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Messinian-Zanclean canyons in the Digne nappe (southwestern Alps): tectonic implications

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Key-words.- Messinian canyon, Drainage system, Alps, Quaternary tectonics, microtectonics, Digne nappe, Barles

Abstract

Mapping thick conglomerates in the subalpine chains around Digne allows reconstruction of a deeply incised Messinian-Pliocene paleo-drainage network. It shows that the main rivers (Bléone, Bès, Mardaric, Eaux-Chaudes) have existed since at least the Messinian. Pollen analysis reveals that the Pliocene-Early Quaternary continental infill of these canyons did not start at 5.3 Ma, like in the Zanclean rias, but in the Late Pliocene (between 3.4 and 2.6 Ma). This 2 Myrs delay results in part from the timing of the retrogradation of the alluvial wedge, and in part from the inland shift of the river mouths that accompanied the Zanclean flooding of Messinian canyons. This shift corresponds to a shortening of hundreds of kilometers of the river profiles that caused the river to gain more erosive energy. This strong Zanclean erosion is contemporaneous with the main infill of the rias downstream.

We describe sections of paleo-canyons that were uplifted, tilted, overthrust or truncated by strike-slip fault. The geometry of this dissected drainage network provides new constraints on the tectonic evolution of the southern Subalpine chains. An about 2.3 km strike-slip separation of the Bléone River paleo-canyon confirms that the front of the Digne nappe is an oblique ramp of the South-verging thrust system of the 'Arc de Castellane'. This nappe moved South-Southwestward along the N015 trending tear fault. Fault striation analysis in the Late Pliocene-Quaternary conglomerates shows that this displacement was characterized by ENE-WSW compression, along the Digne oblique ramp, consistent with its dextral slip. Most of the Digne nappe displacement (~20 km) occurred prior to the Late Pliocene as shown by the La Bonnette section of the Bléone paleo-canyon that incises a block of the overthrust "residual basin". It was followed by ~2.3 km southward displacement along out-of-sequence faults during the Late Pliocene and the Quaternary. This out-of-sequence reactivation of the Digne nappe is contemporaneous with the formation of the Barles Half-window nappe anticline as shown by the 345 m uplift of the l'Esquichière paleo-canyon. The reconstructed paleo-drainage network attests for the tectonic activity of the Barles nappe anticline, the Bès tear fault, the Saint Benoît tear faults and the Digne nappe during the Pliocene and the Quaternary.

Canyons messino-zancléens à remplissage continental dans la nappe de Digne (Alpes du Sud). Implications tectoniques.

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Mots-clés.- Événement messinien, Canyons messiniens, Réseau hydrographique, Tectonique quaternaire, Nappe de Digne, Barles

Résumé

Dans les chaînes subalpines de Digne, la cartographie de conglomérats qui ont rempli de profonds canyons permet de reconstruire un réseau hydrographique attribuable au Messinien et au Pliocène. On met ainsi en évidence que les principales rivières (Bléone, Bès, Mardaric, Eaux-Chaudes) existent depuis au moins le Messinien. L'analyse de pollens provenant du fond de ces canyons révèle que leur remplissage Pliocène-Quaternaire n'a pas commencé à 5.3 Ma comme pour les rias Zancéléennes, mais pendant le Pliocène supérieur (entre 3.4 et 2.6 Ma). Ce retard de 2 Ma est expliqué pro parte par le temps nécessaire au prisme continental rétrogradant, engendré par la sédimentation alluviale, pour arriver dans cette zone, mais surtout par le saut en amont de plusieurs centaines de kilomètres de l'embouchure des rivières qui résulta de l'ennoiement des canyons messiniens au Zancéen. Le raccourcissement du profil d'érosion des rivières accéléra l'érosion en amont, tandis que le matériel érodé participa au remplissage sédimentaire des rias Zancéléennes.

Près de Digne, nous décrivons des segments de paléo-canyons qui ont été soulevés, basculés, chevauchés ou bien tronqués par des failles décrochantes. La géométrie du réseau de drainage déformé tectoniquement apporte des contraintes nouvelles sur l'évolution tectonique des chaînes Subalpines Méridionales. Un décalage de 2,3 km du paléocanyon de la Bléone confirme que le front de la nappe de Digne est une rampe décrochante oblique du système de chevauchement à vergence sud de l'Arc de Castellane. Cette nappe s'est déplacée vers le Sud Sud-Ouest le long de la faille décrochante du Bès de direction N015. L'analyse des stries tectoniques dans les conglomérats remplissant les canyons permet de caractériser des directions de compression ENE-WSW confirmant le glissement dextre Plio-Quaternaire du décrochement du Bès. L'essentiel du déplacement de la nappe de Digne (~20 km) s'est produit avant le Pliocène supérieur car le canyon de la Bléone a entaillé les blocs chevauchés du « bassin résiduel » (site de La Bonnette). La mise en place principale de la nappe de Digne a été suivie durant le Pliocène supérieur-Quaternaire par un déplacement de ~2.3 km le long de failles hors-séquences. Ce déplacement hors-séquence est contemporain de la formation de l'anticlinal de nappe de Barles comme le montre le soulèvement de 345 m du paléocanyon de l'Escuichère. Le réseau de drainage reconstitué met donc en évidence l'activité de l'anticlinal de nappe de Barles, de la faille du Bès, de la faille de Saint Benoît, et de la partie interne de la nappe de Digne jusque dans le Pliocène et le Quaternaire.

I- INTRODUCTION

The Digne nappe is one of the most important thrust sheets in the external Alpine zones of France (fig. 1). On its front, Jorda (1970, 1982) and Jorda et al. (1988; 1992) described tectonic deformation in alluvial deposits considered as Early and Middle Pleistocene in age. However, Clauzon (1999) proposed that these alluvial deposits are relicts of Pliocene formations infilling the Bléone Messinian canyon that globally seals the front of the Digne nappe. The choice between these two contrasting interpretations has important consequences in particular on the seismic risk assessment in the Digne area.

During the Messinian salinity crisis, the Mediterranean Sea underwent the strongest eustatic oscillation of its history that resulted in deep incision of the Mediterranean rivers including the Rhône and the Durance Rivers (Clauzon 1982; 1979; Clauzon et al., 1996). According to Clauzon (1999), the Messinian river incision that has penetrated the Alps at Nice (Clauzon, 1978; Fauquette et al. 1999), might have penetrated the Alps at Digne as well, because it was still 100 to 200 m deep at Pont de Mirabeau (fig. 1; Clauzon, 1979). At Nice, like in the Rhône valley (Clauzon, 1982; Lofi et al., 2003; Gorini et al., 2005) and in the Durance valley, the Zanclean flooding transformed the Messinian canyons into rias, rapidly filled by marine deposits (Clauzon, 1979; 1982). If the alluvial deposits of Digne represent the Pliocene infill of Messinian canyons, they would provide a unique opportunity to study the upstream part of these canyons, entirely filled by continental deposits.

A detailed tectonic study of these alluvial deposits and their dating are also important for understanding the geodynamic evolution of the Alps. Each year, the front of the Digne nappe between Digne and Barles is a favorite site to learn mapping and structural geology for hundreds of geologists. However, the tectonic evolution of this area is still controversial and many questions remain on the timing of deformation (e.g. Fournier et al., 2008). Age constraints on recent formations are crucial because previous authors attribute several phases of folding and thrusting to the Pliocene-Quaternary (e.g. Haccard et al., 1989a). In this paper, we present a detailed mapping of the “ancient” alluvial deposits around Digne. We give an age to these deposits, based on their pollen assemblages and their relationship with dated formations and geomorphologic surfaces, and we describe the recent tectonic deformation of the Digne nappe and the evolution of its river system during the Neogene.

II- STRUCTURAL SETTING

The outcrops of thick conglomerates described in this paper are located on both sides of the Digne nappe front (figs. 1 and 2). The Digne nappe is a thrust sheet mainly made of a thick Mesozoic rock sequence (“Dauphinois facies” characterized by up to 2000 m of Liassic to Dogger) that was carried over thinner Mesozoic rocks sequence (“Provençal facies” with less than 200 m of Liassic to Dogger) (e.g. Gubler et al., 1961; Haccard et al., 1989a). The front of this thrust sheet extends from the Ecrins external massif in the North (Kerckhove et al., 1979), to the western tip of the so-called ‘Arc de Castellane’ in the South (fig. 1). According to Gidon and Pairis (1986a) this NNW-trending front represents the oblique ramp of the South-verging thrust system of the ‘Arc de Castellane’. Altogether they form the eastern part of the southern Subalpine chains, characterized by a thin-skinned tectonic style with a décollement level situated in the weak rocks of the late Triassic sequence (gypsiferous layers, salt and shales; Goguel, 1936; Lemoine, 1972). The southern Subalpine chains formed during two tectonic phases: the Pyrenean-Provençal phase of Late Cretaceous to middle Eocene age, and the alpine phase of Oligocene-Neogene age. Tertiary rocks, unconformably lying over the Cretaceous rocks, are present in the Digne nappe only in its northeastern part, where they are overthrust by the Ubaye-Embrunais nappes (fig. 1; Kerckhove, 1969; Merle and Brun, 1984). They mainly consist of the mid Eocene to lower Oligocene Grès d’Annot Formation that deposited in the foreland basin of these internally derived nappes (e.g. Kerckhove, 1969; Sinclair, 1997; Lickorish and Ford, 1998; Joseph and Lomas, 2004).

To the west, the front of the Digne nappe is complex because of its probable mainly strike-slip origin and of the inherited Mesozoic structural grain (Gidon and Pairis, 1986a, 1986b).

Between Digne and Barles this front shows a salient, the so-called “La Robine Lobe”, a large syncline with minor folds and thrust on its southern side, and a re-entrant, the Barles half-window (fig. 2). This re-entrant results from the largest erosion of a nappe anticline by the Bès River (Haccard et al.; 1989a). Effectively, it is clear that the Barles half-window was previously overthrust by the Digne nappe, and that the Bès River previously flowed in the Digne nappe, because the N-S route of this river is superimposed on the E-W trending folds of the autochthon (fig. 2; Gigot et al., 1974).

The La Robine Lobe is separated from the main body of the Digne nappe by the Bès Fault (Jorda, 1982; Gidon and Pairis, 1988; Haccard et al., 1989a). This fault runs along the Bès River from the north of the La Robine Lobe to the confluence with the Bléone River (Haccard et al., 1989a). To the south it was also mapped from Digne to the Cousson Mtn (fig. 2; de Graciansky, 1981). In between, its trace is not clear and it was not mapped by Haccard et al. (1989b). It may run in the Triassic formations (Gidon and Pairis, 1989; Jorda et al., 1992), or it may be concealed beneath the Bléone riverbed (Jorda, 1982 in Haccard et al., 1989a), or simply it does not cut the Digne nappe sequence above the Sinemurian (Haccard et al., 1989a).

According to Jorda (1982) and Jorda et al. (1992), the Bès fault was active during the Quaternary, and its dextral slip is responsible for the bending of a series of fold axes revealed by the variation in elevation of Pleistocene alluvial deposits. According to Gidon and Paris (1988) the southward motion of the La Robine Lobe was impeded by the thick accumulation of sediments of the Valensole Basin in front of it, and the Bès fault formed as a tear fault of the still moving eastern part of the nappe. The recent displacement of the main body of the Digne nappe would explain the southern offset of its leading edge at the Cousson mountain compared to La Robine. For Haccard et al. (1989a), on the contrary, the fact that the Bès fault does not cut the autochthon supports the idea that it is an old structure predating the emplacement of the Digne nappe. It is however noticeable that this fault offsets the Carixian-Lotharingian transition along the Bès River (Haccard et al., 1989a) by about 3 kms, and that this displacement is similar to the apparent offset of the leading edge of the Nappe (Southwest front of the La Robine Lobe and Cousson mountain) and similar to the apparent offset of the La Robine syncline and the Marcoux syncline (fig. 2).

The study area is also of particular interest for dating the emplacement of the Southern Subalpine ranges because here the Digne nappe overthrusts the Neogene sequence of the Valensole foreland basin (figs. 1 and 2; Haug, 1891; 1894; Goguel, 1939). Even if a broadly Miocene-Pliocene age is admitted for the Digne nappe displacement (e.g. Lemoine, 1973) its precise timing is still debated and the presence of recent conglomerates can provide additional constraints.

