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Untangling the Annot sand fairway: structure and stratigraphy of the Eastern Champsaur Basin (Eocene-Oligocene), French Alps.

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ABSTRACT

Early foredeep successions can yield insight on tectonic processes operating adjacent to and ahead of fledgling orogenic belts but are commonly deformed by the same orogens. We develop a workflow towards stratigraphic understanding of these deformed basins, applied to the Eastern Champsaur Basin of the French Alps. This contains a down-system correlative of the southern-sourced (Eocene-Oligocene) Annot turbidites. These strata are deformed by arrays of W-facing folds that developed beneath the Embrunais-Ubaye tectonic allochthon. The folds vary in geometry through the stratigraphic multilayer. Total shortening in the basin is around 4 km and the restored (un-decompacted) stratal thickness exceeds 980m. The turbidites are generally sand-rich and bed-sets can be correlated through the entire fold train. The succession shows onlap and differential thickening indicating deposition across palaeobathymetry that evolved during active basement deformation, before being over-ridden by the allochthon. The sand system originally continued over what is now the Ecrins basement massif that, while contributing to basin floor structure, only served to confine and potentially focus further sediment transport to the North. Deformation ahead of the main Alpine orogen appears to have continued progressively, and the past definition of distinct "phases" ("pre-" and "post-Nummulitic") is an artefact of the stratigraphic record.

Keywords: turbidites, structural restoration, foreland basin,

Turbidite systems can offer important constraints on bathymetric continuity of arrays of sedimentary basins (e.g. Smith 2004; Puigdefabregas *et al.* 2004) and thus inform models of basin evolution. For ancient foredeep systems the challenge is to unravel useful stratigraphic information from successions that are involved in orogenic belts and then deformed. If stratigraphic information can be extracted from deformed systems, the insights so gained can then not only inform models of orogenic evolution but also impact on greater tectono-stratigraphic understanding of turbidite systems. This is especially important as many of the key ideas of turbidite sedimentation come from studies of successions in syn-orogenic sedimentary basins. The aims of this paper are two-fold. The first is to document a workflow for developing stratigraphic knowledge from highly folded successions. The second is to provide a linked stratigraphic and structural reconstruction of the Eastern Champsaur Basin – a deformed part of the Eocene-Oligocene Annot Sandstone system of SE France (the Grès d'Annot in Alpine literature: e.g. Sinclair 1997; Joseph & Lomas 2004) that has become incorporated into the Western Alpine orogen. While an extensive re-examination of the Annot system in the light of our reconstructions lies beyond the scope of this paper, we do explore some implications for the extent of the system, how crustal-scale deformation migrates through time and how tectonic evolution is represented in the stratigraphic record.

Geological context and motivation

The Annot system of SE France as a whole occupies a pivotal position in turbidite research, with outcrops providing test-beds for models of deep-water sedimentation and analogues for hydrocarbon reservoirs in the subsurface. Bouma's pioneering descriptions of turbidite facies come from proximal parts of the Annot system (e.g. Bouma 1959; Stanley & Bouma 1964). This turbidite system was deposited in a broadly north-south trending foredeep basin, adjacent to the ancestral Alps and fed from eroding granitic basement to the south (Maures-Esterel massif, Fig. 1a) together with Corsica that, at the time, lay adjacent to the south coast of mainland France. Much of the early research is cited by Joseph & Lomas (2004) and papers that follow this introduction greatly expand upon these works. More recent studies include Mulder *et al.* (2010), Etienne *et al.* (2012), Salles *et al*. (2014), and Cunha *et al.* (2017).

Existing work has almost entirely focussed on sites that have experienced rather little deformation. The system is known to continue into more strongly deformed regions to the north and northeast (e.g. Sinclair 1997). By increasing understanding of the Annot system, insight is gained on the continuity and early deformation of the Alpine "foreland". As subaqueous gravity flows, turbidity currents seek low bathymetry. Therefore, the continuity of sand fairways, the geological record of the routes taken by their causative flows, provides evidence for relative bathymetry in front of the evolving Alpine orogen. The various relationships between the turbidites and their substrate chart not only the syndepositional deformation of the foredeep basin floor but also the deformation that predated basin subsidence. This understanding is important for evaluating the tectonic significance of unconformities associated with orogens and their implications for evaluating the progression of continental deformation. By increasing understanding of the Annot system, insight is gained on the continuity and early deformation of the Alpine "foreland".

Our case study here focusses on the south-eastern flank of the external Alpine basement massif of the Ecrins (Fig. 1a). The Eocene-Oligocene litho-stratigraphy of the area, in common with the main Annot system (Fig 2; e.g. Joseph & Lomas 2004), consists of three main lithofacies (Debelmas *et al.* 1980) that comprise the "Nummulitic trilogy". Collectively this represents the foredeep megasequence developed during this early stage of Alpine orogenesis. The megasequence oversteps a substrate of crystalline basement, continuous with the neighbouring Ecrins massif, together with remnant patches of the Triassic-Jurassic cover to the massif (e.g. Debelmas *et al.* 1980). The eastern and southern margins to the basin are now buried beneath the tectonic allochthon of the Embrunais-Ubaye thrust sheets.

The first part of the Nummulitic trilogy is the Nummulitic Limestone, a shallow-water transgressive unit here of Priabonian age (Debelmas *et al.* 1980; Dumont *et al.* 2012). Locally, the Nummulitic Limestone is underlain by conglomerates derived from the adjacent crystalline basement, interpreted to be the fills to subaerially-incised palaeovalleys (e.g. Gupta 1997). The second part of the Nummulitic trilogy are the Blue Marls ("Marnes à Globigérines" on published maps, e.g. Debelmas *et al.* 1980). These calcareous mudstones chart palaeo-bathymetries increasing to several hundred metres depth. The final part of the trilogy are turbidites – the Champsaur Sandstone ("Grès du Champsaur" on published maps, e.g. Debelmas *et al.* 1980). Locally, there is a facies intermediate between these turbidites and the Blue Marls, the Brown Marls (e.g. Stanbrook & Clark 2004). These are generally inferred to have accumulated on local intra-basin highs from dispersed suspension clouds associated with the turbidity currents that deposited the Champsaur (and main Annot) Sandstone.

The Nummulitic trilogy is capped by a shaley olistostrome termed the "Schistes à Blocs" that lies directly under the Embrunais-Ubaye thrust sheets. It is classically inferred to have been shed off the advancing thrust sheets as the foredeep basin was closed (Kerckhove 1969). Detailed sedimentological investigation of the Schistes à Blocs in the Eastern Champsaur Basin is strongly inhibited by the intense penetrative deformation within this unit, which presumably reflects distributed shear deformation in the footwall to the overlying thrust sheets. Consequently, it is generally difficult to establish whether the unit represents a series of amalgamated debris flow deposits or is the product of a single submarine mass-wasting event.

Although given the single designator "Champsaur Sandstone", early Oligocene siliciclastic sandstones along the southern flank of the Ecrins massif have two distinct compositions and, by inference, provenances, lying in distinct depocentres (Debelmas *et al.* 1980). Following our previous usage (Vinnels *et al.* 2010; Butler 2017), we term these depocentres the Western and Eastern Champsaur Basins. They are separated by a zone of deformation generally termed the Selle Fault (e.g. Tricart 1981; Ford 1996 and others since). To date, sedimentological research in the region has mainly focussed on the westerly-derived, volcaniclastic turbidites that outcrop in the Western Champsaur Basin, with detailed descriptions not only of depositional architectures (e.g. Brunt *et al.* 2007) but also of the discrete fold-thrust structures that have deformed the successions (Butler & McCaffrey 2004). Separated from this western basin by the Selle Fault Zone, the Eastern Champsaur Basin is significantly more deformed than its western counterpart (Fig. 3). It is characterised by folds on various wavelengths and amplitudes that generally have tight hinges and straight limbs, approximating to chevron geometry. This style of deformation is typical of successions with a pronounced planar mechanical anisotropy such as is provided by inter-bedded sandstones and shales (Ramsay 1974). The folds face westwards with axial surfaces inclined moderately to the east. The structures were described by Kerckhove *et al.* (1978) and studied in detail by Bürgisser & Ford (1998). These studies show that the folds developed beneath, and locally incorporate, the Embrunais Ubaye thrust sheets which overran both the Eastern and Western Champsaur Basins. The thrust sheets provided tectonic burial sufficient for peak temperatures in Eastern Champsaur of c 300 °C (Bellanger *et al.* 2015).

