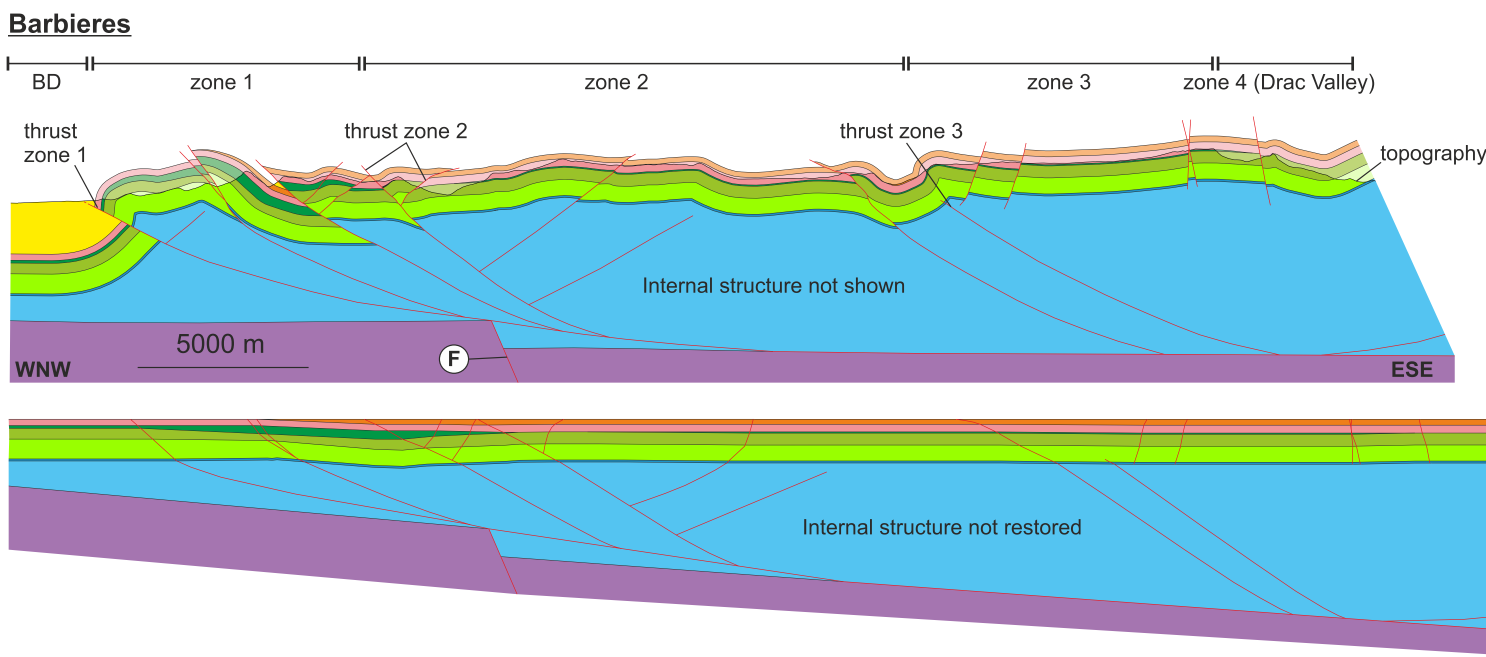

Fig. 6. Top: Barbieres cross section running WNW-ESE from the Bas Dauphine (BD) to the Drac Valley (zone 4). F: Faille de L'Isere fault. See Fig. 2b for section trace line. Bottom: cross section following line-length restoration. Line length restoration has been applied only to the top Jurassic-Cretaceous horizons; the internal structure of the Jurassic and basement is not restored.