Since Gigot et al. (1974) it is admitted that the Digne nappe is an epiglyptic thrust emplaced on a relatively flat continental surface that was later folded (during the Quaternary), resulting in the La Robine syncline and the Barles nappe anticline. The most recent stratigraphic formation under the Digne nappe is the Tanaron formation, mainly formed by olistholiths of the folded autochthon that infill a “residual basin” (Gigot et al., 1974). At a time where the Valensole conglomerates were systematically considered as Pliocene, Gigot et al. (1974) assigned a Late Pliocene age to the overlying Tanaron formation and “residual basin”. Considering that tectonic deformation affects late Pliocene deposits in southern more areas along the subalpine front (Clauzon, 1975), Haccard et al. (1989a and b) follow Gigot et al. (1974) for this late Pliocene age of the Tanaron formation. They conclude that even if the Digne nappe probably started to move during the Miocene, at Digne its final emplacement occurred during the late Pliocene, and the post-nappe folding is Latest Pliocene to Quaternary.

However, Gidon and Pairis (1988; 1992) emphasize that the Tanaron formation is not dated biostratigraphically. These authors, who consider that the leading edge of the La Robine lobe was emplaced during sedimentation of the Valensole conglomerates, and that the Tanaron formation is the lateral equivalent of the Valensole Formation (Pairis and Gidon, 1987), propose that the Digne nappe arrived at Digne early, in the Late Miocene. They nonetheless precise that the main body of the nappe continued its displacement after the emplacement of the La Robine Lobe. Our mapping of paleo-canyons will provide new age constraints for the emplacement of the Digne nappe.

III- METHOD

We mapped the conglomeratic formations present along the main rivers around the front of the Digne nappe. We used orthophotos (aerial photographs geometrically corrected) to report out field observations on maps. Observation points were also located using GPS. To measure the elevation of outcrops we generally average several measures with altimeters, but when needed we used dual frequency GPS receivers which allowed 1 to 3 cm accuracy. We used topographic and geologic maps in a Geographic Information System to compare our mapping with the published maps. Draping the geological maps over a Digital elevation model allows displaying the tectonic structures and the paleo-canyons in 3D-views and a better understanding of their geometry. We furthermore measured striated surfaces in the conglomerates to characterize their deformation in terms of paleostresses (Angelier, 1990; 1994). Paleostress reconstruction in conglomerates generally indicates the deformation regime, the orientation of the three principal stress axes (σ_1 , σ_2 and σ_3) and a shape ratio (Φ) (Hippolyte, 2001). We observed that striation with styloliths and calcite are only present in alluvial terraces thicker than 10-20m (Hippolyte and Jouanne, 1998; Hippolyte and Dumont, 2000; Hippolyte, 2001). In places where erosion has remove most of the original depositional sequence, the finding of styloliths can reveal previously deeper conditions of burial during tectonic deformation. More generally, the orientation of the principal stress axes can provide information on the kinematics of larger scale structures (Hippolyte et al, 1995; Hippolyte & Sandulescu, 1996).

IV- EXAMPLES OF PALEO-CANYONS

1) A tilted paleo-canyon in La Grand Colle mountain

In the La Grand Colle mountain, located immediately north of the city of Digne (fig. 2), Jorda (1982) and Jorda et al. (1992) described alluvial deposits affected by tectonic deformation. These alluvial deposits were mapped as three distinct alluvial nappes: Collet de Meunière, Rochassas and the Grand Colle upper nappe (fig. 3) (Jorda, 1970; 1982; Haccard et al., 1989b). At Collet de Meunière, the alluvial deposits are well visible in a 70m-high cliff (fig. 4). These conglomerates are tilted to the East and Jorda (1982) attributes this exceptional thickness to a tectonic deformation and uplift of the areas downstream. Based on their elevation, he correlates the alluvial deposits of Collet de Meunière with a middle Quaternary alluvial terraces located upstream, then proposes an early-Pleistocene age for the two higher alluvial nappes (Rochassas and La Grand Colle) and concludes for important quaternary deformation. In 1999, G. Clauzon proposed that these alluvial deposits are not stepped terraces but represent 200 m of Pliocene infill of a Messinian canyon.

a) Mapping of the alluvial deposits of La Grand Colle mountain

Thanks in particular to the opening of new private dirt roads in this mountain, we can precisely map these alluvial deposits. The use of aerial orthophotos and a GPS allowed accurate mapping. We observed the contact between the alluvial deposits and their bedrock at 22 sites where we measured its elevation (fig. 3B). For example, immediately south of Le Rochassas (elevation 919 m), this contact was known by local people who get spring water coming out between the conglomerates and the Jurassic marls at nearly 820 m elevation (fig. 3B). It shows that, at the Rochassas like at Collet de Meunière, the conglomerates are very thick (about 100 m). Finally, our mapping confirms that conglomerates cover most of the western side of the Grand Colle mountain without discontinuity (Clauzon, 1999). In all the outcrops of La Grand Colle, these alluvial deposits are constituted by poorly sorted boulders, cobbles and pebbles with similar petrology and shape. They correspond to a unique and thick lithological unit (fig. 3B). This conglomeratic formation was previously only partially mapped (fig. 3A; Haccard et al., 1989b). The three "alluvial terraces" of Jorda (1982) are in fact relatively flat areas within this lithological unit (compare figs. 3A and 3B). We interpret them as erosional terraces in a thick conglomeratic formation. Note that in 1970, Jorda mapped the same extension of the cobbles as in fig. 3B, but he

considered the loose clasts between the “terraces” as colluviums, while the opening of new roads now clearly shows that this loose material is the superficial part of a conglomeratic formation.

b) Fault striation analysis and pre-tilt geometry

As noted by Jorda (1982) the surfaces of cobbles of these conglomerates often show striation. A fault analysis confirmed that they are mainly tectonic striation and allowed reconstruction of ENE-WSW trends of σ_1 (maximum compressional stress axis) (Hippolyte and Dumont, 2000). This trend of compression is consistent with the proposed dextral movement of the Bès fault (fig. 2 and 3; Jorda et al., 1992). At Collet de Meunière, the conglomerates dip 12° toward the east and the base of the alluvial formation is cut by a reverse fault parallel to the Bès fault (fig. 4). At sites 1 and 2 (fig. 3), striated clasts and little faults with calcite steps cutting the conglomerates confirm that the stress regime was mainly compressional (cf. faults diagrams of fig. 3C). At site 3, located at the northern end of a fault that offsets dextrally the Domerian limestone (fig. 3B), the stress regime in the conglomerates is strike-slip (σ_3 horizontal, fig. 3C).

At the southern tip of the conglomeratic unit (site 4, fig. 3), the contact with the Aalenian beds dips 33° to the east (fig. 5). This dip was interpreted as of tectonic origin (Jorda, 1982). To check if this unconformity was originally horizontal, we measured striated cobbles and reconstructed paleostresses. Paleostress axes can be used to identify paleo-verticals because the vertical stress axis mainly results from sub-vertical gravitational forces (Angelier, 1994; Hippolyte et al, 1995; Hippolyte & Sandulescu, 1996). This technique is particularly useful for reconstructing the paleo-vertical and paleo-horizontal in non-bedded conglomerates (Hippolyte, 2001).

At site 4, we found conjugate normal faults, probably resulting from local compaction on the irregular surface of unconformity (fig. 5). In their present attitude, the conjugate normal faults are tilted, and the corresponding σ_3 and σ_2 axes are in a plane nearly parallel to the stratigraphic unconformity. Rotating this unconformity to the horizontal results in bringing σ_1 back to the sub-vertical position that it had during compaction. That the backtilted position of σ_1 is sub-vertical, confirms that the stratigraphic unconformity was sub-horizontal during compaction and normal striation. At site 4, we also found the ENE-trending compression evidenced in the other sites. The σ_1 axis slightly dips toward the west (fig. 5), like the present topography. This state of stress, influenced by the present topography, postdates the tilted normal faults. We infer that it is the ENE compression that tilted the compaction faults and the unconformity. Finally, from North to South, the conglomerates of La Grand Colle show similar deformation. This unit was tilted eastward of about 12° by an ENE compression. Locally (e.g. site 4), this tectonic tilt can be up to 33° owing to local undulations of the structure (fig. 6).

c) A paleo-canyon morphology

Taking into account the tectonic dips mentioned above, we can infer the original morphology of the contact between the conglomerates and the bedrock. This basal contact was sub-horizontal at site 4, but eastward, it climbs rapidly to 920 m elevation and it was originally a steep slope (Fig. 3B). We mapped a similar steep paleo-morphology east of Rochassas, between 800m and 983 m elevation (fig. 3B). We conclude that the conglomerates filled up a paleo-valley with steep flanks, in other words, a canyon.

Based on our mapping and 3D views, we could draw the eastern flank of this canyon (fig. 3B). It is oriented NNW-SSE. In contrast to this steep flank, most of the bedrock surface to the West is rather flat. A cross-section through the middle of the mapped conglomeratic unit illustrates the morphology of this paleo-canyon (figs. 3 and 6). It shows that the conglomerates were at least 172 m thick. But considering the tectonic tilt to the East of 12°, their thickness might have been about 300 m (fig. 6). With such a thickness of conglomerates, it is understandable that the burial depth and confining pressure were large enough to generate stylolites and steps of calcite on clast surfaces during tectonic deformation.

To the West, at the southwest of Collet de Meunière (fig. 3B), the contact of the conglomerates with the Liassic rocks rises from 820 m to 875 m (fig. 6). Therefore, the bedrock has a shape of the gutter oriented NNW-SSE. Note that this orientation is perpendicular to the

drainage direction previously proposed for the alluvial deposits of Le Rochassas (Jorda, 1982) (fig. 3A).

The lithology of the clasts clearly indicates that this paleo-canyon was filled up by alluviums of the Bléone River. The conglomerates contain 44 % of cobbles of the local Late Jurassic and early Cretaceous light limestone, 30 % of the early-middle Jurassic dark limestones, 17% of Grès d'Annot, a sandstone typical of the Bléone catchment basin in the Digne nappe, and a few percents of Triassic dolomites and Oligocene pink sandstones. These latter are typical from the Bès River, a tributary of the Bléone River with a catchment basin mainly in the foreland of the Digne nappe (fig. 2).

The Grand Colle mountain is located immediately to the southeast of the present confluence of these two rivers. At this confluence, the Bléone River changes of direction from E-W to N-S (fig. 2). To check if the paleo-Bléone in the Grand Colle mountain was flowing east to West or North to South, we reconstructed its flow direction from clast imbrication at Collet de Meunière. The imbricate arrangement of clasts is characterized by flattened surfaces dipping up-current. The upper Schmidt diagram of figure 3C shows the statistic analysis of measurements of the upper faces of relatively flat imbricate clasts. These surfaces dip to the NW and indicate a flow direction toward N145E. This direction confirms our mapping of the eastern flank of the canyon trending NNW-SSE. We conclude from these directions, and from the presence of Oligocene pink sandstones, that the Bléone paleo-river was flowing toward the SSE and that its confluence with the Bès paleo-river was located upstream of Collet Meunière.

d) A paleo-canyon back-tilted

In the flow direction, the elevation of the base of the paleo-canyon of La Grand Colle climbs from 790 m at Collet de Meunière, to 870 m at Biscaron (fig. 7). This geometry shows that, after its sedimentary infilling, the canyon was tilted longitudinally. As the bed of the modern Bléone River dips of about 0.6° to the south, and the base of the canyon dips 2.9° to the north (80 m on 1570 m) we infer a tectonic tilt of the paleo-canyon of about 4° to the NNW. Note that this tilt is reverse to the flow direction (fig. 7). This direction of tectonic tilt agrees with the structure of the Digne nappe along the Bléone River, characterized by a progressive increase of bedding dip in the Digne nappe toward the south, that brings to outcrop the early Liassic and Triassic rocks at Digne. This structure suggests that, if other relicts of the canyon infill are preserved to the south, they might be present at a higher elevation.

2) Paleo-canyons in the Cousson massif

Immediately south of Digne, in the Cousson massif, the geological map shows a little outcrop of conglomerates overthrust by the Digne nappe in a gully called Les Fontaines (Gigot, 1973), and another outcrop at La Fonse near Les Hautes Bâties de Cousson (de Graciansky et al., 1981). These isolated outcrops of conglomerates were first ascribed to the Valensole Formation of Late Miocene to Late Pliocene age (Gigot, 1973; de Graciansky et al., 1982; Gidon and Pairis, 1988). Along the Barbejas trail (fig. 8), Jorda (1982) found two other alluvial formations with tectonic deformation at 840 m and 920 m elevation. Then Jorda et al. (1988) described the outcrop of Les Fontaines as a section starting with up to 30 m of conglomerates with striated clasts, covered by about 10 m of sandy loams. This sequence rests unconformably on the overturned Caramantran syncline, but dips of up to 60° to the east, and is overthrust by the Digne nappe (fig. 8A). Jorda et al. (1988) found plant leaves in the loams (unfortunately devoid of pollen grains). Based on the absence of subtropical species, they interpreted these plant macroremains as corresponding to a temperate climatic phase of the Late Pliocene or Early Pleistocene¹. Moreover, analyzing the type of heavy minerals contained in the sands, they showed that these alluvial deposits are distinct from the Valensole conglomerates but similar to the alluvial deposits of the Grand Colle Massif.