Provenance of the Eastern Champsaur Sandstone has been disputed. Sinclair (1997) depicts their turbidites to be the down-system continuation of the Annot system otherwise preserved in the SW Alps of Provence. However, in their regional overview, Joseph & Lomas (2004) indicate a northern provenance, sourced from the an elevated, proto-Ecrins massif. The argument is resolved by Vinnels *et al.* (2010) who present palaeocurrent data to show a southerly derivation and document that the sandstones of the Eastern Champsaur basin have the same composition as the Annot Sandstone in its type area to the south. Thus Sinclair's (1997) view is supported. Vinnels *et al.* (2010) note that, although deflected by subtle basin-floor topography, the causative turbidity currents continued over what is now the uplifted Ecrins basement massif. However, Vinnels *et al.* only focused on the lower stratigraphic intervals, establishing facies variations and palaeoflow deflections along the basal onlap surface of turbidites onto the Blue Marls that drape uplifted substrate within the basin. The current paper focusses exclusively on the Eastern Champsaur Basin, building on our previous work (Vinnels *et al.* 2010). The regional structural setting is discussed extensively by Butler 2017). The stratigraphic relationships between the eastern and western Champsaur Basins and the role of the Selle Fault in partitioning distinct deep-water systems lie beyond the scope of the current paper and are reserved for later contributions.

A workflow

Geologists working in mountain belts have long had to grapple with the complexities of deformation when attempting to build stratigraphic knowledge. However, the methods used for creating this understanding are rarely documented, making it difficult to assess uncertainties in the larger-scale basin reconstructions. Furthermore, there has been a reluctance for many researchers investigating sedimentary basins associated with mountain belts to examine their more-deformed components. In presenting a workflow here we hope not only to promote research within these settings but also to encourage clearer documentation of how deformed stratigraphic sections are reconstructed.

The Champsaur area exhibits just under 2 km of topographic relief with cliff sections that are of limited accessibility, attributes that are typical of much of the Alpine mountain ranges and of young orogenic belts in general. A virtue of the relief in our Champsaur study area is that major hillsides trend east-west, perpendicular to the trend of fold axes. They therefore provide ideal cross-sections, akin to in-lines in grids of seismic reflection data. Accessible routes up these hillsides provide excellent vertical sections, equivalent to boreholes for subsurface examples. Consequently, we apply a workflow similar to that adopted for surface stratigraphic-structural mapping, tying detailed stratigraphic observations from vertical sections (boreholes) to remotely sensed cross-sections (in this case by direct observation from opposite valley-sides, equivalent to seismic profiles).

The first decision lies in selecting the best vertical section from which to build a stratigraphic succession. The west face of Le Piquet provides a strike section, 3.5 km across, that runs from up from the base-Nummulitic unconformity to a small klippe of Embrunais-Ubaye thrust sheets (Fig. 5a). Only the upper part of this hillside provides continuous outcrop that is also amenable to direct observation – and this yields stratigraphic logs (Fig. 5a). Logged units include a c 380m interval that is sandstone-dominated (labelled A6 on Fig. 5a), capped by Schistes à Blocs. However, the broad bed-set characteristics of the underlying succession may be established by remote observation. These include shale-dominated levels that are more recessive on hillsides (A3 and A5 on Fig. 5a).

The boundaries between the bed-set units can be traced through the hillsides on Le Piquet and across the Dourmillouse Valley onto the dip section provided by its northern slopes (Fig. 5b). The upper part of the valley side, including the ridge line, provides near continuous, if largely inaccessible, outcrop within which the main folds can be identified. The fold axial traces can be mapped down dip into the Dourmillouse Valley. Then the bed-set stratigraphic units of the Champsaur sandstone can be traced through the fold train. This section is moderately accessible and locally provides accessible sections for detailed stratigraphic logging.

The axial traces of the folds provide the key linking structures to tie adjacent transects. These can be traced over the ridge line bounding the Dourmillouse Valley to the north and into the adjacent Fornel Valley (Fig. 4). The northern side of the ridge-line is much steeper than its southern counterpart so that accessibility is severely restricted. However, fold axial traces may be readily traced through the cliffs and the bed-set stratigraphy defined and similarly tracked through the fold array (Fig. 5c). Note that there is some polyharmonic folding but the axial surfaces for the main fold closures may be traced from the ridge-line down to the Blue Marls.

The bed-set stratigraphy

Following the workflow laid out above it is possible to map out not only the axial traces of the principal folds but also the bed-set stratigraphic units within the Champsaur sandstone (Fig. 4). Although structural deformation hinders identification of individual beds across the whole basin, thicker intervals can be laterally traced continuously for several kilometres and probably extend much further. Vertical stratigraphic sections display significant heterogeneity in sandstone to shale ratio. These are well-illustrated by the cliff sections of Le Piquet (Fig. 5a),

As noted above, it is the variety in sandstone-shale abundance that provides a framework, on the bed-set scale, for dividing the basin stratigraphy into mappable units (Fig. 5). These units are illustrated on arrays of composite logs (Fig. 6). Principally, our sedimentary logs were measured from the fold limbs to avoid hinge areas, where beds show significant layer parallel shortening strain manifested by cleavage, and tracts of strongly overturned strata where bed thinning is likely. Strains in both of these structural settings are localised in the shales – sandstone beds retain unmodified sedimentary structures suggesting penetrative strains in these units are very low. We estimate an uncertainty of less than 10% on the normally-compacted thickness of sandstones and perhaps up to 20% for the shales on the values reported in Fig. 6, as we cannot rule out deformation even in the normal limbs of folds. The bed-set sequences may still be identified regardless of strain variations and we now use these to erect a basin-wide lithostratigraphy.

The Champsaur Sandstone onlaps its substrate towards the western basin margin (Vinnels *et al*. 2010 and references therein): the oldest preserved parts of the sandstone sequence are only present on the vegetated lower slopes of the far eastern exposures of the basin. In the Narreyroux valley (log location 4 on Fig. 4), a 670m thick section of Champsaur Sandstone (A4 on Fig. 6) is underlain to the east by considerably more stratigraphy but precise correlation has proven elusive. The higher parts of the stratigraphy are more tractable. Two levels are especially sandstone-poor and form key markers (A3 and A5 in Fig. 6). The lower of these two shaley intervals is approximately 50m thick and contains a distinctive couplet of 2 m thick sandstone beds that can be found in all sections that include this stratigraphic interval. There are a few thin sandstone beds present in the higher shale-dominated interval (A5 in Fig. 4) but these are laterally discontinuous. Between the two shaley sections lies an interval with abundant thick sandstone beds (A4 in Fig 4). The section below the lower shaley interval also has higher sandstone content; its upper portion contains beds that are 3-5 m thick while the lower portion is bedded on the 50 cm – 1 m scale. These distinctions provide confirmations of stratigraphic correlations to elsewhere within the Eastern Champsaur district.

The lower shaley interval (A3) can be readily correlated between the Narreyroux, Fournel and Dourmillouse valleys (Fig. 4) to parts of the study area where more complete sections of the underlying sandstone-rich intervals are exposed. In these places we can separate a thicker-bedded upper component from a thinner-bedded lower component (A2 and A1 respectively in Fig. 6). The thicker-bedded interval (A2) is about 40 m thick. The logs from the Fournel and Dourmillouse valleys (Fig. 6) only demonstrate about 60 m of this lower portion. However, in the Narreyroux valley it achieves a thickness in excess of 150 m with a further 200 m represented by the poorly exposed and deformed terrain deeper in the section.

The upper shaley horizon defined in the Narreyroux valley (A5 on Fig. 6) can be correlated across the Dourmillouse valley (Fig. 4) to the cliffs of Le Piquet. This is the "Thick Shale" of Vinnels *et al.* (2010). Overlying this, 380 m of sandstone-rich turbidies (A6 on Fig. 4) are capped by the "Schistes a' Blocs" that directly underlie the Embrunais-Ubaye thrust sheets. The sandstone rich interval (A6) can be traced through the fold structures of the upper Dourmillouse and Fournel Valleys, and constitute the upper 60m of the logged section in the Narreyroux valley (Fig. 4). In the upper Fournel Valley the thickness of this interval exceeds 400 m (log 5 on Fig. 6). Individual beds may be traced through folds and across the ridge line between the upper parts of the Dourmillouse and Fournel valleys. For example, a prominent shale interval (5-15 m thick; X on logs 5 and 6 on Fig. 6), at the base of interval A6b) can be traced between sections.

The Eastern Champsaur Basin continues over the watershed at the head of the Dourmillouse Valley into drainage of the Champoleon Valley (Fig. 4). Individual beds may be traced along the ridge line (Pointe des Estaris - Pointe des Pisses: log locations 8 and 9, Fig. 4) to complete the upper stratigraphy of this part of the Champsaur Sandstone up to the Schistes à Blocs (Fig. 6).