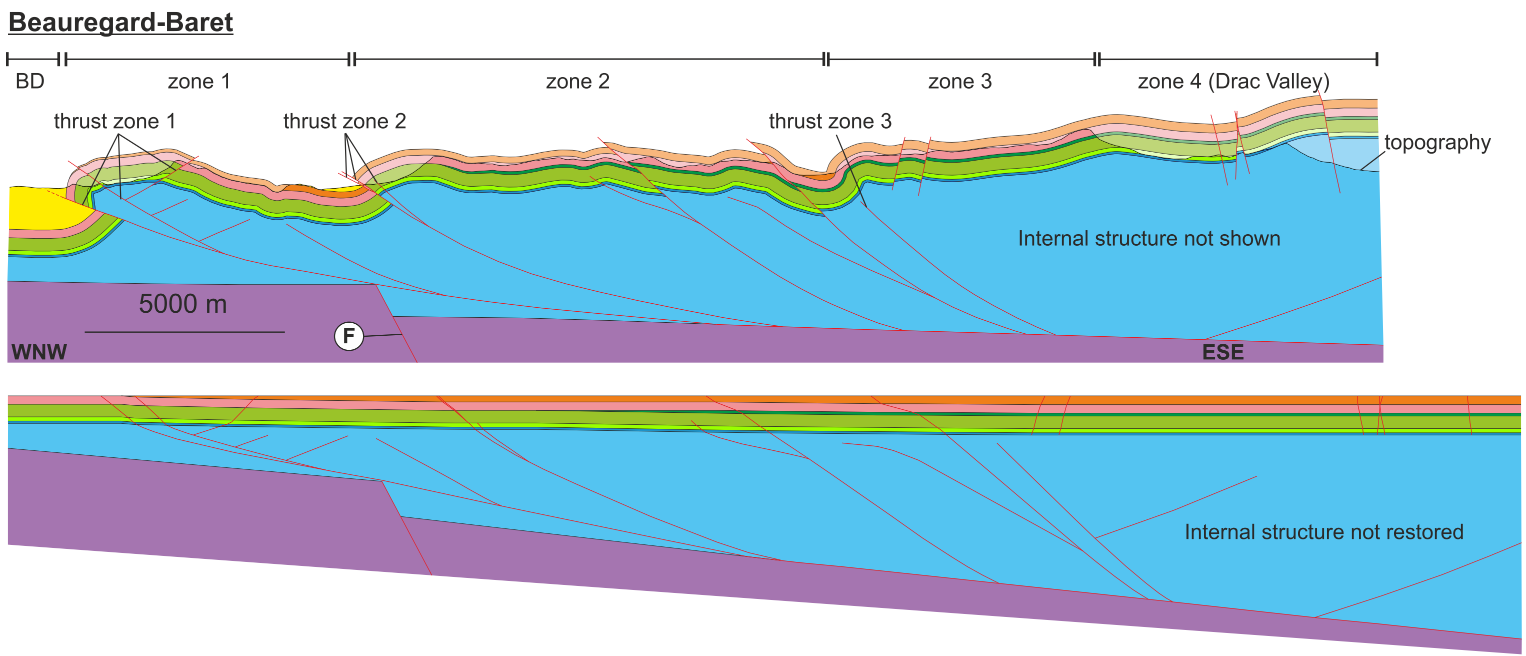

Fig. 7. Top: Beauregard-Baret cross section running WNW-ESE from the Bas Dauphine (BD) to the Drac Valley (zone 4). F: Faille de L'Isere fault. See Fig. 2b for section trace line. Bottom: cross section following line-length restoration. Line length restoration has been applied only to the top Jurassic-Cretaceous horizons; the internal structure of the Jurassic and basement is not restored.

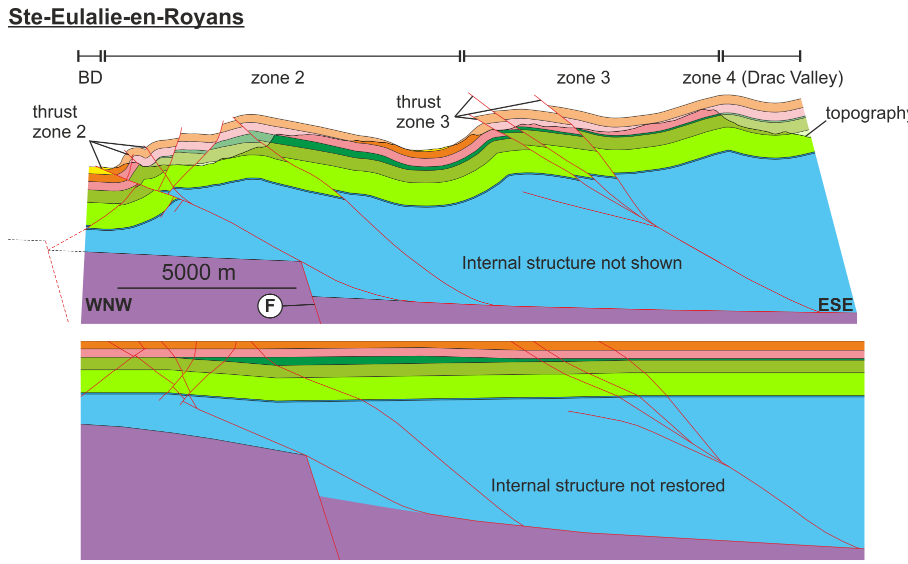

Fig. 8. Top: Ste-Eulalie-en-Royans cross section running WNW-ESE from the Bas Dauphine (BD) to the Drac Valley (zone 4). F: Faille de L'Isere fault. See Fig. 2b for section trace line. Bottom: cross section following line-length restoration. Line length restoration has been applied only to the top Jurassic-Cretaceous horizons; the internal structure of the Jurassic and basement is not restored.

increase from Sassenage to St-Romans, before decreasing in the Ste-Eulalie-en-Royans section and increasing again to the Barbieres section. On the southern two cross sections (Beauregard-Baret and Barbieres) the shortening distance becomes larger than the total thrust displacement, probably due to the presence of well-developed folds on lower displacement thrusts (Figs. 10 and 11).