¹ Recently, the Pliocene-Pleistocene boundary has been lowered at 2.58 Ma and, as a consequence, the temperate phases of the previous Late Pliocene which belong to the earliest Northern Hemisphere glacial-interglacial cycles have henceforth an Early Pleistocene (i.e. Early Quaternary) age (Gibbard et al., 2010).

a) A paleo-canyon overthrust: Les Fontaines-Caramantran

Using GPS and aerial orthophotos we remapped these outcrops. Along the Barbejas trail to Caramantran, whereas the Digne geological map shows ancient scree deposits, Jorda (1982) reports two alluvial nappes at 840 m and 920 m. We however found that conglomerates with local sand intercalations are visible all along the trail to Caramantran between these two elevations (fig. 8A). This outcrop of conglomerates extends to the east of the trail and apparently merges with the conglomerates of Les Fontaines (fig. 8D). Moreover, the outcrops of Caramantran and Les Fontaines show similar conglomerates. At these two outcrops, the conglomerates are tilted to the NE. At Les Fontaines, the upper sandy loams dip 54° to the NE (Jorda, et al., 1988), and at Caramantran our mapping shows that the base of the conglomerates dips 18° to the NE. The increase of dip toward the East is consistent with the presence of splay faults that may branch on the Digne thrust at Les Fontaines (Jorda et al., 1988). Moreover, the thickness of the conglomerates can be estimated to 50 m at Caramantran, which is similar to the 40 m proposed for the outcrop at Les Fontaines (Jorda, et al., 1988).

Based on our mapping and these similarities, we infer that the outcrops of Caramantran and Les Fontaines are parts of an unique conglomeratic formation that is overthrust by the Digne nappe on the northeast. Its thickness and its tectonic deformation suggest that it represents the relict of a paleo-canyon infill that has been largely eroded to the west before being overthrust. A plunging view illustrates the 3D geometry of this overthrust canyon (fig. 8E). Note that, if the paleo-river came from the Cousson mountain and flowed toward the NNW, as presented by Jorda (1982) in Haccard et al. (1989a), the steep Liassic limestone between the two main outcrops would have been a waterfall. We rather interpret this steep paleo-morphology, where a modern gully has eroded the conglomerate, as part of the southern edge of the canyon.

To check this interpretation of southwesterly oriented flow direction, we looked for clast imbrication. We found a suitable exposure of imbricated clasts at Les Fontaines where the alluvial formation dips 54° to the Northeast. The imbricated flattened clasts are broadly vertical and oriented NE-SW (fig. 8B). Rotating the bedding back to its original horizontal attitude (axes of rotation N133), we obtain a Westward direction of flow (fig. 8B). This direction is close to the trend of the supposed edge of the canyon (fig. 8D) and suggests that the paleo-river flowed toward the Valensole Basin and not toward the Digne nappe. This conclusion is also supported by the analyses of heavy minerals contained in the sands (Jorda, 1982), and by the presence of clasts of the Upper Eocene - Lower Oligocene Grès d'Annot, a sandstone formation still present in the Bléone catchment basin, but absent in the Cousson mountain only constituted by Triassic and Jurassic rocks.

b) A paleo-canyon uplifted by thrust ramps: The Fonse windgap

Another alluvial formation is present at La Fonse (de Graciansky et al., 1981), only 750 m south of Les Fontaines, but about 90 m higher (fig. 8A). As a difference with Les Fontaines conglomerate, the clasts are less rounded and exclusively of local origin (Jurassic and Triassic rocks) in agreement with a catchment basin in the Cousson Massif. The size of the clasts (up to 1m) also agrees with alluvial deposits of a local torrent.

The La Fonse conglomeratic unit appears within a windgap. It is a relatively high-level notch (or pass) in the upper part of a mountain ridge through which a waterway once flowed (fig. 9). The closest modern stream is the Eaux Chaudes torrent located 1 km to the northeast of La Fonse (fig. 8). Between this stream and the La Fonse conglomerate, there is a mountain top at 1110 m elevation (fig. 9). To explain the shift of the Eaux Chaudes torrent from the La Fonse paleo-valley (or windgap) to its modern position, one can invoke a stream capture, or a process frequently found in the evolution of Messinian canyons and named by Clauzon (1996): "aggradation epigenesis". This dynamic process occurs in three steps: first, infill of the canyon with aggradation of the alluvial surface; second, lateral migration of the stream on the alluvial surface; third, Quaternary incision and entrenchment of the stream with "epigenesis" (superimposition or antecedence).

Stream capture would mean that there were at the same time two local streams in the Eaux Chaudes catchment basin, which we have no argument for, because we only know one local conglomerate. The origin of La Fonse windgap through a process of “aggradation epigenesis” implies an infill of the paleo-valley above the 1110 m high, and therefore an original thickness of more than 100 m for the conglomeratic infill. In the La Fonse conglomerates at 1030 m elevation, we found striated clasts with styloliths, which are indicative of a deep burial during deformation (several tens of meters; Hippolyte and Jouanne, 1998; Hippolyte and Dumont, 2000; Hippolyte, 2001). We conclude that the La Fonse windgap is the relict of a deep paleo-canyon, and that the Eaux Chaudes torrent was extracted from this canyon through a process of “aggradation epigenesis”. Note that as a difference with a classical wingap, the Fonse paleo-valley has been infilled and then re-opened by erosion.

Like the Les Fontaines-Caramantran paleo-canyon, the La Fonse paleo-canyon has undergone compressional deformation as shown by the reverse and strike-slip slips on clast surfaces (fig. 8C). The measurement of these striated surfaces allows computation of N45E-trending compression (fig. 8C). Remark that this trend is similar to those obtained in the Grand Colle paleo-canyon (fig. 3C). Like at the Grand Colle, the La Fonse canyon is located in the Digne nappe main body that has overthrusts the Caramantran unit (fig. 10). We interpret the 210 m difference in elevation between the thalweg of the overthrusts Caramantran-Les Fontaines paleo-canyon (800 m, fig. 8D) and the thalweg of La Fonse paleo-canyon (~1010 m, fig. 9), as resulting from the movement of the Digne nappe on its thrust ramps in the Cousson-Caramantran mountains (fig. 10).

Finally, the elevation of the thalweg of the studied paleo-canyons follows the structure of the Digne nappe. Along the Bès strike-slip fault (Jorda, 1982; Gidon and Pairis, 1989; Jorda et al., 1992) the Grand Colle canyon is tilted of only 4° to the NNW (fig. 7). To the South, above the Caramantran unit, an imbricate that overthrusts the Valensole Basin (fig. 10), the Caramantran-Les Fontaines canyon is tilted of about 18° to the NE. Finally, the La Fonse Canyon is uplifted over the main thrust ramp of the Digne Nappe (that overthrusts the Caramantran-Les Fontaines canyon) of about 210 m (fig. 10).

Taking into account this deformation pattern and the petrography of the clasts of the paleo-canyons, we interpret the Caramantran-Les Fontaines canyon as the downstream prolongation of the Bléone canyon found in the Grand-Colle mountain. In agreement with the back-tilting of La Grand Colle canyon (fig. 7), in the South of the Digne nappe we found a relict of the paleo - drainage network (La Fonse) at higher elevation (1010 m) than its upstream relicts (870 m; figs. 7 and 10). We interpret the paleo-Eaux Chaudes canyon as a tributary of the Bléone (Caramantran-Les Fontaines) canyon. As we have not found the paleo-Eaux Chaudes canyon in the Caramantran tectonic unit, we infer that its confluence with the Bléone paleo-stream was located in the upper tectonic unit, the Digne nappe. The flow direction in the Bléone paleo-canyon at Caramantran-Les Fontaines toward the Valensole Basin, and the thrust movements, suggest that down-stream relicts of the Bléone canyon might be found in the Valensole Basin and at lower elevation.

3) A fault-truncated paleo-canyon : La Bonnette-Les Hautes Siéyes

In the West of Digne, the Bléone River flows in the folded Miocene molasses of the Valensole foreland basin (fig. 2). On the right bank of this river, several outcrops of thick conglomerate, mapped as ‘ancient terraces’ because located at 100 to 200 m above the valley floor (de Graciansky et al., 1981, 1982) can be interpreted as relicts of a canyon infill: La Bonnette, Les Ajoncs, Les Hautes Siéyes, and Les Plaines (1 km west of Les Hautes Siéyes; figs. 11 and 2).

At La Bonnette (fig. 11), the geological map shows a 50 m thick ‘ancient terrace’ (de Graciansky et al., 1981). The base of the conglomerates is often hidden by colluviums. However, we could see it at three places thanks to the presence of galleries locally called “mines” from the Provençal term ‘mina’ (fig. 11). These ‘mines’ are ‘horizontal wells’ dug to collect groundwater (fig. 12). They were dug exactly along the unconformity between the conglomerate, which acts as an aquifer, and its impermeable bedrock, the Miocene Valensole clays. For a better accuracy, we

used dual-frequency GPS receivers to measure the elevation of the conglomerate/bedrock contact at the entrance of the 'mines'. These measurements reveal that the conglomerates are presently 90 m thick at La Bonnette (fig. 11). Note that a Quaternary talus slope truncates its top, and that these conglomerates were originally thicker. The mapping of these conglomerates finally reveals that, like at the Grand Colle, they infill a paleo-valley with a rather flat bottom and a steep slope (figs. 11 and 13). We found the same geometry at Les Hautes Siéyes (fig. 13). Correlations between these outcrops allow a geometric reconstruction of the northern flank and the bottom of the canyon (fig. 11). It indicates that the river flowed E-W. Notice that the lowest points of the canyon floor are preserved at La Bonnette and Les Hautes Siéyes, suggesting that the canyon was not larger than twice its presently mapped width (figs. 11 and 13).

Upstream from the Bonnette conglomerate, an excavation for a water tank found the Triassic rocks of the Digne nappe at 715 m elevation, which is 19 m higher than the bottom of the canyon observed in the 'mines' (fig. 11). It shows that either the canyon made a sharp turn around the Triassic gypsum, or there is a fault contact between the conglomerates and the Triassic formation, which is usually the basal décollement layer of the Digne nappe.

To check these hypotheses we measured imbricated cobbles on the eastern side of the La Bonnette hill. The density plot of these measurements confirms the E-W flow direction indicated by the canyon morphology (fig. 11). In the same site, we found striated cobbles with reverse-dextral fault slips. Paleostress computation indicates N50E trending compression. This trend is similar to those obtained in the Grand Colle and in La Fosse conglomerates (fig. 3C and 8C). Considering that we have not found striations on the western side of La Bonnette hill or in the canyon infill further west (Les Hautes Siéyes, Les Plaines), we conclude that these reverse-dextral slips on N-S trending surfaces are related to a reverse dextral slip along the North-South oriented St. Benoît fault that we map along the Triassic gypsum of the Bonnette water tank (fig. 11).

A view of the right bank of the Bléone River (fig. 14) effectively shows the truncation of the Bléone paleo-canyon at La Bonnette by the St. Benoît strike-slip-reverse fault. With its E-W orientation, the Bléone canyon cannot be followed upstream, where instead we observe Liassic layers of the Digne nappe (figs. 11, 13 and 14).

4) Estimation of the fault displacement

The St. Benoît fault was recognized on the La Javie geological map (Haccard et al., 1989b) but interpreted either as reverse sinistral fault cutting the Givaudan syncline to the East (Haccard et al., 1989a) or as a dextral fault equivalent to the Bès fault to the South (Haccard et al., 1989a; Jorda, 1982). This fault effectively truncates the eastern side of the Givaudan syncline where there is now the St. Benoît petrifying spring (fig. 2; Haccard et al., 1989a). To the South, this fault was not drawn on the geological map of Digne (de Graciansky, 1981) because concealed beneath Quaternary talus deposits (fig. 11). We however could map the southern prolongation of this fault that cuts the Bléone paleo-canyon (see above). We emphasize that this fault truncates also the western side of the Caramantran syncline. Effectively, this syncline is present on the left bank (Caramantran mountain) and on the right bank (Saumon mountain) of the Bléone River (fig. 11). We propose that the Givaudan and the Caramantran synclines, located at the front of the Digne nappe (fig. 2), were once the same structure that was cut and offset dextrally of 1.4 km by the St Benoît dextral-reverse fault. Note that this dextral slip participates to the 3 km offset of the leading edge of the Digne nappe in the Cousson mountain (fig. 2).