By combining the logs, we estimate that about 950m of Champsaur Sandstone stratigraphy (A6 – A7) overlies the prominent upper shaley horizon

(A5) in the ground between the upper Dourmillouse valley and Pointe des Pisses (Fig. 4). The equivalent interval at Le Piquet is just 380m thick (log 1 on Fig. 6). Both sections are capped by the Schistes à Blocs so the thickness difference is not due to post-depositional tectonic truncation. The difference is also too great to be due to variations in distributed deformation or differential compaction and there are significant differences in the bed-set stratigraphy between these locations. We interpret the thickness variation to result from differential stratigraphic growth across the Eastern Champsaur Basin.

Depositional architecture and growth

Although folding permits construction of substantial stratigraphic sections and deformation has not been sufficient to prevent individual bed-tracing through the high Alpine landscape, it does inhibit the recognition of elements of depositional architecture that might be expressed at the km-scale (such as the development of compensating turbidite lobes or, depending on the scale, of erosional or constructional channels). In the Western Champsaur basin, adjacent to our study area (but forming a distinct turbidite system), extensive deep incision and former submarine canyons have been described (e.g. Brunt *et al.* 2007). However, there is no evidence of incision within the Eastern Champsaur Basin, beyond local scours (and associated layers of mudstone rip-up clasts) and bed-scale amalgamation, nor of channel-levee development. The 4-5 km strike section on the western face of Le Piquet (located on Fig. 4, illustrated on Fig. 5a) reveals very low-angle discordances within parts of the upper sandstone interval (A6) consistent with an expansion of stratigraphic thickness from north to south (Vinnels *et al.* 2010). Individual beds appear to thin northwards while bed-sets abut onto underlying beds – relationships we interpret as internal onlap. Collectively these relationships are plausibly interpreted as representing syn-depositional tilting within the Eastern Champsaur Basin elevating Le Piquet area relative to the Pointe des Pisses area during deposition of these upper sandstone intervals. Vinnels *et al.* (2010) suggest that these thickness changes reflect differential growth of an anticline in the basin floor. We infer that the intrabasinal slopes during deposition of at least this part of the Champsaur Sandstone were relatively gentle, there being no evidence for significant mass-wasting within the succession. Therefore, evolving basin floor structures were largely swamped by concurrent sedimentation.

The post-depositional structure of the basin

The stratigraphic template of mappable bed-sets permits full correlation of units through the fold systems. These correlations are illustrated on our summary map (Fig. 4) and underpin two cross-sections through the Eastern Champsaur Basin (Fig. 7). The sections are necessarily simplified at the scale reproduced here, and no attempt is made here to illustrate detail of the thickness changes in the younger units (A6-A7), nor the precise geometry of polyharmonic folding deeper in the stratigraphic pile (A1).

The two cross-sections (Fig. 7) show a similar structural style: a train of asymmetric, west-facing folds with axial surfaces dipping towards the east. The folds detach downwards into the Blue Marls (Bürgisser & Ford 1998). Thrust faults are rare, show bed offsets of a few metres and are restricted to fold hinge zones. The attitude of the fold axial surfaces and fold interlimb angles vary through the region and, according to Bürgisser & Ford (1998), these variations reflect heterogenous simple shear strains distributed into the footwall of the Embrunais-Ubaye thrust sheets. Folds occur in clusters, separated by segments where stratigraphic sections are only weakly deformed. Within the clusters the folds have wavelengths of 200-500m and amplitudes of around 200m. The larger folds are broadly harmonic, with axial surfaces that can be traced through the visible succession of the Champsaur Sandstone. Prime examples are those folds that cross the ridge-line on the north side of the Dourmillouse valley near the summit of Pic Felix Neff (Figs 5b,c, 7). The distribution of these larger folds is consistent with a model that considers folds as ductile equivalents to imbricate thrusts (e.g. Pfiffner 1985; Butler 1992). Qualitatively, the general form of the folds appears to be influenced, at least in part, by variations in bed-thickness in the Champsaur Sandstone. The thicker, sandstone rich sequences (e.g. Fig. 2a; A6 on Figs 4 and 5) appear to act as “control units”, in the sense of Price & Cosgrove (1990), determining the wavelength of the main fold sets (Fig. 8). The older, thinner-bedded units (Fig. 2; A2-A4 on Figs 4 and 5) deform poly-harmonically with respect to the younger, thick-bedded stratigraphy (e.g. unit A6), and are characterised by folding at short-wavelength. Together with this layer-dependence, the location of folds in the Champsaur Sandstone may relate to variations in the properties of the basal detachment zone in the Blue Marls, as is well-known in other detachment systems (e.g. Cotton & Koyi 2000 and many others). Less effective detachment would promote folding in the overlying strata. These aspects of the deformation await more detailed investigations.

The cross-sections (Fig. 7) demonstrate the regional discordance between the lithostratigraphic units in the Champsaur Sandstone and the Blue Marls. As noted by Vinnels *et al.* (2010, but well-known informally), this represents a regional onlap surface, albeit modified by the tectonic detachment. It charts deformation of the basin floor during the accumulation of the Nummulitic trilogy. Vinnels *et al.* (2010) treat the onlap angle qualitatively. To consider the angle of this onlap in profile, and to establish an estimate of tectonic shortening in the basin, we present a balanced and restored section (Fig. 8) for the Dourmillouse transect (Fig. 7b).

The restoration assumes that the sand-rich parts of the succession deformed largely by concentric folding, without appreciable changes in bed thickness by distortional strain. To track this assumption, we chart the thicknesses of bed-sets through the cross-section. These thicknesses are reported on both the final state and restored cross-sections (thin bed-perpendicular rulings). With the assumption of concentric folding, restorations can be performed simply by restoring the length of strata, conserving the sinuous lengths measured on the final state section. This is line-length restoration, as proposed by Dahlstrom (1969). Note that in this analysis we do not consider the impact of broad arching of the enveloping surfaces of the folds with in the Champsaur Sandstone. This longer-wavelength deformation couples with the underlying basement and it is the architecture of the basin fill that we wish to reconstruct.

The graphical restoration (Fig. 8b) is hung from the younger stratigraphic levels (A6), the top of which forms a horizontal datum, or “target horizon”, for determining the progress of deformation. This interval, together with those below, retain bed-length and bed-thickness from the deformed state. A complete restoration might be expected to yield strata that are planar and parallel – features that are not evident here. There are various possible explanations for these discrepancies. First, distortional strains, especially within the mudstone-rich intervals, have not been considered in our method, which assumes ideally concentric folding. Certainly, these units are cleaved, implying that they have experienced such distortions. There may also be errors in the drafting of the cross-section, unavoidable given variations in outcrop quality and uncertainties in the precise position of stratigraphic boundaries. Errors arising from these effects amplify away from the "target horizon", creating significant short-wavelength relief on the base of section. These are regarded here to be restoration artefacts (selected examples identified in in Fig. 8b), as the top-basement surface is readily mapped and shows no such abrupt changes in relief where observed in the field.

Notwithstanding the short-wavelength artefacts, the restoration (Fig. 8b) can be used to calculate the angular relationship between the depositional units in the Champsaur Sandstone and the underlying Blue Marls. The restoration implies onlap of 980m of Champsaur Sandstone over 9.4 km – implying that the average angle of the onlap slope was 6 degrees. Note that this angle would have been significantly higher at the time of deposition as we have not allowed for vertical compaction during burial.

Tectonic shortening for the upper stratal levels (A6) is the difference in length between deformed and undeformed state, 4 km. However, the mismatches in restored lengths of the underlying strata indicate that the section is not balanced (the bed-lengths and implied longitudinal strain are not equal in layers, so that the restoration is not complete). We resolve this by inferring significant "top-to-the-west" shear distributed through the Champsaur Sandstone, as invoked by Bürgisser & Ford (1998). Variations in layer-parallel shortening can account for the open folding of underlying sandstone units and in the substrate.

Discussion – implications for tectonostratigraphic evolution

A palaeogeographic sketch is provided (Fig. 9), extending that of Joseph & Lomas 2004, their Fig. 5) which integrates our findings from the Eastern

Champsaur Basin into a semi-regional context. Following our earlier work (Vinnels *et al*. 2010), we consider its turbiditic basin fill to be a down-system continuation of the Annot sand fairway. We show the main Annot turbidite system to be derived from a southern source area and then routed along the sinuous Provencal basins defined by the underlying deformation within the broad foredeep basin (e.g. Salles *et al.* 2012). This system is distinct from a secondary turbidite system that feeds the Western Champsaur Basin.