The shortening percentage has also been calculated for each cross section and plotted on Fig. 12b. This value is commonly used to compare the amount of compression and strain in thrust belts. Fig. 12b shows the shortening percentage trend along strike is different to that of shortening distance (Fig. 12a). The three northern sections (Sassenage, Cognin-les-Gorges and St-Romans, Figs. 6–8) have the highest shortening values (11–14%) and the three southern sections (Ste-Eulalie-en-Royans, Beauregard-Baret and Barbieres, Figs. 9–11) have the lowest shortening values (5–10%). Shortening percentages suggest the two most southerly sections underwent less shortening that the two most northerly sections, however the shortening distance values suggest the opposite (Fig. 12a). The reason for this discrepancy is that the two southerly cross sections are much longer than the northern sections. If you compare two cross sections with the same shortening distance but different lengths, the shorter section will appear to have higher shortening percentage than the longer section. Clearly when analysing thrust belt shortening using cross sections of different lengths it is important to use the actual shortening distance value rather than shortening percentage, for the reason shown above.

5.2. Thrust zone displacement

Three main thrust zones were identified in the study area; zone 1 is the frontal thrust zone in front of the Beauregard-Baret structure (structural zone 1). It can be traced along the mountain front in the southern Vercors. Zone 2 is the thrust zone beneath the Pont-en-Royans structure (structural zone 2), and zone 3 is the Rencurel Thrust zone (bounding structural zone 3) that merges with the Voreppe Thrust in the southern Chartreuse (Fig. 2). Total displacements for each thrust zone were calculated at the top Urgonian horizon for each cross section to determine whether shortening variations along strike occur along a single thrust zone or are due to consistent changes in displacement within all three main thrust zones. Displacement variations along strike on individual thrusts were not analysed because at the surface thrusts are relatively short and usually do not intersect more than one cross section.

Fig. 13 shows how thrust zone displacements vary along strike, as well as on out-of-zone thrust in between major thrust zones. Thrust zone 1 only appears on the two most southerly sections, where its displacement is 900–1100 m. This sudden increase in displacement between the Ste-Eulalie-en-Royans and Beauregard-Baret sections is reflected in the fold geometry; on the northern banks of the Isère river no fold is present and topography is relatively flat; 3 km to the south of this a large fold with a well-developed, steeply dipping forelimb rising 500 m above the river in the Urgonian. Thrust zone 2 is not present on the Sassenage section; its displacement gradually increases from the Cognin-les-Gorges section to the south at a much steadier rate than thrust zone 1. Thrust zone 2 remains a relatively low displacement zone throughout the region. Displacement on thrust zone 3 is high in the north, and decreases gradually to the south where it is interpreted to have zero displacement in the Urgonian; the thrust is still present at depth in the Jurassic succession. On the southern two cross sections thrust zone 3 is represented at the surface as a well-developed fold with a steeply dipping forelimb. This fold geometry contrasts with sections further north along thrust zone 3, where thrust displacement in the Urgonian is much higher, but folds are less well developed and have only shallowly dipping forelimbs. Out-of-zone displacement in between thrust zones 1, 2 and 3 is relatively low in the north, increasing significantly to the south.

The patterns of thrust displacement variation in the three thrust zones and out-of-zone are a good example of how displacement may be transferred along strike in a fold-thrust belt. In the north thrust zone 3 is clearly the dominant one, accommodating the majority of shortening in the Vercors. As displacement within thrust zone 3 decreases to the south, both the out-of-zone and thrust zone 1 displacement gradually increase to accommodate displacement loss from zone 3. Displacement in thrust zone 2 remains low throughout the Vercors, indicating that it has little