Taking into account the truncation of the Bléone paleo-canyon by the St Benoît dextral-reverse fault at La Bonnette, we can expect to find the upstream prolongation of the canyon in the Digne nappe, southward and at higher elevation. This dextral fault-slip therefore supports the interpretation of the Caramantran-Les Fontaines conglomerates as the first relict of the Bléone paleo-canyon upstream from La Bonnette conglomerates (fig. 10). These two parts of the Bléone paleo-canyon were separated dextrally by the St Benoît fault. This conclusion is also supported by the similar E-W flow directions in the Caramantran-Les Fontaines and in the La Bonnette paleo-canyons (figs. 8 and 11), by the similar shape and size of the clasts (cobbles), and by the similar lithology of the clasts in the two outcrops (50-70 % of Jurassic limestone and 10-20% of Grès d'Annot).

As part of the leading edge of the Digne nappe as been eroded by the Quaternary Bléone River between these two relicts of paleo-canyons (fig. 10), it is not possible to quantify the tectonic separation with great accuracy. However, we have enough data to give an estimation of the fault displacement on the two main faults (St. Benoît and Bès faults). As the route of the Bléone paleo-canyon above the Caramantran syncline had to be above the present 934 m elevation (fig. 8E), its vertical offset by the St Benoît fault is certainly greater than 238 m (934-696; fig. 10). Taking into account the nearly E-W flow direction of the Caramantran and La Bonnette relicts (figs. 8 and 11), and the possible width of the canyon bottom (between 540 and 680 m; figs. 6 and 13) we estimate the dextral offset of the Bléone paleo-canyon along the N005-trending St Benoît fault to 1100 +/- 50 m.

On the same way, using the location of the La Fonse paleo-canyon (fig. 10), we can estimate the offset of the canyon by the main fault (the Bès fault; Jorda, 1982). The thalweg of the La Fonse paleo-valley was uplifted of 210 m relatively to the thalweg of the Caramantran outcrop (800 m, fig. 10) and of 314 m relatively to the thalweg of the La Bonnette outcrop (fig. 10). Considering that the 210 m uplift results from the movement of the Digne nappe (as shown by the deformation at the Grand Colle) on a thrust ramp that dips 15+/-2° to N63E (fig. 10), we infer that in a N195 direction (average trend of the Bès strike-slip fault), in which the thrust ramp dips 10+/-2° northward, the horizontal displacement was 1241+/- 253 m. Note that, with such a displacement, the loams of Les Fontaines, presently at 1100 m from the La Fonse paleo-thalweg, were probably deposited near the confluence of the Eaux Chaudes and Bléone paleo-rivers.

Finally, we estimate the total displacement of the Digne nappe since the incision of the paleo-canyons of 2340 +/- 300 m.

V- AGE OF THE PALEO-CANYONS

The recognition of the Bléone paleo-canyon in the Valensole Basin immediately West of Digne (fig. 11; Clauzon, 1999) provides an important constrain on its age. Effectively, at this place the paleo-canyon incised the Valensole conglomerates overthrust by the Digne nappe (figs. 12 and 15). The Valensole conglomerates were deposited over a marine early Miocene molasse (Gigot and Mein, 1973) as a southward prograding continental fan (fig. 16A; Clauzon et al., 1987; 1989). Its diachronous base was dated near Digne of the early Serravallian (figs. 15 and 16A; Clauzon et al., 1987; 1989) giving a lower limit to the age of the Bléone paleo-canyon.

Still in the Valensole Basin, at La Bonnette, the conglomeratic infill of the paleo-canyon is truncated by erosion and covered by talus deposits with Levallois artefacts indicating a probable Middle Pleistocene age (figs. 11, 15; Dubar, 1970; 1976). At Les Fontaines, the same conglomerates are topped by sands and loams that gave a fossil-leaf assemblage attributed to a temperate to cool climatic phase of the Early Quaternary (see above; Jorda et al., 1988; fig. 15). The age of the canyon infill can therefore be bracketed with fossils between the early Serravallian and the Early Quaternary.

A better bracketing of this age can be proposed in re-evaluating the age of the upper part of the Valensole conglomerates around Digne according to regional marker surfaces related to the Messinian salinity crisis defined by Clauzon (1988, 1996). Three marker surfaces are of particular interest for this purpose: (1) the pre-evaporitic abandonment surface (fig. 16B), which is synchronous with the triggering of the salinity crisis at 5.96 Ma (Gautier et al., 1994; Krijgman et al., 1999) and its about 1500 m Mediterranean sea-level drop (e.g. Clauzon, 1996); (2) the Messinian erosional surface (Cita and Ryan, 1978), which includes the deep canyons incised in response to the huge river base level fall (Barber, 1981; Clauzon, 1982), and whose development was stopped by the refilling of the Mediterranean Basin and rias at 5.332 Ma (fig. 16C; Gautier et al., 1994; Lourens et al., 2004); (3) the "Pliocene" (Valensole II) abandonment surface ending the infilling of the Messinian canyons at 4.2, 3.8 or 2 Ma, depending on the location (Clauzon et al., 1995; fig. 16D).

In the middle part (Puimichel Plateau) and southern part (Valensole Plateau) of the Valensole Basin (fig. 1), the recognition of the Messinian erosional surface allowed distinction of two stratigraphic units: the Valensole-I conglomerates of pre-Messinian Miocene age and the

Valensole-II conglomerates of Pliocene age (Mercier, 1978; Clauzon, 1979; Dubard, 1983, 1984; Clauzon, 1996). In the northern part of the Valensole Basin, this erosional surface was not recognized by Haccard et al. (1989a) who proposed that the Messinian erosion did not affect this region. Without age constraints it was assumed, in the geological map of La Javie (Haccard et al., 1989b) and in that of Digne (de Graciansky et al., 1981), that the upper part of the Valensole conglomerates and the overlying Tanaron olistoliths formation (Haccard et al., 1989a) are of late Pliocene age (fig. 15).

However, as first noted by Clauzon (1999) the Messinian erosion followed by the Pliocene infill is the only combination of eustatic events capable of generating the thick accumulations in deep canyons encountered at Digne (up to 100 m of alluvial deposits in the La Grand Colle mountain). Moreover, the presence of deep Messinian canyons at Digne is compatible with the >170 m incision (its base is not observable) of the Asse Messinian canyon (Dubar, 1984) in the Valensole-I conglomerates near Oraison (fig. 1). In this area, the Durance valley floor is at 340 m elevation and the Valensole-II abandonment surface, as defined by Clauzon et al. (1995), is at ~610 m elevation, which gives a thickness of the Pliocene alluvial deposits infilling the Asse Messinian canyon of more than 270 m, compatible with the >100 m thick alluvial deposits upstream, at Digne. It must be noticed also that the flat top surface of the Grand Colle mountain, at ~990 m elevation (fig. 7), could well be the Valensole-II abandonment surface in the Digne nappe (fig. 16E). The elevation of this surface is compatible with the northeastward increase in elevation from ~610 m to 830 m of the Valensole-II abandonment surface in the neighboring Puimichel plateau (northeast of Oraison, fig. 1) (Hippolyte and Dumont, 2000). Note that the high elevation (990 m) of the abandonment surface at the Grand Colle is probably a combination of the original dip of the continental wedge top surface (fig. 16D), of Quaternary tectonic uplift (at least 80 m on the Quaternary Lambruissier thrust, Hippolyte and Dumont, 2000) and of a flexural isostatic response of the Alps to Quaternary erosion (Champagnac et al., 2008).

To constrain the age of the paleo-canyons at Digne, one of us (J.-P. Suc) analysed the pollen assemblages from two clay samples from the base of the Bléone paleo-canyon. We know from $\delta^{18}\text{O}$ records in the Mediterranean Sea that the last 5 Ma were a transition from the Messinian warm climate to the fluctuating Pleistocene cooler climate (Shackleton et al., 1995). In Europe, the Lower Pliocene was warmer and moister than the Upper Miocene (Suc, 1989; Suc et al., 1995a; Fauquette et al., 2007; Jiménez-Moreno et al., 2007). A first cooling event is recorded at 3.4 Ma and corresponds to a significant opening of the vegetation in relation with the TB 3.4-3.5 cycle sea level fall (Haq et al., 1987). Starting with a second cooling event at 2.58, rapid climatic variations (glacials: open vegetations; interglacials: warm-temperate forests) and sea level fluctuations characterise the Quaternary (Suc and Popescu, 2005; Popescu et al., 2010).

Sample D1 comes from a lens of clays found at the base of the Grand Colle canyon at 800 m elevation (fig. 3; geographic coordinates: 44°7'19" N; 6°14'56" E). Sample D2 comes from the base of Les Plaines conglomerates in the Valensole Basin, at 690 m elevation (fig. 2; geographic coordinates: 44°5'8" N; 6°11'53" E).

The two samples are rich in pollen grains. They contain the same taxa, which supports the correlation between the outcrops of conglomerates in the Valensole Basin (D2) and those in the Digne nappe (D1). The pollen assemblage is dominated by herbs (Asteraceae with Cichorioideae and *Centaurea*, Malvaceae, Dipsacaceae as *Scabiosa* and *Knautia*, Poaceae, *Linum*, *Convolvulus*, etc.). Arboreal pollen grains are not frequent but include high-altitude elements like firs (*Abies*) and spruces (*Picea*) and mid-altitude elements such as cedars (*Cedrus*), *Tsuga* and *Cathaya* attesting for a significant elevation environment. The presence of *Cathaya*, *Tsuga* and *Cedrus* without any Taxodiaceae pollen is indicative of the Late Pliocene and Early Pleistocene in the Northwestern Mediterranean region (Suc et al., 1995b; Suc & Popescu, 2005). In addition, prevalence of pollen of herbas favours a climatic episode younger than the cooling at 3.4 Ma while the absence of *Artemisia* (widespread during the earliest glacial events at 2.6 Ma) allows proposing an age between 3.4 and 2.6 Ma (Piacenzian). This age is consistent with the age proposed for the plant macroremain of Les Fontaines site (Jorda et al., 1988) situated stratigraphically above our samples.

D1 and D2 have been sampled at the base of the canyons, at the contact with the bedrock. At the Grand Colle, the site of sample D1 is only 10 m higher than the lowest conglomerates at 790

m elevation (figs. 3 and 6). At Les Plaines the site of sample D2 is 4 m above this paleo-thalweg (690 m). Therefore, their probable Piacenzian age can be considered as dating the beginning of the infill of the canyon.

With the exception of local alluvial fans of up to 1 Ma (Balène breccias, Dubar et al. 1998), the uppermost dated formation of the Valensole Basin is the Ségriès travertine, which contains a fauna attributed to the Saint Vallier mammal biozone (MN 17) close to 2 Ma (Dubar et al., 1978; Heintz and Dubar, 1981). The Valensole-II abandonment surface (the Valensole Plateau) is therefore dated at around 2 Ma (Clauzon et al., 1990; Dubar et al. 1998), which is in agreement with the age of the top of the canyons at Les Fontaines (Jorda *et al.*, 1988).

Finally, taking into account the pollen flora and the age of the other formations and marker surfaces (fig. 15), the age of the paleo-canyon infill at Digne appears to be constrained between 3.4 and 2 Ma. This Pliocene to Early Quaternary age is in agreement with the age of the infill of Messinian canyons around the Mediterranean Basin (e.g. Barber, 1981; Clauzon, 1982), but at Digne the Zanclean clays are missing.

This age is about 2 Ma younger than the beginning of the Gilbert-type fan delta progradation downstream (5.3 Ma). It indicates that fluvial incision was active probably until 3.4 Ma around Digne. Note that this erosion was active during the filling of the rias downstream. Therefore, whereas the Zanclean flooding, that occurred in only a few tens of years (Blanc, 2002), rapidly stopped the incision of the downstream part of the canyons at 5.332 Ma, their unflooded upstream part continued to be incised. As a difference with the Pliocene rias where the Messinian erosional surface was fossilized, the floor and sides of the continental canyons mapped around Digne, are post-Messinian and diachronous.

To explain this lack of Zanclean deposits one can invoke, like on the Gulf of Lions margin, either a tectonic control on erosion (Gorini et al., 2005), or their erosion during the 3.8 sea level fall (Haq et al., 1987; Lofi et al., 2003). However, a tectonic uplift of the Digne nappe would not explain the thick accumulation that followed the Late Pliocene, and the Pliocene sea level falls have small amplitude compared with the >1500 m Messinian sea level drop (Barber, 1981; Clauzon, 1982).

The lack of Zanclean deposits in the continental canyons may simply result from its non-deposition. This non-deposition is in part explained by the slow retrogradation of the alluvial sedimentation along the Pliocene rivers (fig. 16D). After the Messinian incision of canyons (fig. 16B), the flooding of the Mediterranean Basin at 5.332 Ma transformed the rivers into rias that extended far inland (fig. 16C). Sediments transported by the rivers started to deposit at the head of these rias in the earliest Zanclean, and sedimentation prograded from this place toward the Mediterranean Basin in constructing Gilbert-type fan deltas (Clauzon et al., 1990; 1995; Clauzon, 1999) (fig. 16C). The structure of these Gilbert-type fan deltas includes submarine terms (bottomset beds and foreset beds) underlain by a continental portion (topset beds composed of alluvial fans). This continental term progressively filled the rivers starting from the head of the rias and retrograding upstream (fig. 16D).