<u>Down-system continuity of the Annot Sand Fairway</u>

The total (compacted) stratal thickness of the Champsaur Sandstone in the Western Champsaur Basin approaches 1km. Stratal patterns together with onlap at the base and within the Champsaur Sandstone indicate active deformation of the underlying basement during deposition. We propose that it is this deformation that provided the basin floor structure that served to confine and guide turbidity currents, facilitating sediment transport further down-system. The high proportion of coarse sandstone compared to finer-grained fractions, coupled with palaeocurrent data (Vinnels *et al*. 2010) implies that there was significant bypass through the Eastern Champsaur Basin. The Annot sand fairway therefore continued north from Champsaur, with no ponding behind the ancestral Ecrins massif (cf. Joseph & Lomas 2004; Fig. 9); turbidity currents are inferred here to have transited the region and fed down-system depocentres (Fig. 9). Certainly, the area of the Ecrins massif did not form a bathymetric high during deposition of the Annot system (cf. Ford *et al*., 1999) – it must have been deeper than the upstream Annot fairway. Future studies should address the sedimentology of the likely correlatives of the Annot turbidites further down-system, in the strongly deformed sections along the eastern part of the Ecrins and north in the Aiguilles d’Arves (Fig. 1).

<u>Eastern confinement of the Annot system</u>

For Joseph & Lomas (2004, their fig.5) and references therein) the eastern edge of the Annot sand system was confined by the Embrunais-Ubaye thrust sheets, an exotic tectonic allochthon emplaced from the internal Alpine domain onto the foreland domain (see also Ford *et al.* 2006). The sheets were sufficiently thick to have buried the southern Ecrins district so that it reached temperatures of c 300°C (Bellanger *et al.* 2015). Presumably they created significant relief within the fordeep. Olistostromes were shed from this relief during thrust sheet emplacement, manifest as the Schistes à Blocs (e.g. Kerckhove 1969) which cap the turbidites in the Eastern Champsaur Basin and elsewhere in the Annot system. Ford & Lickorish (2004) suggest that it was the emplacement of the Embrunais-Ubaye thrust sheets that closed off the Annot basin system. The implication is that this was a progressive process, with the advance of thrust sheets gradually restricting the pathways available for turbidity currents. However, the relationship between the olistostomes and the Champsaur Sandstone is not consistent with this implication. Muddy debris flows, such as carried the Schistes à Blocs, would be expected to have had significant run-out distances, potentially forming obstructions within the main flow paths for the Annot turbidity currents. Deposits accumulating from axial flows in the case of the turbidity currents, and from coeval basin flank-derived olistostromes, should be interleaved. No such interleaving has been recognised by us in the Eastern Champsaur Basin, nor elsewhere in the Annot System. Therefore, we deduce that the olistostromes and Annot turbidites are not coeval – rather that the Schistes à Blocs forms a distinct, younger depositional unit that overran (and entrained) dark-shales. The corollary is that the flux of Annot turbidity currents had terminated for reasons unrelated to the emplacement of the Embrunais-Ubaye thrust sheets and that some other feature must have provided the lateral (eastern) confinement to Annot flows.

If lateral confinement was not provided by the tectonic allochthon of the Embrunais-Ubaye thrust sheets, then presumably it was provided by weakly inverted parts of the ancestral rifted margin of Europe adjacent to the suture of the closed Ligurian Tethys seaway. These may have formed additional basement ridges, equivalent to the Ecrins but now buried beneath Alpine thrust sheets. Alternatively, the Annot system may have abutted against deformed Brianconnais and Sub-Brianconnais units, as illustrated on Fig. 9. Both units contain sedimentary successions that are broadly time-equivalent to the Annot turbidites – the so-called "Flysch Noir". This is a succession of pelites and thin, fine sandstones of mid-late Eocene age (e.g. Debelmas

1989). We tentatively suggest that the Flysch Noir represents an early part of the Annot turbidite system and that its pathway was elevated as its substrate of Brianconnais and Sub-Brianconnais units became deformed. Note that, by the early Oligocene, the eastern edge of the Brianconnais in this sector of the Alps had been incorporated into the Alpine orogen and was experiencing blue schist metamorphism, and maybe even greater burial (e.g. Michard *et al.* 2004; Dumont *et al.* 2012). Regardless of the nature of the eastern retaining margin to the Annot System, there is no documented evidence that it provided detritus into the sand fairway, until the emplacement olistostromes of the Schists à Blocs from the advancing Embrunais-Ubaye thrust sheets.

<u>Structuring of the Eastern Champsaur Basin and the evolution of crustal shortening</u>

The onlap of Champsaur Sandstone onto a tilted succession of Blue Marls and Nummulitic Limestone indicate that the floor to the Eastern Champsaur basin was actively deforming during deposition (Vinnels *et al.* 2010). Our studies confirm our earlier work and extend it – stratigraphic thickness variations across the Eastern Champsaur Basin (Fig. 6) strongly suggest that open folding continued to influence sand accumulation. However, sedimentation generally swamped the folds, with turbidites overstepping the anticline crests. These folds are cored by crystalline basement which outcrops in the Dourmillouse and Fournel valleys (Fig. 4) and it is this deep-rooting deformation style that is illustrated on Fig. 9. Basement-rooting deformation is also shown to provide the structural barrier that separated the distinct turbidite systems that characterise the Eastern and Western Champsaur Basins. Folds and thrusts in the adjacent crystalline basement now forming the Ecrins massif (located on Fig. 1a) are generally interpreted as resulting from tectonic inversion of half-graben inherited from Jurassic-aged continental rifting (e.g. Gillcrist *et al.* 1987; Dumont *et al.* 2008).

In Provencal basins (Fig. 9), active deformation during deposition of the Annot turbidites has been characterised as “wedge-top” (Salles *et al.* 2012 and references therein). The term harks back to idealised conceptualisations of orogenic margins that are divided into a foreland basin and an adjacent thin-skinned thrust system (e.g. De Celles & Giles 1996). In these models, deposition can occur in the yet-to-deform foreland basin and in small basins perched on the advancing thrust system (or wedge). However, such distinctions appear inappropriate to us for the Champsaur district as deformation of the basin floor during the turbidite deposition was thick-skinned. Concepts of thrust wedges are unlikely to be directly relevant to inversion tectonic systems such as the Ecrins or the initial deformation of the Brianconnais as illustrated on Fig. 9.

In Provence, two distinct phases of folding are recognised – one inferred to result from north-south contraction and traditionally related to "Pyrenean-Provencal" orogeny (early Tertiary), and a subsequent SW-directed thrust system (e.g. Siddans 1979; de Graciansky *et al.* 2011). Likewise, deformation in the crystalline basement and the structural evolution of the Ecrins basement massif has long been considered result from punctuated tectonic activity - i.e., two distinct episodes of Alpine deformation, separated by the unconformity that underlies the transgressive Nummulitic Limestone (e.g. Gidon 1979). Ford (1996) correlates these with the two tectonic episodes of Provence. Gupta & Allen (2000) argue that the southern Ecrins was structured by folds and uplifted fault blocks to modulate the Nummulitic transgression. It is a deduction that is consistent with the punctuated model for tectonics in this part of the Alps. However, it seems unlikely that initiation of a second episode of tectonic activity simply coincided with the transgression of the Nummulitic megasequence across the basement.

Recent radiometric dating of thrust zones in the Ecrins massif (Bellanger *et al.* 2015) implies that deformation in the basement straddled deposition of the post-Nummulitic successions of the Eastern Champsaur Basin. Using these data, Butler (2017) proposes that crustal shortening in the Ecrins and, by inference, beneath the Eastern Champsaur Basin was continuous in time. Where the instantaneous syn-orogenic surface is sub-areal, deformation is accompanied by erosion, marked by exhumation and cooling of the basement. Where the instantaneous syn-orogenic surface moves to below sea-level, deformation is accompanied by deposition. The transition between these states is marked by transgression and its diachroneity reflected by the sub-Nummulitic unconformity.

Dividing deformation episodes on the basis of an unconformity has a long tradition in orogenic geology (see discussion in Gray *et al.* 1997). However, is the interplay between uplift due to crustal shortening, with concomitant erosion, and subsidence due to long-wavelength orogenic loading of the lithosphere, with concomitant deposition, that defines the stratigraphic record of orogenesis. Focussing on unconformities, with their implications for missing time-sections, can create the false impression that deformation was punctuated. It is our proposal that the crust beneath the Champsaur district experienced deformation that was essentially continuous over geological time, through the late Eocene and into the Oligocene.

The arrival of the Embrunais-Ubaye Thrust Sheets in the late Rupelian (Dumont *et al.* 2008) marked a transition in the tectonic style to thin-skinned shearing. Deformation of the turbidites of the Eastern Champsaur Basin, dominantly by folding, happened beneath this over-riding allochthon. Shortening within the basin was approximately 4 km with differential shortening through the Champsaur Sandstone stratigraphy implying significant simple shear distributed penetratively through the multilayer (Bürgisser & Ford 1998). It is likely that thick-skinned deformation in the underlying crust continued, eventually arching the Embrunais-Ubaye thrust sheets and uplifting the adjacent Ecrins massif. The challenge facing further investigations of syn-tectonic sedimentation lies in unravelling deformed sedimentary basins to reveal their stratigraphy. These are endeavours that we hope will be encouraged by our study of the eastern Champsaur Basin.