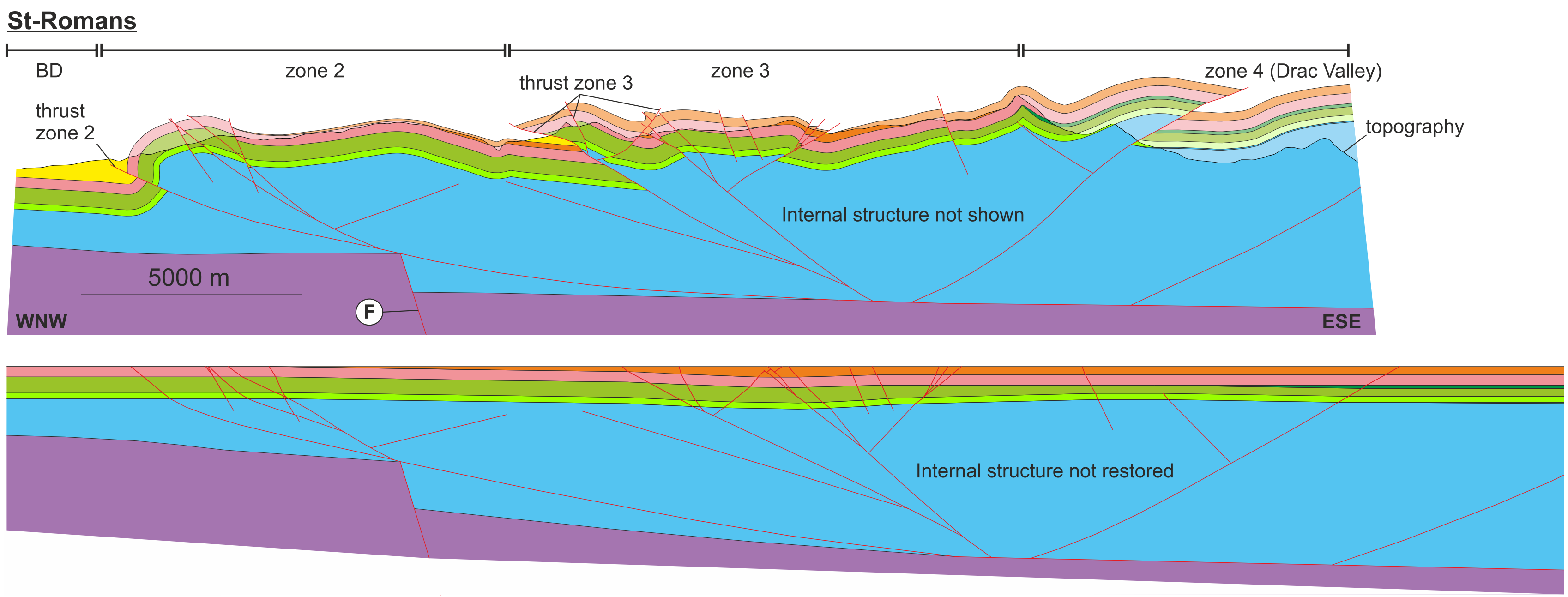

Fig. 9. Top: St-Romans cross section running WNW-ESE from the Bas Dauphine (BD) to the Drac Valley (zone 4). F: Faille de L'Isere fault. See Fig. 2b for section trace line. Bottom: cross section following line-length restoration. Line length restoration has been applied only to the top Jurassic-Cretaceous horizons; the internal structure of the Jurassic and basement is not restored.

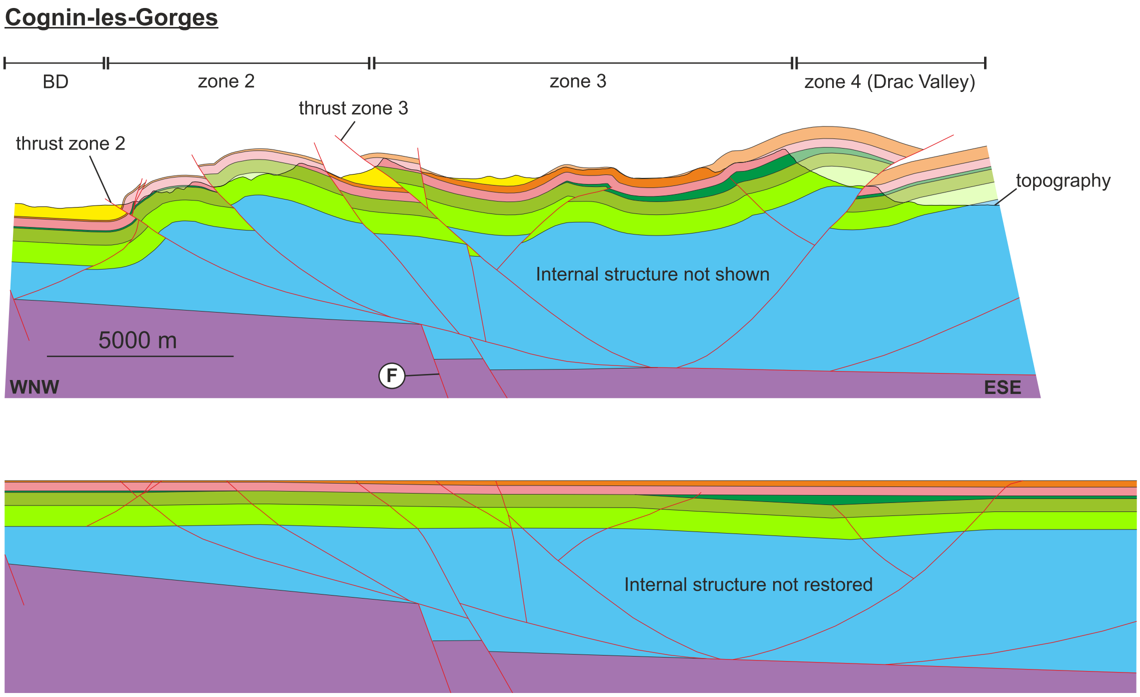

Fig. 10. Top: Cognin-les-Gorges cross section running WNW-ESE from the Bas Dauphine (BD) to the Drac Valley (zone 4). F: Faille de L'Isere fault. See Fig. 2b for section trace line. Bottom: cross section following line-length restoration. Line length restoration has been applied only to the top Jurassic-Cretaceous horizons; the internal structure of the Jurassic and basement is not restored.