However, the retrogradation of the continental term took ~2 Ma to arrive at Digne and the location of our samples show that during this time-interval the canyons were almost empty. We propose that a non-eustatic post-Messinian erosion participated to this long delay. This erosion, during the Zanclean, simply resulted from the change in location of the river mouth (fig. 16). Of course, the Zanclean flooding results from a >1500 m sea level rise, but in the deep Messinian drainage network a consequence of this sea level rise was also a major inland shift of the river mouth. The base level of the rivers was shifted hundreds of kilometres inland (fig. 16C). In the Valensole Basin, the Durance ria probably arrived North of Manosque (Mercier, 1978), less than 40 km from Digne, a place where the Durance riverbed is now at >300 m elevation. In mountainous areas, the + 80 m Zanclean river base was much lower than the present rivers. This inland shift of the river base resulted in a shift and a shortening of the concave river profiles. This shortening resulted in an increase of the river gradients that were still not graded fluvial profiles after the Messinian erosion. The increase of river gradients caused the river to gain more erosive energy and generated a new phase of erosion that started in the Zanclean and may have lasted until the Gellasian in the upstreammost parts of the rivers (figs. 16C and 16D).

The infill of the canyons at Digne, that was delayed by the Zanclean erosion, started during the Piacenzian as a result of the retrogradation of the continental wedge (fig. 16D). This

retrogradation, occurred contemporaneously with the basin-ward progradation of the Gilbert-type fan delta and the basin-ward shift of the river mouth (fig. 16D). Finally, the river mouth returned close to the Mediterranean shelf and the head erosion was restricted to the higher mountains. This model of Zanclean inland shift of the river bases can explain that in the mountainous areas the infilling of the paleo-canyons was only delayed, but finally occurred. We conclude that the paleo-canyons of Digne result from two phases of erosion: a Messinian one, contemporaneous of the Messinian Mediterranean sea level drop, and a Zanclean one, that may have lasted until the Gellasian in the upstreammost canyons, that started with the Zanclean Mediterranean high sea level. Notice that the presence, in the boulders of the base of these canyons, of up to 40% of clasts of Grès d'Annot, shows that this erosion had already reached the Trois Evêchés Massif, 30 km upstream of Digne, in the Pliocene.

VI- NEW CONSTRAINS ON THE REGIONAL TECTONICS

1) A tectonically dissected paleo-drainage network

The alluvial deposits at La Grand Colle, Les Fontaines-Caramantran, La Fonse, and La Bonnette-Les Hautes Siéyes show similar characteristics including their large thickness (around 100 m), contrasting with the 20-30 m thick classical Quaternary alluvial terraces of the area, and pervasive tectonic deformation (many striated clasts with styloliths and calcite steps). Other outcrops of conglomerates in the Digne area share the same characteristics: Les Plaines (fig. 17), L'Escuichière (fig. 18; Goguel, 1964; Jorda, 1970), Chauvet (fig. 18; Jorda et al., 1992) and Beaumont (Jorda, 1982; Haccard et al., 1989b) (fig. 2). They allow reconstruction of a paleo-drainage network with consistent clast petrography (fig. 19). The Bléone paleo-river, characterized by the presence of Grès d'Annot flowed through Chauvet, La Grand Colle, Caramantran-Fontaines, la Bonnette, Les Hautes Siéyes and Les Plaines. Three tributaries with clasts of local origin can be recognized: the paleo-Bès (L'Escuichière), the paleo-Mardaric (Beaumont) the paleo-Eaux Chaudes River (Fonse).

This paleo-drainage network has been dissected by thrust faults (fig. 19). Thrust movements have tilted and uplifted the paleo-thalweg and river clasts are now present at various elevations. We will show how this deformation allows a better understanding of the tectonic evolution of the Digne nappe and Valensole Basin.

2) Age of folding of the North Valensole Basin

The Valensole conglomerates represent one of the most recent formations of the Valensole foreland basin. In the Digne area, in contrast with the southern part of this basin, the Valensole conglomerates have been folded in NW-SE to N-S-trending anticlines: Gaubert, Mirabeau, Préfaissal, Châteauredon, Sargan and Lambruissier (de Graciansky et al., 1982). These folds were probably syndepositional during the Miocene (de Graciansky et al., 1982). However the northern part of the Valensole Basin shows seismic activity and the folding of the Valensole plateau abandonment surface shows that the Lambruissier anticline was also active during Quaternary times (Hippolyte & Dumont, 2000).

The Pliocene paleo-canyon crosses the northern limb of the Gaubert fold at Les Hautes Siéyes and Les Plaines (fig. 2). This south-vergent asymmetrical fold involves the Valensole-I conglomerates of Serravallian-Tortonian age (Clauzon, 1979; Clauzon et al., 1987; 1989). The recognition of the Bléone Pliocene paleo-canyon allows a better dating of this fold. At Les Plaines (fig. 2), we can see that the base of the Pliocene canyon lies horizontally on the northeastward tilted Valensole-I formation (fig. 17). This angular unconformity shows that the Gaubert anticline mainly formed before the Late Pliocene. Using dual frequency GPS receivers, we measured the lowest elevation of the base of the Bléone paleo-canyon at its outcrops of La Bonnette (696 m), Les Hautes Siéyes (693 m), and Les Plaines (682 m; fig. 2). The thalweg of the canyon dips of 4.1 m on 1000 meters while the profile of the modern river (Bléone) shows a dip of 9.4/1000 at this place. This difference suggests that a small tectonic tilt occurred after the Late Pliocene. Note that we have not found any striated clast in the Pliocene conglomerates to the West of La Bonnette (fig.

2) in agreement with the weakness of this deformation that could result from a regional tilt rather than from local folding.

3) Age of the Digne nappe emplacement

As mentioned above, the precise timing of the Digne nappe emplacement is still controversial because the most recent formation overthrust by the La Robine Lobe, the Tanaron formation, is not biostratigraphically dated. The N-S component of movement of the Digne nappe is probably over 20 km (Gigot et al., 1974; Gidon and Pairis, 1986a). The outcrops around the La Robine Lobe show that the Digne nappe overlies the residual basin of Gigot et al. (1974), infilled by a complex tectonic-sedimentary *mélange*, extending on more than 11 km, that includes the Tanaron olistolitic formation (Haccard et al., 1989a) and probably also tectonic slices (fig. 2). Therefore the main emplacement of the Digne nappe occurred after the infill of the residual basin.

Our mapping of the Bléone paleo-canyon at the front of the Digne nappe provides an upper age bracket for this infill. At La Bonnette, the erosional surface of the Bléone paleo-canyon has truncated a block of Cretaceous limestone that according to (Haccard et al., 1989b) belongs to the “residual basin”. It is not clear if this tectonic slice was first an olistolith, but its emplacement is certainly related to the advancement of the La Robine Lobe of the Digne nappe that overthrusts these blocks between Tanaron and Digne. Anyway, the incision by the Bléone paleo-canyon of blocks like those of “residual basin” shows that the Tanaron Formation predates the Zanclean erosion. Therefore the Tanaron Formation cannot be of Late Pliocene age, and does not show that the Digne nappe was emplaced during the Late Pliocene-Quaternary as it is widely accepted (Haccard et al., 1989a).

Conversely, that the Bès fault displaced the Bléone paleo-canyons of “only” 2341 ± 303 m while its total offset is about 3 000 m (fig. 19) suggests that its dextral slip started before the Late Pliocene. As this fault slip results from the stop of the La Robine Lobe (Gidon & Pairis, 1988) we infer that the La Robine part of the nappe was emplaced before the Late Pliocene.

We can further propose an interpretation of the Tanaron Formation and its basal surface. The relationship between the Tanaron formation and the Valensole Formation was largely debated in particular before the publication of the 1/50 000 scale geological map (Haccard et al., 1989b). This formation is well exposed in the “Vélodrome” of Esclagon (fig. 2) where it is mainly composed of olistoliths of folded rocks from the autochthon. Gigot et al. (1974) proposed that this formation unconformably overlies the Valensole Formation. Pairis and Gidon (1987) however proposed that the “olistolitic formation” is a lateral equivalent of the Valensole marls and conglomerates, and that there was no erosion of the Valensole layers before the arrival of the olistoliths.

The 1/50 000 scale geological map (Haccard et al., 1989a) does not confirm the presence of Valensole conglomerates over olistoliths as mapped by Pairis and Gidon (1987), but following Gigot et al. (1974) considers the basal surface of the Tanaron Formation as an erosional surface that immediately north of Tanaron shows the geometry of a large channel incised in the Valensole formation after its tectonic deformation. Crumeyrolle et al. (1991) also follow this interpretation and emphasize the presence of a deeply incised paleo-valley filled by giant olistoliths dispersed in floodplain marls. However, none of these authors gave an interpretation for this large incision.

The Velodrome corresponds to the northern border of the Valensole Basin. In most of the Valensole Basin an unconformity is present at the top of the Valensole-I Formation (Dubar, 1983, 1984): the Messinian erosional surface (Cita and Ryan, 1978) and its local deeply incised canyons (Barber, 1981; Clauzon, 1982). In the Velodrome we can see that the basal Tanaron erosional surface has incised the conglomerates and most of the underlying marls forming the Valensole Formation (fig. 20). The Valensole Formation is tilted to the West by 35-40° (fig. 20A and D). The contact between the Tanaron formation and the Valensole marls is well exposed (fig. 20B, C and D). It is a sharp unconformity, and no breccia or olistolith of the Tanaron formation is visible in the Valensole marls to support lateral transition of facies (fig. 20). This unconformity can be followed up in the Valensole sequence from 1075 m to 1105 m elevation (fig. 20) which confirms that it is an erosional unconformity. This unconformity has a shape of a channel and its lower part is infilled by breccias of Jurassic and Cretaceous limestone. Above this basal infill we see reddish clays with olistoliths of Oligocene sandstone and Cretaceous limestone. These deposits of the Tanaron

Formation can be observed lying unconformably above the folded Valensole marls at elevation 1105 m (fig. 20D). To the West this unconformity is masked by the forest and Quaternary talus deposits, but the proximity of two contrasting facies: (1) the Tanaron clays with abundant olistoliths of Oligocene sandstone and no rounded clasts; (2) the Valensole fluvatile conglomerates mainly made of rounded limestone cobbles and boulders; supports its prolongation up to Les Gardes hill (figs. 20A).

We infer that the Tanaron formation infills a paleo-gully deeply incised in the folded Valensole-1 formation and whose thalweg is visible at 1075 m elevation on the flank of Les Gardes hill. Considering that the Valensole-1 formation is preserved from erosion at 1208 m we conclude that the pre-evaporitic abandonment surface (e.g. Clauzon, 1996) was at least at this elevation, and that the incision is now visible on 133 m at Les Gardes (incision of 66 m if corrected from the 60° southern dip of the Tanaron formation, Haccard et al., 1989a). If we replace the Digne nappe its northern position before the overthrusting of the “residual basin”, the mouth of the Bléone River in the Valensole Basin would be close to this deep paleo-gully, and it is possible that the Tanaron paleo-gully, that trends NW-SE, was a tributary of the Bléone River.

In the northern part of the Valensole Basin, like in the rest of the basin (Dubar, 1984), an erosional surface that postdates the Valensole-I conglomerates, and predates the Zanclean canyons is much likely the Messinian erosional surface. Consequently, the Tanaron Formation is probably of Messinian to Early-Pliocene age. We infer that the overthrust of the La Robine Lobe on the Valensole Basin (displacement of 11 km) did not occur earlier than the Messinian.

Finally, in the Digne area we have preservation of two erosional surfaces: a Messinian one (under the Tanaron olistoliths formation) and a Zanclean one (under the alluvial deposits infilling the canyons) (fig. 19B). The infill of the Messinian drainage network by local olistoliths at the front of the Digne nappe, and their overthrusting, allowed the preservation of part of the Messinian erosional surface, while further to the South, the Messinian canyons were re-incised by their streams during the Zanclean erosion.

4) Direction of tectonic transport of the Digne nappe

Most of the authors agree that the direction of transport of the Digne nappe was from the NNE to the SSW (N20 to N30) based on the trend of the Aspres and Le Poil tear faults (Gidon and Pairis, 1986a) or the direction of styloliths (Haccard et al., 1989a). However, paleomagnetic studies have revealed quite systematic anticlockwise rotations in the Jurassic rocks of the Digne nappe (Aubourg and Chabert-Pelline; 1999) and the precise direction of transport is hard to establish from microstructural data owing to the lack of recent and/or unrotated rocks in this nappe.