Conclusions

Linked stratigraphic, sedimentological and structural studies in the Eastern Champsaur Basin, SE France, reveal:

1 – The Champsaur Sandstones of the basin represent a continuation of the late Eocene-early Oligocene Annot system. Therefore, the well-known type locations in Provence represent only a small part of this system and their causative turbidity currents continued up to, and presumably over and beyond what is now the Ecrins basement massif. There is no evidence of flow ponding in the Eastern Champsaur Basin, indeed bed character suggests

substantial sediment bypass continuing into more distal settings. These locations await further study.

2 – The continuity of sand fairways around the orogen can only arise where foredeep axial slopes and hence palaeobathymetry dipped monotonically in the direction of sediment dispersal. Therefore, during the early Oligocene, the Alpine foredeep became progressively deeper clockwise around the western Alpine arc in SE France. This implies greater tectonic subsidence, perhaps coupled with the building of depositional gradients in this direction, during the late Palaeogene. The proto-Ecrins basement massif did not lie at shallow bathymetric levels as suggested in some Alpine syntheses but, during the early Oligocene, lay under water depths significantly deeper than the Provencal sector of the foredeep.

3 – The floor to the foredeep basin within which the Annot turbidites were deposited was actively deforming. This has been inferred elsewhere for the type localities of the Annot system to the south of Champsaur where the foredeep megasequence rests on a gently folded substrate of Mesozoic strata. For the Eastern Champsaur, Mesozoic strata have been largely eroded so that the foredeep megasequence unconformably overlies basement. Small pockets of Triassic and Lower Jurassic strata are preserved, folded and thrust into basement beneath this unconformity, testifying to significant crustal deformation predating the deposition of the Nummulitic Limestone. We interpret the pre-Nummulitic deformation to form simply an early part of crustal shortening that progressed steadily through the late Eocene and early Oligocene.

4 – The Champsaur Sandstone succession is capped by the Schistes à Blocs, an olistostrome encased in dark shales, a harbinger of the advancing Embrunais-Ubaye thrust sheets. Notwithstanding the likely run-out distance of the causative debris flows ahead of the advancing thrust sheet, this olistostromal formation is not interbedded with the Champsaur Sandstone. Presumably these flows arrived on a basin floor that had largely been starved of sand supply and were not themselves the cause of this starvation.

5 - Deformation continued after the deposition of the sedimentary fill to the Eastern Champsaur Basin, with c. 4 km of shortening accommodated in the

footwall to the over-riding the tectonic allochthon represented by the Embrunais-Ubaye thrust sheets.

Our study demonstrates that even in deformed parts of the Alpine orogen it is still possible to establish detailed stratigraphies in turbidites, thereby opening opportunities to extend tectono-stratigraphic investigations elsewhere in this and other orogens. Such work may improve understanding not only of the turbidite systems and their use as analogues for modern deep-water systems but also of the tectonic relationships between orogens and their “forelands”.

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Figures

Fig. 1. a) Location map of the Eastern Champsaur Basin (boxed area is Fig 4) in the context of the western Alps (modified after Schmid *et al*. 2004). b) the continuity of the Annot sand system in SE France, in the context of other Eocene-Oligocene turbidite units in the external Western Alps (modified after Joseph & Lomas 2004). The grey area represents thrust sheets, including the Embrunais-Ubaye and lateral equivalents that have over-ridden the Annot sand system, which are shown as inferred at depth. SF – Selle Fault.

Fig. 2. Idealised Nummulitic stratigraphy (modified after Joseph & Lomas 2004)

Fig. 3. Fold geometries, all of which face west, in various parts of the Champsaur Sandstone (see Fig. 4 for place names). a) looking NNW onto Pic Felix Neff, to illustrate the broadly harmonic and relatively long-wavelength folding of the upper stratigraphic packages (unit A6 on Figs 4 and 6). b) looking SE onto polyharmonic folding in sandstone units (unit A3 on Figs 4 and 6) directly above the regional detachment zone of the Blue Marls. The visible cliff height is 100m. c) looking SSW onto chevron-style folding in the lower units of the thinly bedded Champsaur sandstone (Unit A1 on Figs 4 and 6). The bottom of the image is at an altitude of c 2200m, the skyline reaches up to 3085m.

Fig. 4. Geological map of the Eastern Champsaur Basin showing the distribution and structure of the mappable units within the Champsaur Sandstone as defined by this study (Fig. 4). The location of lines of section in Fig 5a, b are annotated (X-X’ and Y-Y’ respectively), along with logged stratigraphic sections (circled numbers, 1-9; Fig. 6) and field photographs of Fig. 5.

Fig. 5. Selected key panoramas that serve to trace the bed-set stratigraphy of the Champsaur Sandstone, with varying accessibility. The viewpoints are shown on Fig. 4. Stratigraphic boundaries are shown as yellow lines while

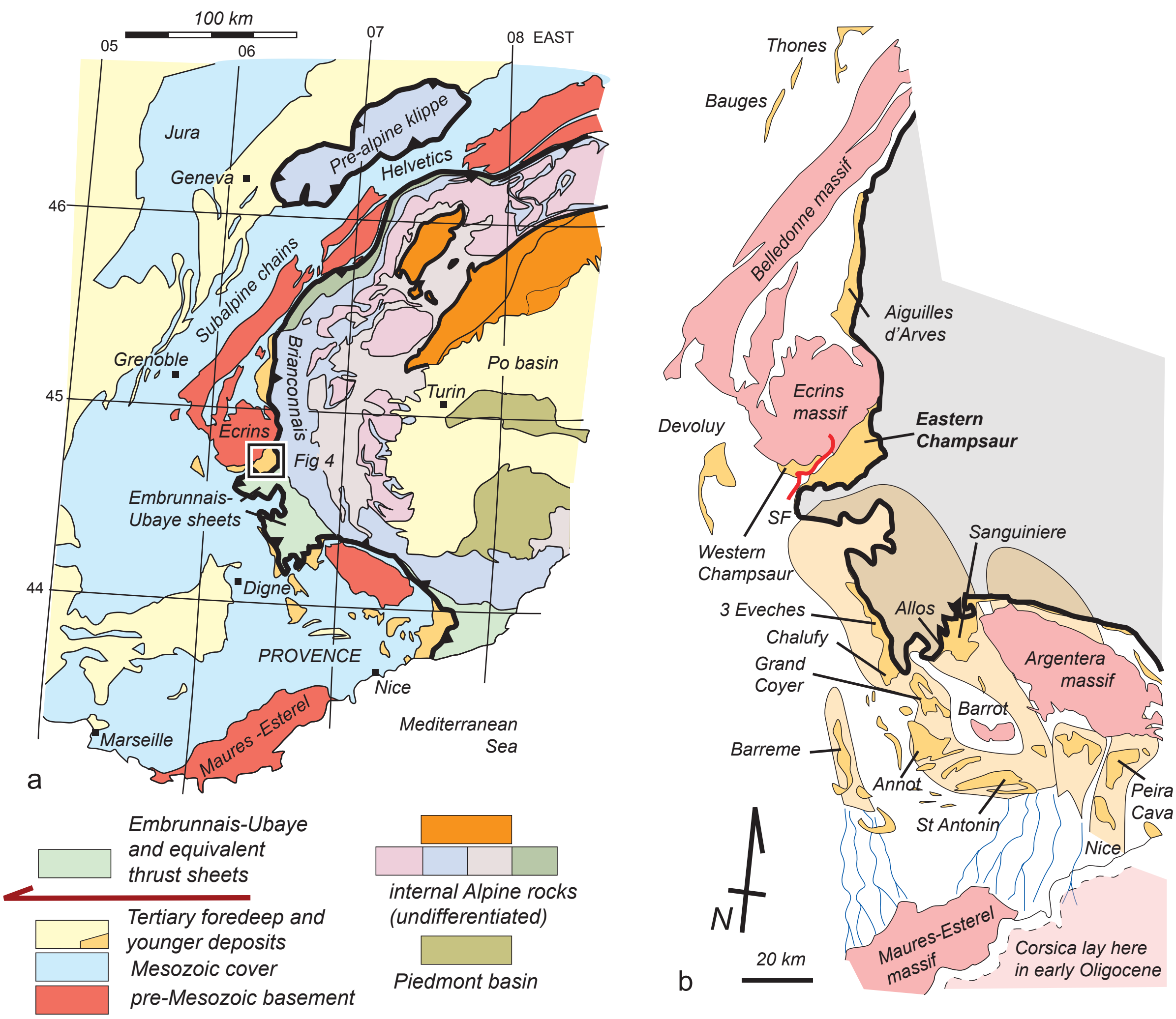
fold axial traces are shown by red dashed lines. a) illustrates the west face of Le Piquet, a strike-section, together with the location and content of two sedimentary logs (1 and 2 on Fig. 4) that characterise the upper part of the Champsaur Sandstone. b) Is an oblique view of the north side of the Dourmillouse Valley, which provides a dip-section through the fold belt. This hillside is partly accessible permitting ground-truthing of units and completion of measured sections. c) illustrates part of the steep south side of the Fournel Valley. This provides exceptional exposures for the stratigraphy and folds but has limited accessibility.