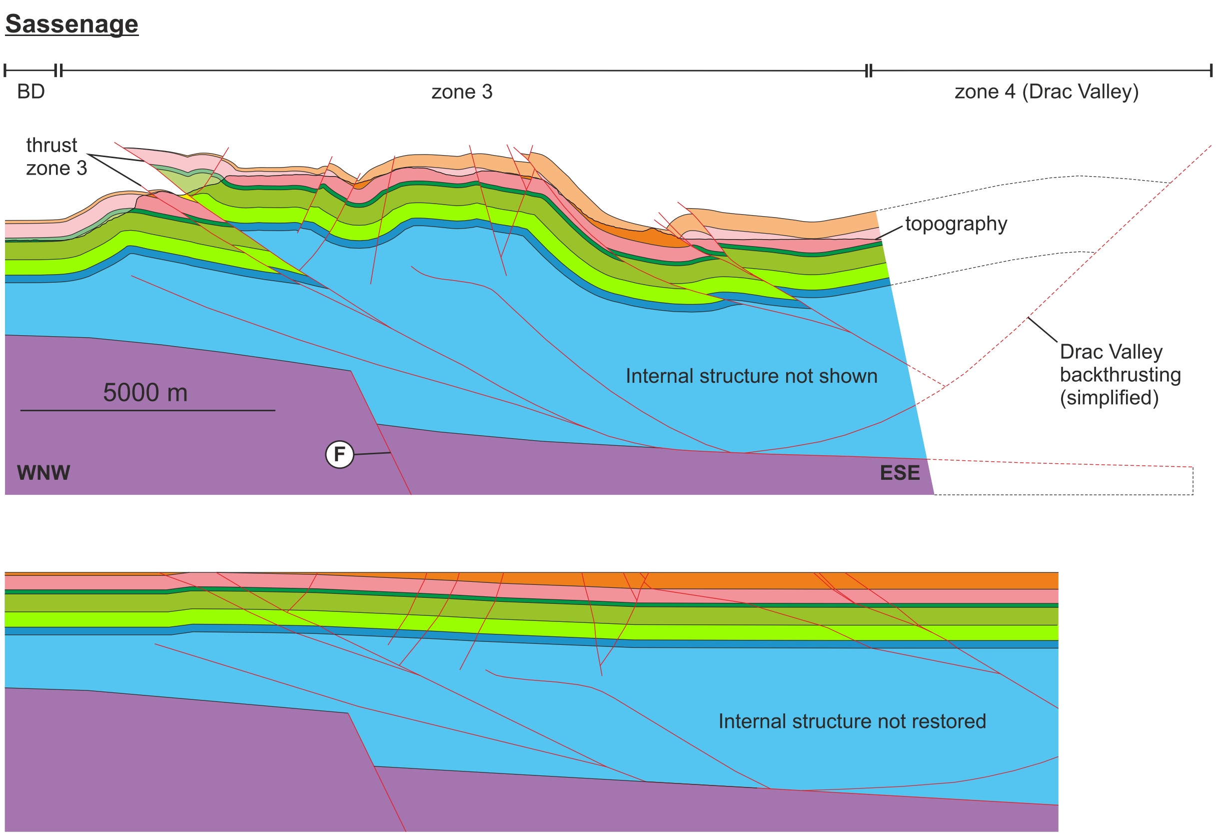

Fig. 11. Top: Sassenage cross section running WNW-ESE from the Bas Dauphine (BD) to the Drac Valley (zone 4). F: Faille de L'Isere fault. See Fig. 2b for section trace line. Bottom: cross section following line-length restoration. Line length restoration has been applied only to the top Jurassic-Cretaceous horizons; the internal structure of the Jurassic and basement is not restored.