Mainly based on the measurement of rock cleavages along the front of the Digne nappe, Houget (1998) confirms a N30 shortening direction, while Faucher et al. (1988) conclude for two successive families of Neogene directions of shortening: N20-30 and N80. They interpret this second orientation as lateral escapes toward the Valensole Basin during the NNE-SSW principal movement. This second direction is similar with the N70E stretching lineations measured in Triassic evaporites south of Digne, on the nappe front close to the Le Poil strike-slip faults (Malavielle and Ritz, 1989). Lickorish and Ford (1998) also proposed a partitioning of deformation on N-S dextral faults and SW directed thrusting within the southern Subalpine chains. However, like Vann et al. (1986) they conclude for a WSW-directed displacement of the Digne thrust sheet and choose this direction (N60), which is between the N-S trend of the Digne front and the E-W trend of the Castellane fold belt, to restore a cross-section. Likewise, the magnetic fabric of Late Jurassic shales from the Digne nappe does not show a clear transport direction and exhibits a fan pattern in close agreement with the arcuate shape of the thrust (Aubourg et al., 1999).

Using paleostress inversion of fault striation, Ritz (1992) also conclude that two directions of compression characterize the western edge of the Digne nappe, but with a NE trend followed by a N-S Quaternary trend. Based on a detailed fault analysis in the Barles half-window (fig. 2), Fournier et al. (2008) however conclude for a unique NNE-trending Mio-Pliocene compression. Southward, in the Valensole conglomerates along the front of the Digne nappe, Combes (1984) found ENE-WSW trends of compression. A fault analysis of the Quaternary Lambruissier anticline in the Valensole Basin (Hippolyte et al., 2000) confirms the recent age of this ENE-WSW compression.

Our fault analysis in the Late Pliocene-Quaternary infill of the paleo-canyons (figs. 3, 5, 8 and 11) shows that a unique compression, trending between N45 and N80, characterises the recent movement of the Digne nappe between Tanaron and Digne. This trend is similar to the stress orientation computed from focal plane mechanisms of the Digne area (Baroux et al., 2001; Hippolyte, 2001) and to the shortening directions revealed by comparison between triangulation and GPS data in the north of the Digne nappe (Jouanne et al., 2001). Nonetheless, we point out that paleostress orientations may strongly differ from shortening directions and thrusting directions in strike-slip zones (Angelier, 1994). It is therefore interesting to evaluate the directions of transport of the Digne nappe from the dissection of the paleo-drainage network.

If we compare the elevation of the thalweg of the paleo-canyons with the elevation of modern river nearby, the lower part of the Grand Colle (790 m) is at +160 m, La Fonse (1010 m) is at + 360 and La Bonnette (696 m) is at + 115 m. Therefore, the Bès fault has uplifted the Grand Colle paleo-canyon of only 45 m compared with the La Bonnette paleo-canyon located in the Valensole foreland basin. The dominant dextral offset of the paleo-canyons (2341 \pm 303 m in a dextral sense in a N195E direction) demonstrates that the Bès fault has a mainly strike-slip movement at the Grand Colle (fig. 19). Of course, at La Fonse, its vertical offset increases to 245 m because the Bès fault passes to a thrust ramp. That the Bès fault was a tear fault along the Bès River north of the Grand Colle allows concluding that at Digne the main body of the nappe moved to the south along its trend: N15. Finally, the offset of the paleo-canyons confirms the NNE to SSW direction of displacement of the Digne nappe proposed by Gidon and Pairis (1986a). This direction is also close to the N-S azimuth of the striations that can be measured on the décollement surface near Esclangon.

The NW-trending folds and thrusts present at the southwestern edge of the La Robine lobe (fig. 2) were interpreted as old (pre-Oligocene, Oligocene or Aquitanian) structures transported by the Digne nappe because they seem to be truncated by the sole thrust (Gigot et al., 1974; Haccard et al., 1989a). The N15 to N195 displacement of the Digne nappe, if it has not changed through times, rather suggests that these compressional structures are frontal imbricates, related to the Southward displacement of the nappe (Goguel, 1964; Gidon & Pairis, 1988). These kinds of secondary thrusts, duplexes and folds are common at the frontal part of a thrust sheet in the direction of movement, the leading edge of the thrust (e.g. Twiss and Moores, 1992) (fig. 19).

5) Age of the Barles half-window

Since Gigot et al. (1974), it is admitted that the folding of the Digne nappe occurred after its emplacement, during the Quaternary. The presence of several outcrops of alluvial deposits on the Barles nappe anticline allows a better stratigraphic dating of this folding.

At Chauvet, 8 km north of Digne (fig. 2), thick alluvial deposits present at about 1100 m elevation (fig. 18) were interpreted by Jorda (1970) as equivalent to those of the Grand Colle Massif based on their clast petrography and their high elevation. We mapped these conglomerates between 1020 and 1120 m elevation. Taking into account their great thickness (100 m) and the presence of many striated clasts, we confirm the interpretation of Clauzon (1999) that they are a relict of the Bléone paleo-canyon upstream of the Grand-Colle.

Close to Chauvet, other conglomerates, representing the Bès paleo-river, are present at the Escuichère pass at 1242 m elevation (fig. 18; Goguel, 1964; Jorda, 1970). According to their elevation, higher than Chauvet, Jorda (1982) and Haccard et al. (1989b) consider that they represent an older early Quaternary alluvial nappe. However, the conglomerates at Chauvet dip of about 10° to the southeast, and this tectonic tilt can explain the difference in elevation between these two outcrops. Moreover, similarly to La Fonse (fig. 9), the conglomerates of l'Escuichère appear in a windgap between the Bléone and the Bès valleys (fig. 18) and they might have been originally as thick as in the other studied paleo-canyons. We mapped these conglomerates and found the thalweg of the Bès paleo-river at 1200 m elevation, which indicates a present thickness of about 50 m (fig. 18). Moreover, if the Bès River was extracted from this paleo-valley through the process of "aggradation epigenesis" (Clauzon, 1996), the conglomeratic infill might have been more than 126 m thick to allow the river to move above the 1326 m elevation (fig. 8). This thick infill allows concluding that the Escuichère conglomerates are also part of the Messinian-Pliocene paleo-canyon drainage network.

At Chauvet the alluvial deposits are less tilted than their bedrock that dips 20° to the SSE. It shows that half of the tilt of the Digne nappe occurred before the infill of the canyon. At l'Escuichère, the paleo-canyon lies on older Liassic formations, confirming that the tilt of the Digne nappe partly occurred before the incision of this paleo-river. At this place, the Liassic rocks of Digne nappe dip 40° to the SSE and we are at the southeastern edge of the Barles nappe anticline (fig. 2). The paleo-Bès canyon clearly cuts through the Barles nappe anticline.

In the conglomerates of l'Escuichère, we found a few gravels of Oligocene red molasses typical of the autochthon along the Bès River. They indicate that in the Late Pliocene the Bès River had incised all the Digne thrust nappe and its Oligocene autochthon. Note that pebbles of Oligocene molasse are even more frequent in the upper part of the Pliocene infill observable downstream in the Grand Colle Massif (Jorda, 1970) suggesting that the incision of the Oligocene below the Digne nappe was only beginning in the Late Pliocene.

The thalweg of the paleo-Bès at l'Escuichère, at 1200 m elevation, is 460 m above the modern Bès River. If we compare this relative elevation with those of La Bonnette (+ 115 m) in the foreland basin, we conclude that the paleo-canyon was uplifted of about 345 m at l'Escuichère. This is the major local uplift observed in the studied paleo-canyons. It shows that the Barles nappe anticline continued to form after the Pliocene infill of the canyons. This napped anticline is thus, at least in part, contemporaneous with the Late Pliocene-Quaternary southerly displacement of the main body of the Digne nappe. Note that the La Robine and Marcoux synclines (fig. 2), which were probably the same structure that have been offset dextrally by the Bès fault, predate this Late Pliocene-Quaternary deformation. The contemporaneity of the Barles nappe anticline and the Bès fault can be understood if this later is a transfer fault between two décollement surfaces: the basal (Triassic) décollement of the Digne nappe to the East, and a deeper décollement (probably in the Triassic of the folded autochthon) beneath the Barles half-window to the Northwest. The Bès transfer fault would thus transfer the shortening in the thrusts of the Cousson mountain to a blind thrust system to the Northwest (the South-vergent folds of the Barles half-window) that generates the Barles nappe anticline and tilts the Tanaron Formation to the South. The existence of this décollement beneath the Barles "autochthon" is also supported by the thrust ramp necessary to generate the Verdache nappe anticline and to bring to outcrop lower units, including the carboniferous (fig. 2). This transfer between two different décollement surfaces (Triassic of the nappe and Triassic of the "autochthon") explains why the Bès fault does not extend north of the La Robine lobe.

VII- CONCLUSION

The thick alluvial deposits of Digne are the remnants of the Late Pliocene-Quaternary (3.4-2 Ma) infill of a Messinian-Zanclean drainage network that has been dissected by tectonic deformations. We found paleo-canyons of all the main rivers: Bléone, Bès, Mardaric and Eaux Chaudes. They show that, in this tectonically active part of the Alps, the present rivers exist since at least the Messinian.

Our pollen rich clay samples D1 and D2 provide the first age constraints for the continental infill of the upstream part of a Messinian canyon. They show that the infill of the canyons was delayed of 2 Ma at only 40 km from the Zanclean rias. This delay is partly related to the increase of the river gradients, a consequence of the shift of the river mouth from the Liguro-Provençal margin to the head of the rias during the Zanclean flooding. The Late Pliocene age of beginning of infill thus reveals the phenomena of Zanclean erosion, contemporaneous with the Zanclean infill of the rias downstream.

An older erosional surface visible locally between the Valensole conglomerates and the Tanaron Formation is probably the Messinian erosional surface that has been protected by erosion where covered by the Digne nappe. Therefore, In the Digne area, we have the exceptional preservation of two superposed erosional surfaces related to the Messinian event: the Messinian erosional surface (beneath the La Robine lobe of the Digne nappe) and the Zanclean erosional surface.

The thickness of the Late Pliocene-Early Quaternary conglomerates in the paleo-canyon, that might have been >126 m at l'Escuichière, >100 m at La Fonse and is presently 100 m at Rochassas and 90 at La Bonnette, is compatible with the thickness of the equivalent Pliocene-Early Quaternary conglomerates in the Valensole Basin: >270 m at Oraison.

The evaluated thickness of conglomerates in the Grand Colle mountain before erosion, about 300 m, contrasts with the thickness of conglomerates above the Cousson thrust ramp (50 m at Caramantran, >100 m at La Fonse). It suggests that, as it was proposed by Jorda (1982), the infill of the canyons was syntectonic. This interpretation is also supported by the horizontal attitude of the V-II abandonment surface above the tilted Bléone paleo-canyon at La Grand Colle (fig. 7). The Bléone paleo-canyon would therefore be a sort of piggyback basin, with a thick stratigraphic wedge in the Grand Colle mountain, while the uplift above the frontal thrust ramp limited the thickness of the conglomerates in the Cousson mountain.

The supposed ages for the Valensole and Tanaron formations at Digne drove some authors (Gigot et al., 1974) to place in the latest Pliocene-Quaternary most of the successive deformational events of the area: the main Digne nappe emplacement, including La Robine lobe, and the folding of the Digne nappe. The presence of Pliocene-early Quaternary deposits in the Digne nappe and its foreland basin allows a better dating of the Digne nappe emplacement, of the activity of the Bès transfer fault, of the formation of the Barles nappe anticline, and of the folding of the Valensole Basin.

The deformation of the Messinian-Zanclean paleo-canyons of Digne confirms the interpretations of Jorda (1982) of an important out-of-sequence Quaternary deformation of the Subalpine front at Digne. Similar recent out-of-sequence reactivations might also characterize the front of the Digne nappe to the South (Clauzon, 1975, 1983; Vann et al., 1986). This tectonic deformation is probably still active as shown by the ENE-WSW compressional deformation found in the Champourcin Late Quaternary alluvial terrace located immediately north of Digne in the Bès fault zone (Hippolyte & Dumont, 2000).

The N195 direction of nappe displacement deduced from the horizontal/vertical offsets of the Late Pliocene Bléone paleo-thalweg is in agreement with a leading edge of the Digne nappe located in the Castellane arc. The magnitude of the nappe displacement was 2.3 km in less than 3.4 Ma and possibly 11 km in 5.9 Ma, which gives a slip rate between of 0.7 and 1.9 mm/yr.

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Figures caption:

Fig. 1: Shaded relief from a digital elevation model of the southwestern Alps with location of the study area. The Digne nappe is the eastern part of the Digne nappe-Castellane arc thrust system. Between Digne and Barles it clearly overthrusts the Valensole Neogene foreland basin.