Fig. 6. A selection of lithostratigraphic logs with defined mappable units (A1 – A6-A7), correlated through the basin. The locations are shown on Fig. 4. These sections were constructed with direct bed-measurement and field observations – their location being restricted by accessibility in the terrain.

Fig. 7. Cross-sections through the Eastern Champsaur Basin. The lines of section are shown in Fig. 2. a) the northern basin; b) the Dourmillouse transect.

Fig. 8. A line-length restoration of the Dourmillouse cross-section through the basin. The thicknesses of bed-sets are shown (intra-formation rulings), and retained between the final state section (a) and its restored version (b). Selected bed-set levels are illustrated (in colour) together with the top basement (in red).

Fig. 9. A schematic representation of the extent of the Annot turbidite system, connecting its well-studied proximal areas in Provence to the almost un-studied, more distal regions that include the Aiguilles d'Arves basin, via the Eastern Champsaur Basin described here. The diagram is inspired by an equivalent perspective provided by Joseph & Lomas (2004). Evidence for deformation and its timing beneath the sand fairway within the Ecrins and beneath the Aiguilles d'Arves sector is discussed by Butler (2017).


100 km
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06
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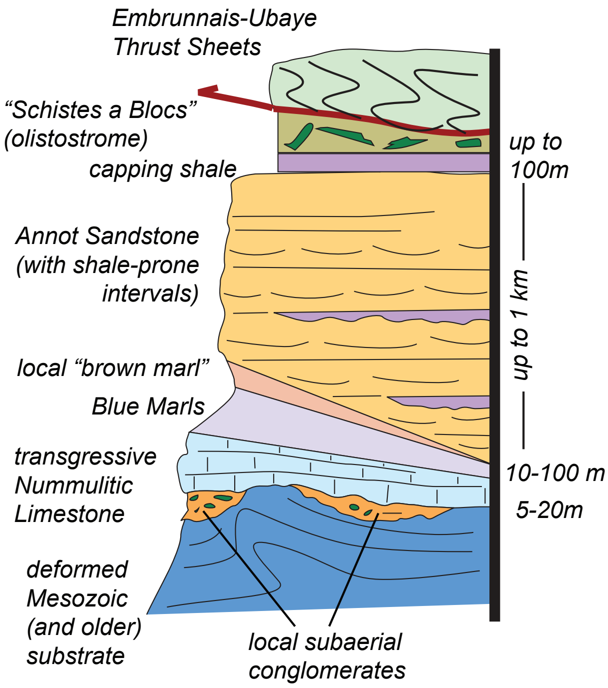
46
45
44
Jura
Geneva
Pre-alpine klippe
Helvetics
Subalpine chains
Grenoble
Brianconnais
Po basin
Turin
Ecrins
Fig 4
Embrunnais-
Ubaye sheets
Digne
PROVENCE
Nice
Mediterranean
Sea
Marseille
Maures -Esterel
a
Embrunnais-Ubaye
and equivalent
thrust sheets
Tertiary foredeep and
younger deposits
Mesozoic cover
pre-Mesozoic basement
internal Alpine rocks
(undifferentiated)
Piedmont basin
Thones
Bauges
Belledonne massif
Aiguilles
d'Arves
Ecrins
massif
Devoluy
Eastern
Champsaur
SF
Western
Champsaur
Sanguiniere
3 Eveches
Allos
Chalufy
Grand
Coyer
Argentera
massif
Barrot
Barreme
Annot
St Antonin
Peira
Cava
Nice
N
20 km
Maures-Esterel
massif
Corsica lay here
in early Oligocene
b

figure 2 Click here to access/download;figure;Fig 2 strat NEW.pdf




a)
3243m
NNW
3043m
2648m
b)
SE
Blue Marls
SSW
2611m
c)

figure 4 new

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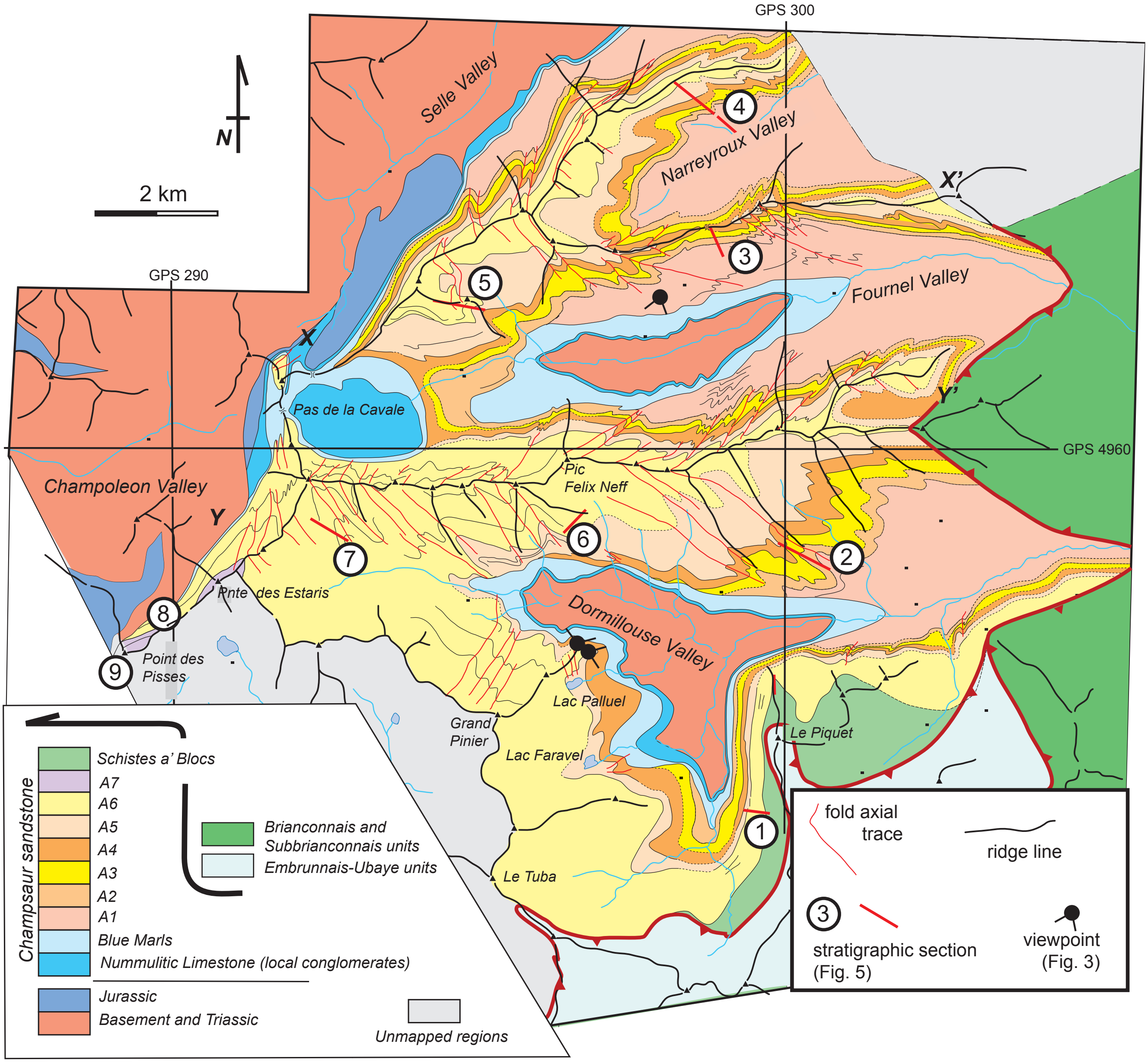
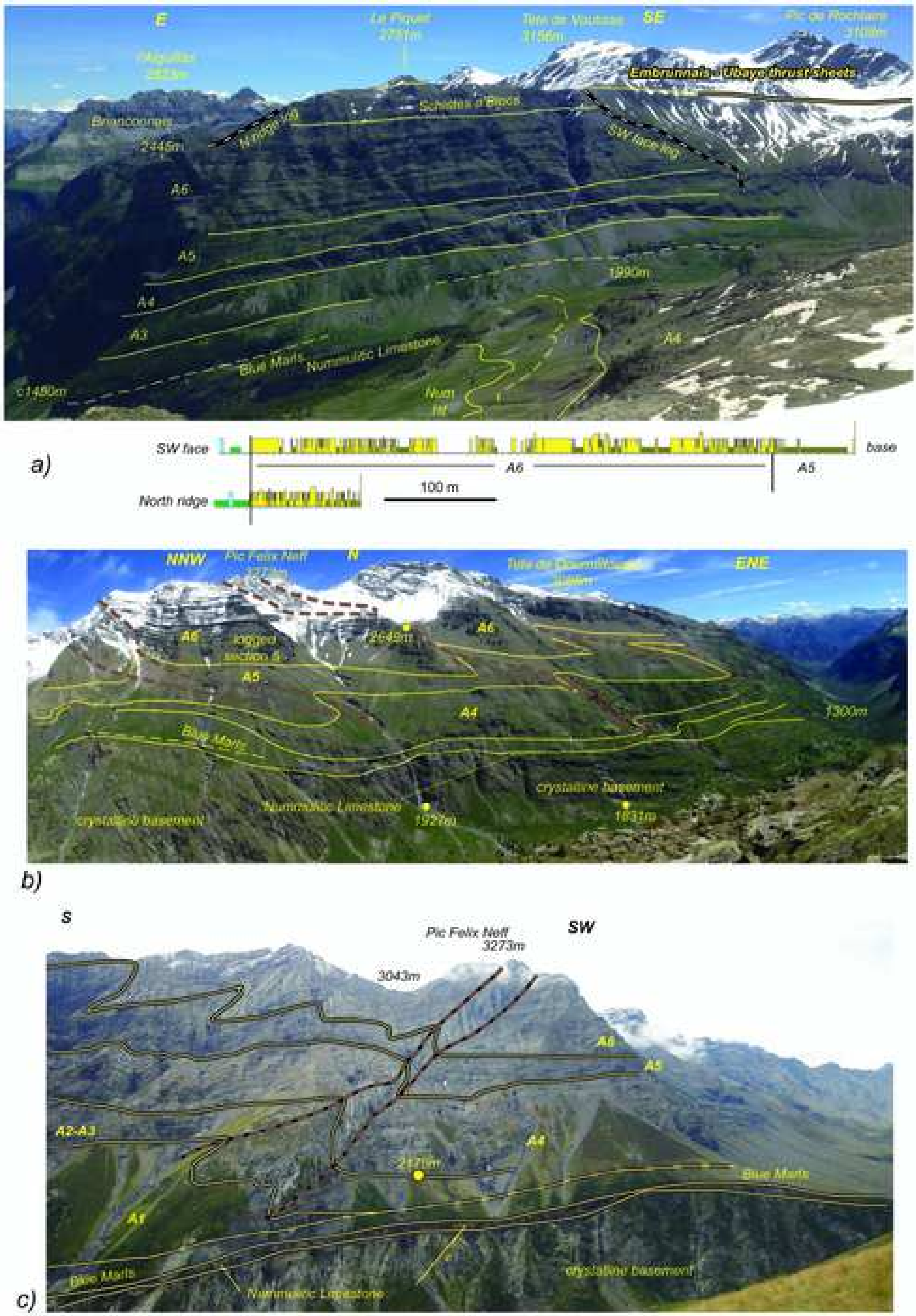