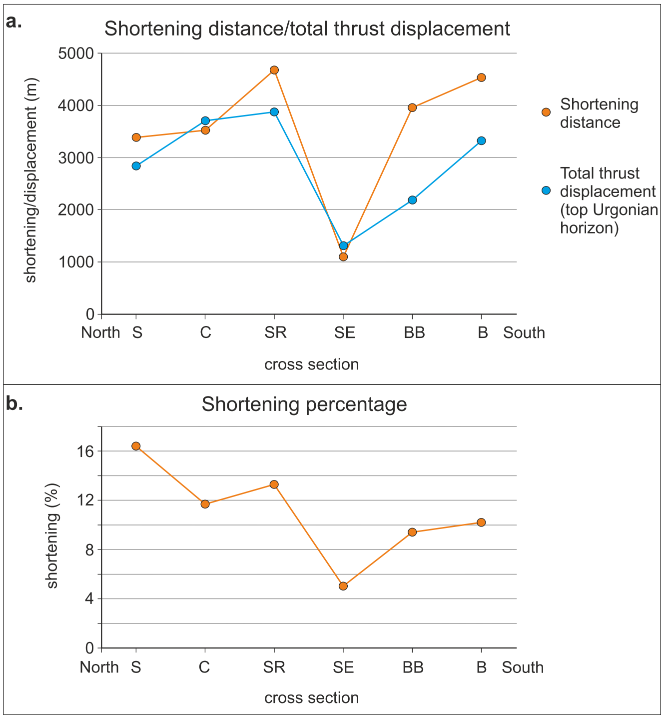

Fig. 12. a) Shortening distance and total thrust displacement profiles showing along strike variations from north to south. A good correlation between the two lines in the north shows thrusting accommodates the majority of shortening; in the south shortening distance is higher than thrust displacement indicating more folding is accommodating shortening. b) Shortening percentage profile suggesting a general decrease in shortening from north to south. S: Sassenage section; C: Cognin-les-Gorges section; SR: St-Romans sections; SE: Ste-Eulalie-en-Royans section; BB: Beauregard-Baret section; B: Barbieres section. Shortening percentages have been calculated by measuring the difference in line length between the present day and restored cross sections (Figs. 6–11) for the top Urgonian horizon, dividing by the original (restored) length and multiplying by 100.

shortening distance on Fig. 12a.

6. Discussion

6.1. Shortening and structural style of the Vercors

The six cross sections presented in section 4 suggest shortening in the Vercors is up to 5 km; this is in contrast to other authors who estimate more shortening such as Butler (1989) and Philippe et al. (1998) who both calculate 10 km of shortening and Bellahsen et al. (2014) who suggests that the value is around 28 km. The reason for the differences in shortening estimates is because the cross sections of Butler (1989) and Bellahsen et al. (2014) extend much further east than our own. In this paper we focus mainly on the deformation in the central Vercors (i.e. structural zones 1–3, see Fig. 2b), however Butler (1989)'s estimate includes large-scale backthrusting present in the Drac Valley to the east of our sections. Fig. 5b showed west-dipping ridges of Jurassic units which are probably the backlimbs of folds formed above backthrusts. The topographic relief of these features is quite high, which might indicate high thrust displacement and significant shortening on these structures, which could accommodate any 'missing' shortening distance.

Total thrust displacement curves (Fig. 12a) suggest a gradual increase in displacement to the south from the Sassenage section to the St-Romans section, before decreasing on the Ste-Eulalie-en-Royans section and increasing again in the Beauregard-Baret and Barbieres sections. This rather complicated pattern can be explained simply by the presence of backthrusts at the eastern end the Cognin-les-Gorges and St-Romans sections (Figs. 9 and 10); if the displacements of these two thrusts were removed from the thrust displacement graph (Fig. 12a), there would be little change in total thrust displacement along strike, with the exception of the Ste-Eulalie-en-Royans section, indicating relatively consistent deformation along the length of the Vercors.

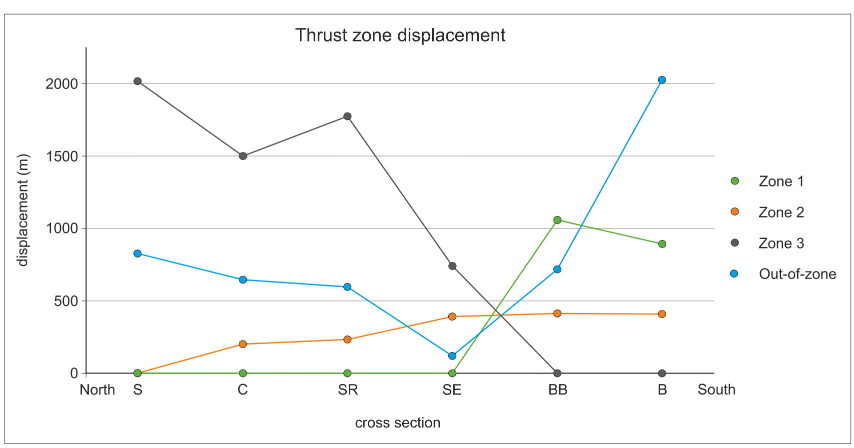

Fig. 13. Thrust zone displacement profiles for thrust zones 1–3 and out-of-zone displacement. Out-of-zone displacement refers to displacement on thrusts that are located within structural zones 1–3 (see Fig. 2b) but not within thrust zones 1–3. A decrease in thrust zone 3 displacement coincides with increases in thrust zone 1 and out-of-zone displacement, indicating displacement transfer between thrust zones. S: Sassenage section; C: Cognin-les-Gorges section; SR: St-Romans sections; SE: Ste-Eulalie-en-Royans section; BB: Beauregard-Baret section; B: Barbieres section.

influence on along strike shortening variation (Fig. 13). Data presented on Fig. 13 shows that variation in shortening along strike is accommodated along certain zones rather than being due to consistent changes in displacement on all thrusts. Fig. 13 also shows that displacement in all three thrust zones, as well as out-of-zone displacement is low on the Ste Eulalie section, causing a low