Fig. 1: Carte en relief ombré des Alpes sud-occidentales avec localisation de la zone d'étude (encadré).

Fig. 2: Geological map of the front of the Digne nappe (Haccard et al., 1989b; modified from Jorda, 1982; Gidon and Pairis, 1988; Jorda et al., 1992; Besson et al., 2005; and this work) with location of the sites with conglomerates infilling paleo-canyons. The "residual basin" is represented as in the structural scheme of the 1:50 000 geological map (Haccard et al., 1989b).

Fig. 2: Carte géologique du front de la nappe de Digne (Haccard et al., 1989b modifiée à partir de Gidon and Pairis, 1988; Jorda, 1982; Jorda et al., 1992; Besson et al., 2005; et ce travail) et localisation des affleurements de conglomérats remplissant des paléo-canyons. La formation de Tanaron est représentée telle que sur le schéma tectonique de la carte géologique (Haccard et al., 1989b).

Fig. 3: Western side of La Grand Colle mountain near Digne (location in fig. 2). A: Topographic map (contour lines every 50m) with the "Pleistocene alluvial terraces" according to the La Javie geological map (Haccard et al., 1989b). B: Same topographic map with our mapping of the thick conglomerates infilling a paleo-canyon (yellow). In dark blue is the modeled eastern flank of the canyon. In light blue is the bottom the canyon. C: Schmidt's diagram with density contour lines of poles of imbrication planes of flattened clasts of cobble size at Collet Meunière. Schmidt's diagrams showing fault planes with striation measured in the conglomerates at sites S1, S2, S3, and computed paleostress axes (Angelier, 1990; 1994). Five-branch star = σ_1 (maximum principal stress axis); four-branch star = σ_2 (intermediate principal stress axis); three-branch star = σ_3 (minimum principal stress axis).

Fig. 3: Le flanc occidental de la montagne de La Grand Colle (cf. fig. 2 pour la localisation). A: Extension des "Terrasses alluviales Pleistocènes" d'après la carte géologique de La Javie (Haccard et al., 1989b). B: Extension des conglomérats (jaune) et reconstruction du flanc (bleu foncé) et de la base (bleu clair) du paléo-canyon, d'après notre cartographie. C: Diagramme de Schmidt avec la direction d'écoulement déduite de la densité des pôles de surfaces de galets plats imbriqués au Collet Meunière; et diagrammes de Schmidt des plans striés mesurés dans les conglomérats et des axes de paléo-contraintes calculées aux sites S1, S2 et S3 (Angelier, 1990; 1994).

Fig. 4: View of the lower part of the La Grand Colle conglomerates at Collet de Meunière. The conglomerates are tilted and its contact with the bedrock is cut by a reverse fault which is parallel to the Bès fault along the Bès valley, and which moved under N62E-trending compression (site S1, fig. 3C).

Fig. 4: Vue de la partie inférieure du conglomérat basculé et faillé de La Grand Colle, au Collet de Meunière (fig. 3).

Fig. 5: Paleostress analysis at site 4 (fig. 3) demonstrating that at Biscaron the eastward dip of the basal unconformity of La Grand Colle conglomerates are not original but results from a tectonic tilt. Fault analysis in the conglomerates reveals compactional vertical movements with a tilted NE-trending σ_3 axis (Schmidt's diagram on the left), and ENE-trending compression (Schmidt's diagram on the right). Same legend as in figure 3C, the dashed

line is the unconformity. The central Schmidt's diagram shows the same compaction faults as on the left diagram, but after back-tilting of the unconformity. That conjugate compaction faults have been tilted shows that the conglomerates and the unconformity have been tilted by the ENE-trending compression.

Fig. 5: Analyse microtectonique du site 4 (fig. 3) démontrant l'origine tectonique (compression ENE-WSW) du pendage du contact basal du conglomérat de La Grand Colle à Biscaron.

Fig. 6: Cross-section of the La Grand Colle paleo-canyon (location in fig. 3B). The conglomerates are preserved from erosion on 172 m height, but taking into account the tectonic tilt, their original thickness might have been around 300 m. The location of sample D1, rich in pollen grains, is projected.

Fig. 6: Coupe géologique du paléo-canyon de La Grand Colle (localisation dans fig. 3B).

Fig. 7: 3-D view (orthophotos draped on a DEM) of the Bléone paleo-canyon in the La Grand Colle mountain. The contour of the conglomerates shows a steep-sided paleo-valley with a relatively flat bottom. Thrust tectonics has tilted this paleo-canyon eastward of 12° (fig. 4), but also backward, reverse to the flow direction indicated by the arrow. V-II: Valensole-II.

Fig. 7: Vue aérienne du conglomérat du paléo-canyon de La Grand Colle (photos aériennes orthorectifiées et drapées sur un modèle numérique de terrain). Le paléo-canyon est basculé dans le sens contraire à son écoulement indiqué par la flèche. V-II surface : surface d'abandon Valensole-II (cf. infra pour son interprétation).

Fig. 8: Paleo-canyons in the Cousson Massif (location in fig. 2). A: Result of our mapping of the conglomerates at Caramantran, Les Fontaines and La Fonse on a topographic map (contour lines every 50m). Yellow for the conglomerates, orange for the sandy loams with fossil leaves (Jorda *et al.*, 1988). In white, the Mesozoic formations of the Digne nappe and Caramantran syncline that overthrust the Neogene formations (in grey) of the Valensole Basin. B: Schmidt's diagram with poles of imbrication planes of flattened clasts at Les Fontaines in their present attitude (bedding plane as broken lines). The Schmidt's diagram with density contour lines shows the same planes and the flow direction after tilting the bedding back to horizontal. C: Schmidt's diagram with striation on clast surfaces measured in the alluvial deposits of La Fonse and computed paleostress axes (NE-SW compression). D: Detail view of the mapping of the Caramantran-Les Fontaines conglomerate. E: NE-plunging 3-D view of the Caramantran-Les Fontaines paleo-canyon overthrust by the Digne nappe.

Fig. 8: Paléo-canyons dans le massif du Cousson (cf. fig. 2 pour la localisation). A: Extension des conglomérats et grès, à Caramantran, Les Fontaines et La Fonse (jaune et orange). B: Diagramme de Schmidt des pôles de surfaces de galets plats imbriqués au site Les Fontaines (plan de stratification en pointillés), et diagramme montrant la direction d'écoulement déduite de la densité des mêmes plans après rotation et remise à l'horizontale de la stratification. C: Diagramme des stries tectoniques mesurées dans les alluvions de La Fonse, et axes de paléocontraintes calculées (Angelier, 1990; 1994; NE-SW compression). D: Détail de notre cartographie du conglomérat de Caramantran-Les Fontaines. E: Vue plongeante vers le NE du paléo-canyon de Caramantran-Les Fontaines chevauché par la nappe de Digne.

Fig. 9: View of the La Fonse conglomerates and windgap, at 1055 m elevation in the Cousson massif, south of Digne (fig. 2). Topographic section illustrating the "aggradation epigenesis" evolution (Clauzon, 1996) of the Eaux-chaudes River. The infill of the La Fonse canyon with aggradation of the alluvial surface is followed by a lateral migration of the Eaux-chaudes

River on its alluvial surface, then by its Quaternary incision and entrenchment with “epigenesis” (superimposition or antecedence).

Fig. 9: Vue du “windgap” de La Fonse (ensellement sur une crête anciennement creusé par une rivière) à 1055 m d'altitude, dans le massif du Cousson au sud de Digne (fig. 2). Coupe topographique illustrant le processus d'extraction de la rivière des Eaux-chaudes du canyon de la Fonse par “épigénie d'aggradation” (Clauzon, 1996).

Fig. 10: 3-D view (orthophotos draped on a DEM) of Digne and the Cousson massif showing the relicts of paleo-canyons infill (La Bonnette conglomerate, Caramantran - Les Fontaines conglomerate, La Fonse conglomerate) and the tectonic structures. The Bléone paleo-canyon lies in the Valensole Basin at La Bonnette. Another relict of this canyon lies in the Caramantran tectonic unit, and has been uplifted of about 238 m. La Fonse paleo-canyon, a tributary of the Bléone paleo-canyon in the main body of the Digne nappe, has been uplifted of about 314 relatively to La Bonnette. The paleo-drainage network has been dissected by frontal imbricates of the Digne thrust including the Caramantran duplex and the Cousson thrust ramp. The Bonnette paleo-canyon is truncated upstream by the St. Benoît dextral fault. The Caramantran-Fontaines paleo-canyon is overthrust by the main body of the Digne nappe.

Fig. 10: Vue aérienne de Digne et du massif du Cousson montrant les conglomérats reliques du remplissage de paléo-canyons (conglomérat de La Bonnette, conglomérat de Caramantran - Les Fontaines, conglomérat de La Fonse) et les structures tectoniques (photos aériennes orthorectifiées et drapées sur un modèle numérique de terrain).

Fig. 11: Front of the Digne nappe at La Bonnette-Les Hautes Siéyes (location in fig. 2). A: Result of our mapping of the conglomerates at La Bonnette, Les Ajoncs and Les Hautes Siéyes (in yellow) on a topographic map (contour lines every 10m). In dark blue is the modeled northern flank of the canyon. In light blue is the bottom the canyon. B: Schmidt's diagram with density contour lines of poles of imbrication planes of flattened clasts indicating an East to West paleo-flow direction at La Bonnette. C: Schmidt's diagrams of striated fault surfaces measured in the conglomerates at site SB, and computed paleostress axes (Angelier, 1990; 1994). The presence of ‘mines’ (Provençal galleries to collect ground water) allows mapping the base of the canyon below the colluviums. The reconstructed northern flank of the canyon is trending E-W and is truncated by the St. Benoît fault and the Digne nappe (fig. 2). The canyon incises the Valensole Formation and an overlying block of the “residual basin” overthrust by the Digne nappe (Haccard et al., 1989b) (olistolith or tectonic slice). The paleo-canyon is truncated upstream by the St. Benoît fault. Minor faults in the paleo-canyon infill indicate reverse dextral movements on N-S trending fault planes in agreement with this fault truncation.

Fig. 11: Front de la nappe de Digne à La Bonnette-Les Hautes Siéyes (cf. fig. 2 pour la localisation). A: Extension des conglomérats à La Bonnette, Les Ajoncs et Les Hautes Siéyes (jaune) et reconstruction du flanc (bleu foncé) et de la base (bleu clair) du paléo-canyon. B: Diagramme de Schmidt avec la direction d'écoulement déduite de la densité des pôles de surfaces de galets plats imbriqués à La Bonnette. C: Diagrammes de Schmidt des plans striés mesurés dans les conglomérats du site SB, et des axes de paléo-contraintes calculés (Angelier, 1990; 1994).

Fig. 12: Inside of a ‘mine’ at La Bonnette (fig. 11). This Provençal typical ‘horizontal well’ was used to collect groundwater along the unconformity between the conglomerates (aquifer) and the underlying Miocene clays of the Valensole Basin (impermeable). Running spring water was preferred to stagnant water from the wells, but these galleries could also be used as a tanks (‘resclausa’ in Provençal) which is the case here, where water rest on the yellowish clays of the Valensole Formation. Four ‘mines’ (see locations in figure 11), allowed

observation of the contact between the conglomeratic infill of the paleo-canyon and its bedrock.

Fig. 12: Intérieur d'une 'mine' (puits horizontal utilisé en Provence pour capter une source) à La Bonnette (cf. fig. 11) montrant le contact discordant des conglomérats du paléo-canyon de la Bléone (aquifère) sur un niveau argileux de la formation Néogène des Conglomérats de Valensole (imperméable).

Fig. 13: Shape of the Bléone paléo-canyon at Les Siéyes and La Bonnette. The canyon with a steep northern side was incised in the Miocene marls and conglomerates of the Valensole foreland basin. The Digne nappe, that truncates the paleo-canyon infill upstream, is visible in the background.

Fig. 13: Vue en enfilade des conglomérats des Siéyes et de La Bonnette montrant la forme du paléo-canyon de la Bléone, creusé dans le bassin de Valensole, et tronqué par la nappe de Digne en arrière plan.

Fig. 14: View of the Saint-Benoît fault truncating the Bléone paleo-canyon in Digne.

Fig. 14: La faille de Saint-Benoît qui recoupe le remplissage du paléo-canyon de la Bléone à Digne.

Fig. 15: Available ages for the recent sedimentary units of the front of the Digne nappe. The age of the canyon infill is constrained by the age of the bedrock and the age of the scree deposits above it. The plants macroremains of Les Fontaines (Jorda et al, 1988) provide an age constraint for the upper part of the canyon infill while our two samples with pollen assemblages provide age constraints for the base of the canyon infill.