E
SE
Embrunnais - Ubaye thrust sheets
Schistes à Blocs
N ridge log
SW face log
2345m
A6
A5
A4
A3
1990m
Blue Marls
Nummulitic Limestone
c1480m
A4
SW face
base
A6
A5
North ridge
100 m
a)
NNW
Pic Felix Neff
N
ENE
A6
2649m
A5
A4
1300m
Blue Marls
crystaline basement
Nummulitic Limestone
1927m
1831m
b)
S
Pic Felix Neff
3273m
SW
3043m
A6
A5
A2-A3
A4
2170m
Blue Marls
A1
crystalline basement
Nummulitic Limestone
c)

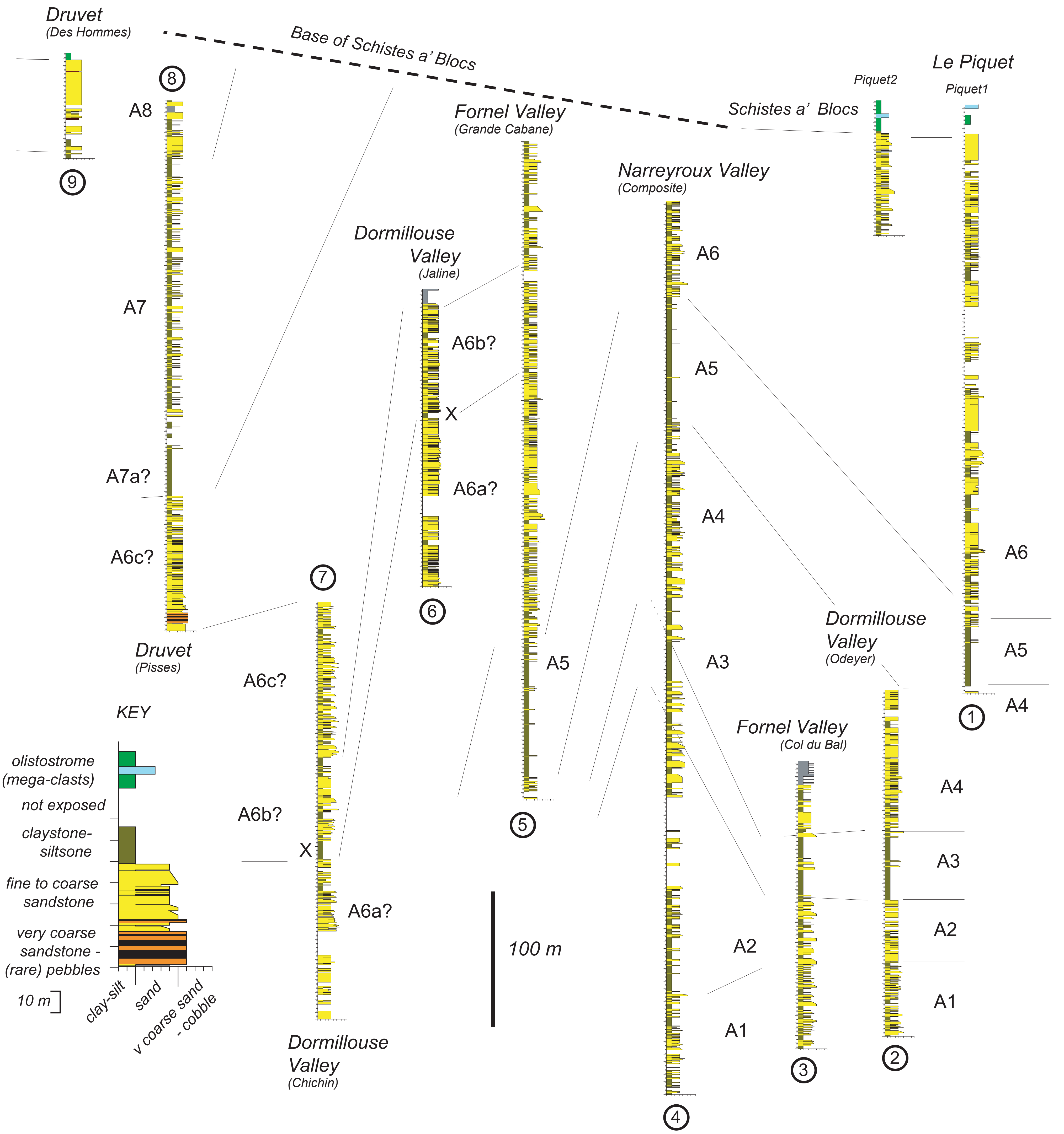
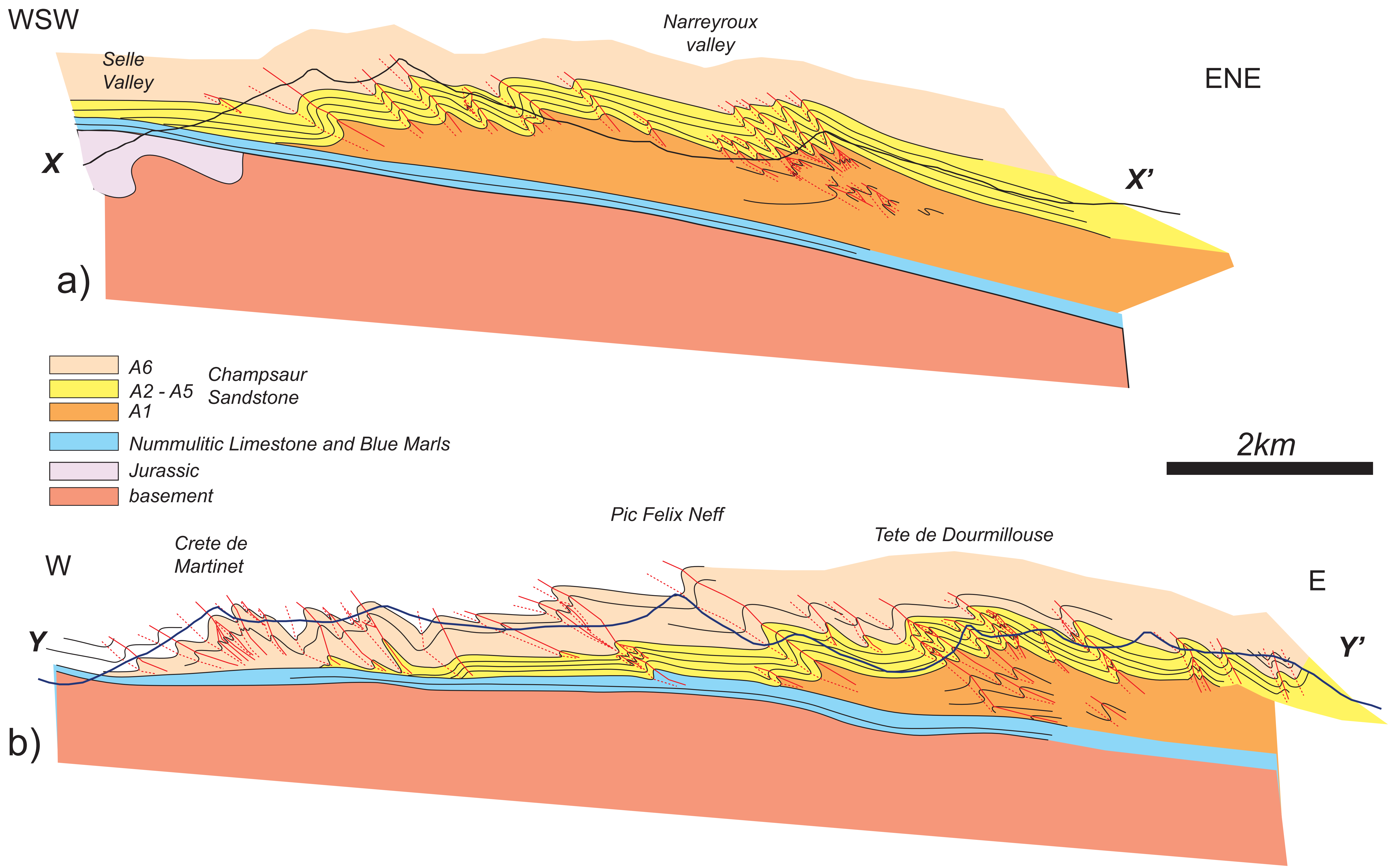
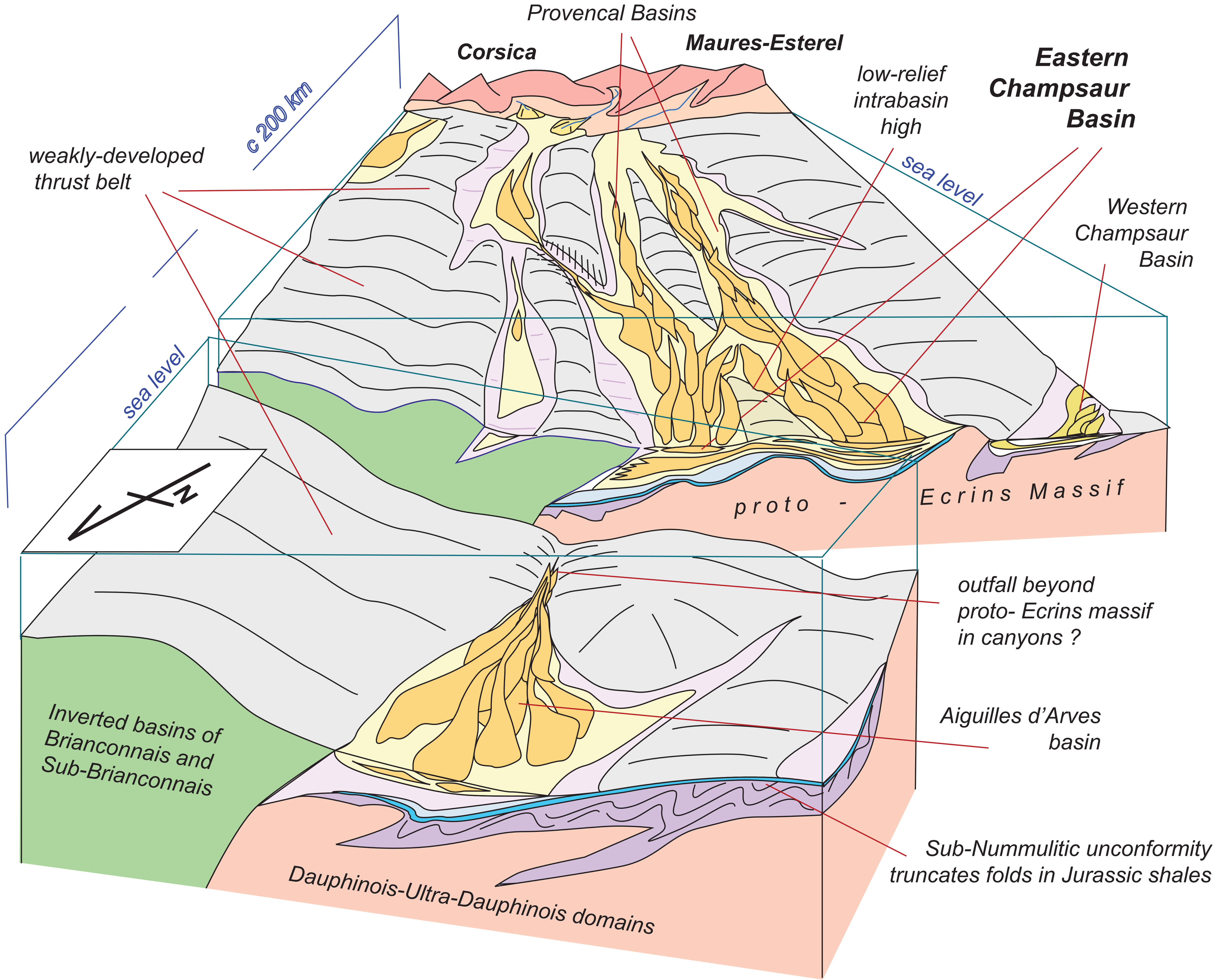

Druvet
(Des Hommes)
Base of Schistes a' Blocs
Le Piquet
Piquet2
Piquet1
Schistes a' Blocs
Fornel Valley
(Grande Cabane)
Narreyroux Valley
(Composite)
Dormillouse
Valley
(Jaline)
8
9
A8
A7
A7a?
A6c?
A6b?
X
A6a?
A6
A5
A4
A3
A2
A1
Druvet
(Pisses)
7
6
5
4
3
2
1
KEY
olistostrome
(mega-clasts)
not exposed
claystone-
siltsone
fine to coarse
sandstone
very coarse
sandstone -
(rare) pebbles
10 m
clay-silt
sand
v coarse sand
- cobble
100 m
Dormillouse
Valley
(Odeyer)
Fornel Valley
(Col du Bal)
Dormillouse
Valley
(Chichin)

figure 7 new

Click here to access/download;figure;Fig 7_ cross sections.pdf




3.8 km shortening
A1
MB
A5
A6
A5
basement
Top A6
pin
A5
A1
restoration artefacts
MB
A6
A5
basement
MB
restoration
artefacts
Top A6
A6
pin
2 km


Provencal Basins
Corsica
Maures-Esterel
low-relief intrabasin high
Eastern Champsaur Basin
c 200 km
weakly-developed thrust belt
sea level
sea level
Western Champsaur Basin
N
proto - Ecrins Massif
outfall beyond proto- Ecrins massif in canyons ?
Aiguilles d'Arves basin
Inverted basins of Brianconnais and Sub-Brianconnais
Sub-Nummulitic unconformity truncates folds in Jurassic shales
Dauphinois-Ultra-Dauphinois domains