The Ste-Eulalie-en-Royans section (Fig. 8) is anomalous to the overall shortening patterns; the total thrust displacement and total shortening distance (Fig. 12a) are much lower than on adjacent sections. If shortening did decrease suddenly around the Ste-Eulalie-en-Royans section line we might expect to see localised faults and folds forming oblique to the main thrusts zones, deviations in the orientation of these thrust zones, and more intense deformation in this region. These features would be required to accommodate the sudden change in shortening distance. The map patterns of thrust zones 1–3 show continuous, parallel features that do not show any significant changes around the Ste-Eulalie-en-Royans section line. This would suggest that the total shortening distance along the thrust belt is relatively consistent with no sudden changes. This suggests that a significant amount of shortening (c. 2500–3000 m) is absent from the Ste-Eulalie-en-Royans cross section (Fig. 8). Displacements on individual thrusts on this section line are well constrained by map patterns and field observations so the 'missing' shortening suggests at least one major compressional feature is absent from this section. The absence of this feature was inferred by analysing and comparing cross sections along strike; when observed in isolation this cross section balances when restored (Fig. 8) and appears as a structurally valid interpretation. Along strike cross section analysis is not only important for determining large scale structural trends, but can also be used as a tool to validate structural interpretation.

The patterns for total thrust displacement and shortening distance on Fig. 12a also indicate a change in the nature of deformation along strike; in the north thrust displacement and shortening are similar, whereas in the south shortening distance is considerably higher than thrust displacement. This relationship reflects a change in structural style, as exemplified by the Rencurel thrust zone (thrust zone 3). In the north brittle deformation dominates; thrust displacement is high but folds are poorly developed. In the south, around the Beauregard-Baret and Barbieres sections, the thrust has zero displacement at the surface but folds are well developed. A similar amount of shortening is accommodated along strike but structural geometries are very different.

There are several reasons behind this change in fold geometry, including variation in burial depth and deformation conditions; rate of deformation; variation in lithology; change in thrust kinematic mechanism, variation in detachment characteristics and proximity to the thrust tip. The change from thrust-dominated shortening in the north to fold-dominated shortening in the south could be explained by deeper burial depths, and therefore warmer deformation conditions in the south. Investigations into the organic maturation and tectonic loading by Moss (1992a, 1992b) suggest the southern Sub-Alpine chains (Vercors and Chartreuse) have undergone shallower burial than the northern chains (Haute-Giffre and Aravis massifs), however data was not collected south of the Gorges de la Bourne in the Vercors (Fig. 2b), meaning little is known about deformation conditions in the southern Vercors, around the Beauregard-Baret and Barbieres sections.

Variation in the rate of deformation may also cause changes in structural style; slower rates might allow well-developed folding without brittle failure to occur in the south, whereas faster rates might be the cause of brittle thrusting and poorly developed folds in the north. Although variation in deformation rate could be behind the observed structural variation, there is no other evidence for it so it is an unlikely cause. A major change in lithology would lead to changes in the rheological behaviour of the deforming rocks, and therefore alter the structural style. However, once again there is little evidence for significant changes in lithology in the Vercors that might cause these changes in structural style.

It is probable that the variation in fold geometry could be caused by changes in kinematic thrusting mechanism along strike and proximity to the thrust tip. The change from a high displacement thrust in the north to a non-emergent thrust in the south suggests the Rencurel Thrust (thrust zone 3) probably dies out south of the cross sections so the folds on the Beauregard-Baret and Barbieres sections (Figs. 10 and 11) are likely to be much closer to the thrust tip than the northern sections. The sections also show a difference in thrust propagation from north to south. In the northern sections (Figs. 6–9) the Rencurel Thrust is shown to have propagated all the way through the Upper Cretaceous whereas on the southern two sections (Figs. 10 and 11) the thrust tip is in the Jurassic or Lower Cretaceous. The difference in structural geometry might relate to the thrust propagation rate: for the same amount of shortening the thrust in the south may have had a slower thrust propagation rate, giving time for the fold to develop in the hangingwall in front of the thrust tip, as in the trishear mechanism (Erslev, 1991). The thrust in the north may have propagated up section much faster, giving little time for folding in the hangingwall, as in the fault-parallel flow or fault-bend-fold mechanisms (Suppe, 1983; Egan et al., 1997; Kane et al., 1997). It has also been suggested (e.g. by Philippe et al., 1998) that the nature of the lower detachment to the fold-thrust belt changes along strike; in the northern Vercors the detachment is thought to be in marls and shales, whereas in the south thrusts are thought to detach in a salt horizon (Philippe et al., 1998). The lithology of a detachment has been found to control the structural style of a fold-thrust belt; frictional detachments create thrusts with asymmetric folds whereas viscous detachments (such as salt) create more symmetric structures with less faulting (e.g. Ruh et al., 2012). The variation in detachment lithology could therefore influence structural style variations in the Vercors.

6.2. Thrust linkage and growth

Analysing displacements in individual thrust zones has shown variations from north to south. Thrust zone displacement curves (Fig. 13) show evidence for displacement transfer along strike; zone 3 dominates in the north and decreases to the south, whereas displacement in zone 1 and on out-of-zone thrusts increases to the north. Displacement in thrust zone 2 appears not to change significantly along strike. These patterns can be compared with the model of Dahlstrom (1969) showing thrusts relaying displacements through an array (Fig. 1a). In the model the total shortening is equal on all sections, suggesting that thrust belt structure is relatively simple on a large scale. However, displacement on individual thrusts varies significantly, which creates structural complexity within the thrust belt. Dahlstrom's model has been reconstructed for the Vercors (Fig. 14), showing that displacement loss in thrust zone 3 to the south is accommodated by displacement gain in thrust zone 1. Thrust zones are not isolated systems, but instead these large features are soft linked. Displacement is transferred between thrusts zones to maintain a relatively constant shortening distance along strike. Although thrusting in the Vercors occurs on a much smaller scale to the Canadian Rockies, on which Dahlstrom (1969)'s thrust transfer zone model was based, we can see the same mechanisms for large-scale thrust linkage.

The relatively low thrust displacements in the Vercors has allowed us to analyse the mechanisms of thrust growth and linkage. Map patterns within thrust zones show them to be made up of multiple short thrust segments rather than single, long thrust structures. These short thrust segments within individual thrusts zones do not branch off one-another and appear isolated on the geological map (Fig. 2b). These patterns suggests that thrust zones must be made of short, soft linked thrusts, which transfer displacement along strike and contribute towards the total thrust zone displacement. These observations suggest the established model for normal fault growth and linkage (Childs et al., 1995, Fig. 1b–c) could also be applied to thrust systems. The soft linked thrusts observed in the Vercors are an under-reported thrusting style, which may represent the early stages of thrust development. In other thrust belt examples (e.g. Diegel, 1986; Hossack, 1983) high displacement thrusts are shown to transfer displacement across

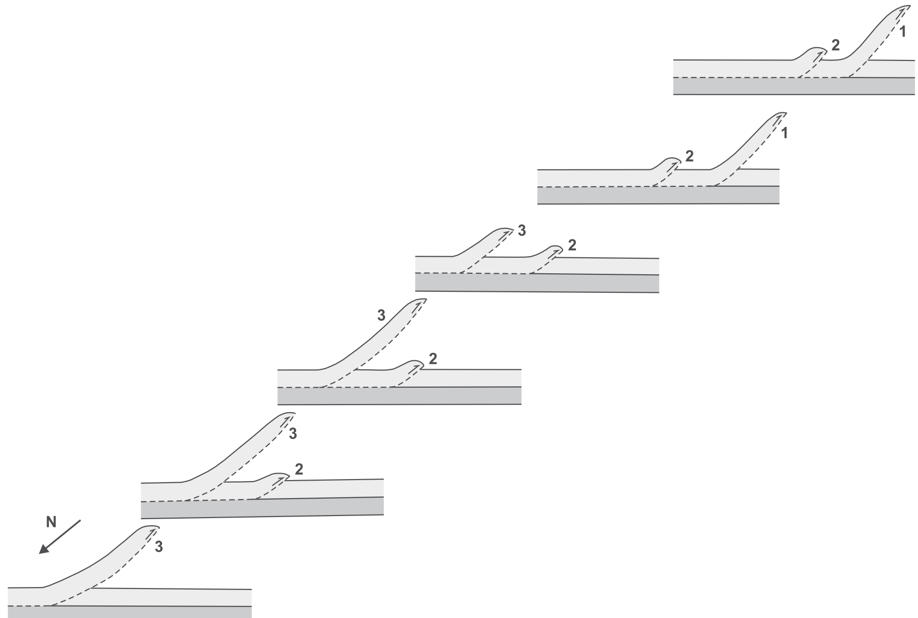

Fig. 14. Model for thrust zone displacement transfer along strike in the Vercors. Displacement in thrust zone 3 gradually decreases to the south, which is accommodated by a gradual increase in thrust zone 1 displacement to maintain constant fold-thrust belt shortening. Displacement in thrust zone 2 varies very little along strike.

branch lines (i.e. they are hard-linked). If the fault growth model (Childs et al., 1995) for extensional systems can be applied to thrust belts, then we have might expected thrust branches to have formed within the Vercors thrust zones, had displacements increased, leading to hard linked, through-going thrust zones.

7. Conclusions

Analysis of parallel cross sections constructed through the Vercors fold-thrust belt has shown the total shortening distance is relatively consistent, however the internal structure is more complex. Cross sections show changes in structural style along strike and significant variation in individual thrust zone displacement with displacement gradients varying significantly from 16 to 107 m/km. Large-scale thrust zone displacement patterns suggest they are soft linked; as displacement decreases in one zone, it increases in another to maintain a constant total shortening within the fold-thrust belt. Individual thrust zones are comprised of short, soft-linked thrust segments. They probably represent an intermediate stage in thrust development at low displacements (up to 2000 m in the Vercors), where thrust splays have not yet formed to create larger, through-going thrust structures, as seen in other global thrust belt examples, such as the Rockies, where thrust displacements are much higher (over 10 km, Price, 1981). The question is are the thrust displacement gradients and linkage patterns in the Vercors applicable to carbonate thrust belts in general or are they dependent on the specific nature of the deforming multiplayer?

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