Fig. 15: Datations disponibles pour les formations sédimentaires récentes au front de la nappe de Digne

Fig. 16: Model of evolution of an alpine river profile from the Messinian desiccation event to the Present. A.s.: Annot sandstone. Z.: Zanclean, G.: Gelasian. Following the Messinian sea level drop and canyon incision (fig. B), the Zanclean Mediterranean sea level rise resulted in the flooding of the Messinian canyon far inland (fig. C). The resulting inland shift of the river mouths, and shortening of the river profiles, generated a Zanclean incision upstream, contemporaneous with the marine infill of the flooded canyons (fig. C). This Zanclean erosion may explain the 2 Ma delay of the canyons infill at Digne (Piacenzian to Gelasian) compared to marine infill downstream (fig. D).

Fig. 16: Modèle évolution d'un profil de rivière alpine de l'événement messinien jusqu'à l'actuel prenant en compte l'érosion zancléenne mise en évidence à Digne. A.s.: grès d'Annot. Z.: Zancéen, G.: Gellasién.

Fig. 17: Angular unconformity between the conglomerates infilling the Bléone canyon at Les Plaines (fig. 2) and the folded Neogene deposits of the Valensole Basin.

Fig. 17: Discordance angulaire des conglomérats du canyon de la Bléone aux Plaines (fig. 2) sur les dépôts néogènes plissés du bassin de Valensole.

Fig. 18: Paleo-canyons uplifted by the Barles nappe anticline (figs. 2 and 19). In the foreground the cobbles and boulders of the Bléone paleo-canyon at Chauvet (fig. 2). In the background the conglomerates of the Escuichière windgap with the thalweg of the Bès paleo-river at about 1200 m elevation (uplift of about 345 m compared to La Bonnette paleo-canyon in the foreland).

Fig. 18: Paléo-canyons soulevés par l'anticlinal de nappe de Barles (figs. 2 et 19). Au premier plan les galets du paléo-canyon de la Bléone à Chauvet (fig. 2). En arrière plan les conglomérats du "windgap" de l'Escuichière avec le paleo-thalweg de la rivière du Bès à

1200 m d'altitude (soulèvement de près de 345 m par rapport au paléo-canyon de la Bonnette dans l'avant-pays).

Fig. 19: A: 3D view of the front of the Digne nappe (geological map of figure 2 draped on a DEM) showing a reconstruction of the Messinian-Pliocene tectonically dissected hydrographic network (same legend as in figure 2). Note that all the main present rivers exist since at least the Messinian times. B: Schematic cross-section showing the Messinian erosional surface preserved below the Digne nappe (T = Tanaron paleo-gully, fig. 20) while the Zanclean to Gellasian erosion enlarged the canyons not tectonically covered (B = Bléone canyon in the Digne nappe and in its foreland).

Fig. 19: A : Vue 3D (carte géologique de la figure 2, drapée sur un modèle numérique de terrain) d'une reconstruction du réseau hydrographique messinien-pliocène déformé par la tectonique au front de la nappe de Digne. B: Coupe schématique montrant la surface d'érosion messinienne préservée sous la nappe de Digne (T= paléo-ravin de Tanaron, fig. 20) alors que l'érosion Zancléenne à Gellasienne a remodelé les cayons non recouverts par la nappe de Digne (B= paléo-canyon de la Bléone dans la nappe de Digne et son avant-pays).

Fig. 20: Paleo-gully in the Barles Half-window at Tanaron (fig. 2). A : Southward view of the erosional unconformity between the folded fluvial sediments of the Valensole Formation and the reddish clays and olistoliths of the Tanaron Formation. B, C and D: Detailed views of the basal unconformity of the Tanaron Formation. Fm. = Formation; S_0 = bedding plane. The thalweg is at 1075 m elevation and the Valensole Formation is at 1208 m elevation at Les Gardes. The basal infill of this paleo-gully is characterized by breccias and rounded boulders that might come from the top of the Valensole formation. The Tanaron olistolithic Formation was overthrust by the Digne nappe. According to our dating of the Digne paleo-valleys and Digne nappe emplacement, this paleo-gully postdating the Valensole-I formation may have been incised during the messinian erosion and infilled during the early Pliocene. This old erosional surface was preserved owing to its olistolithic infill and the overthrusting by the Digne nappe, whereas incision continued in the paleovalleys of the Digne nappe.

Fig. 20: Paléo-ravin à Tanaron dans la demi-fenêtre de Barles (fig. 2). A : Vue de la surface d'érosion entre les dépôts fluviaux plissés de la formation de Valensole et les argiles saumon à olistolites de la formation de Tanaron. B, C et D: Vues rapprochées de la discordance basale de la formation de Tanaron. Fm. = Formation; S_0 = plan de stratification. La base du remplissage de ce ravin fossile est caractérisée par des brèches et galets qui pourraient provenir de l'érosion du sommet de la formation de Valensole. D'après notre datation des paléo-vallées de Digne et de la mise en place de la nappe de Digne, ce paléo-ravin, plus récent que la formation de Valensole-I, pourrait avoir été creusé durant l'érosion messinienne et remplie pendant le Pliocène inférieur. Cette paleo-morphologie a été fossilisée par le remplissage d'olistolites et le recouvrement de nappe de Digne, alors que les paléo-vallées transportées par la nappe de Digne continuaient à se creuser.

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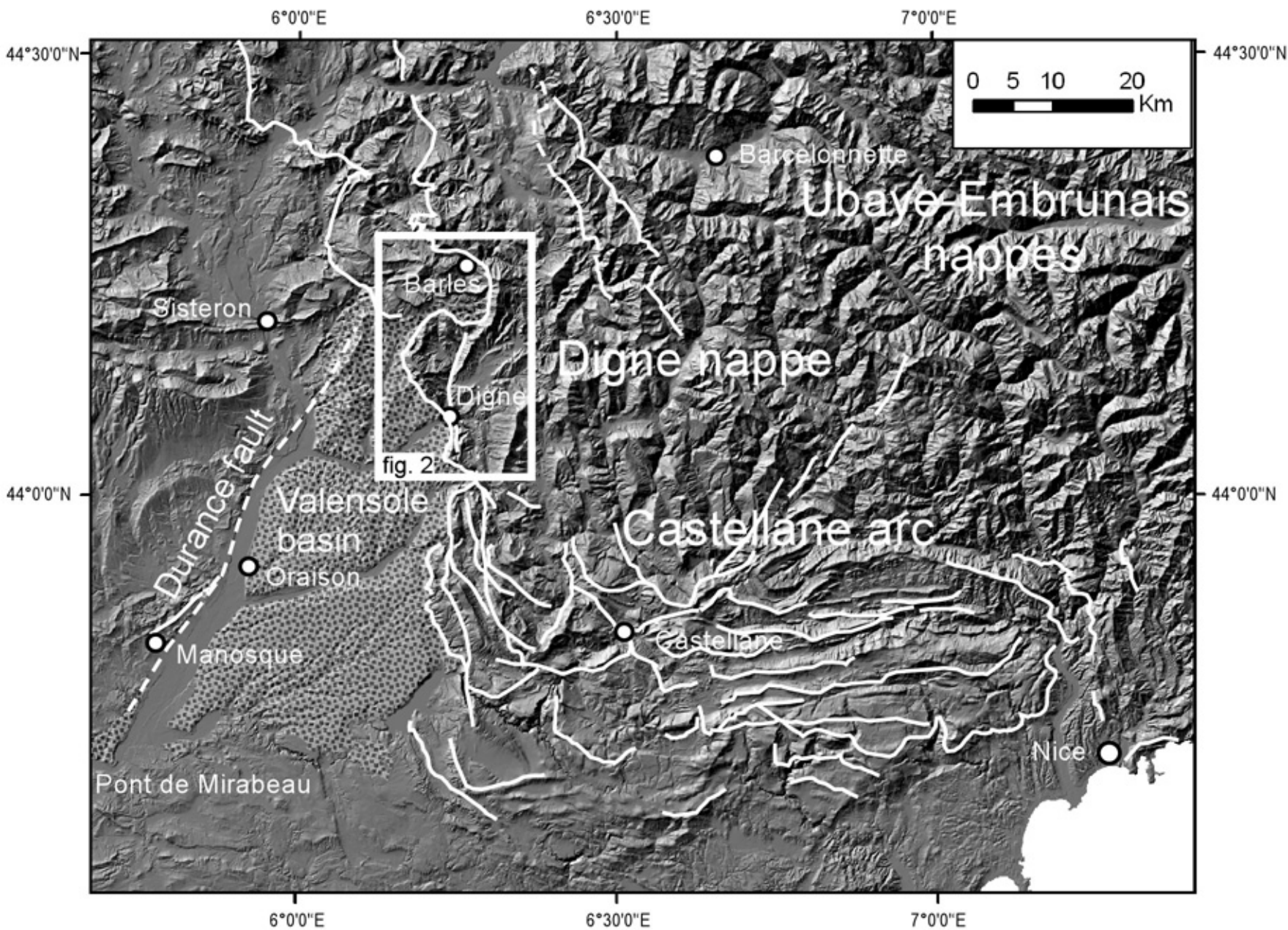
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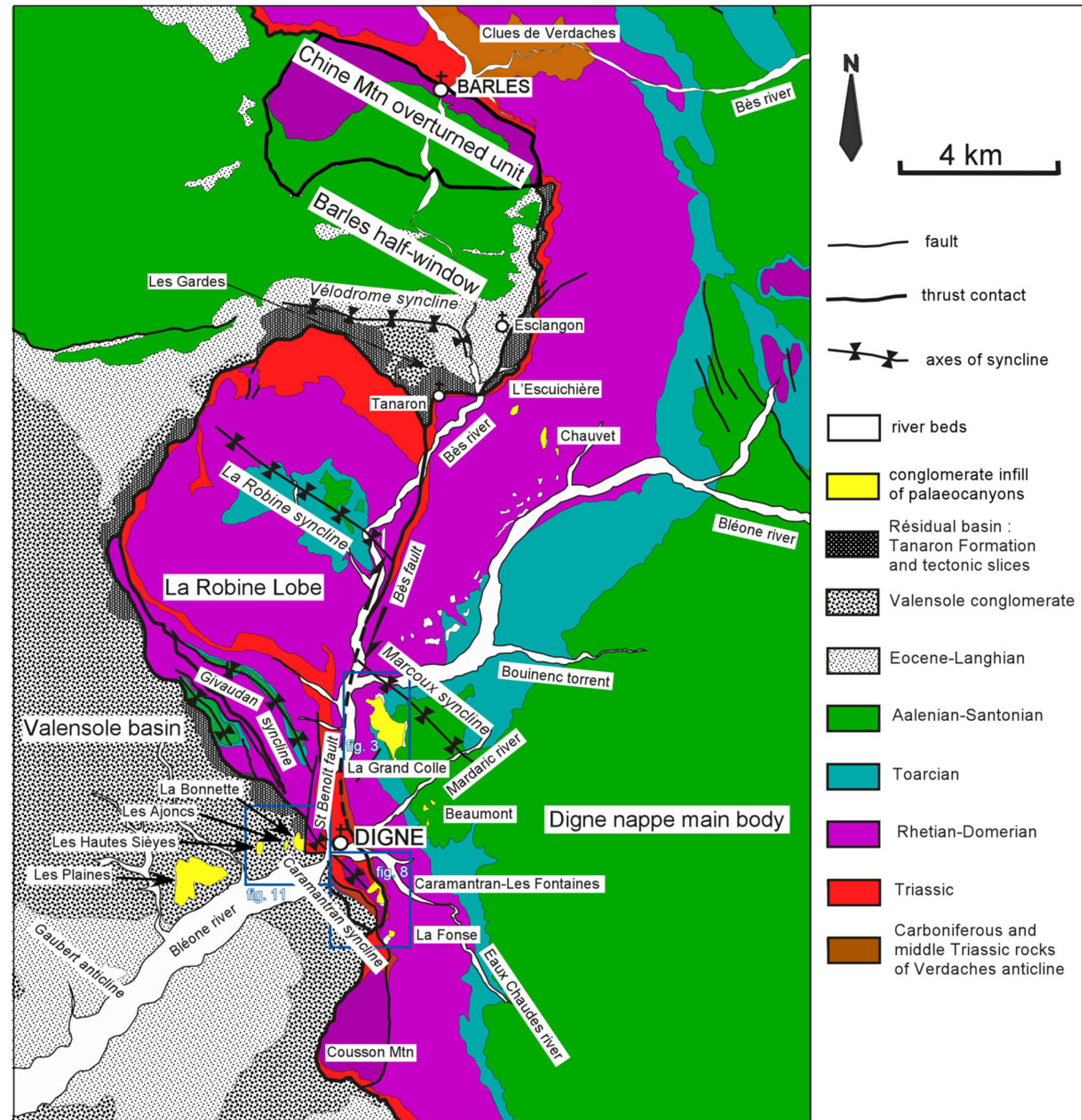
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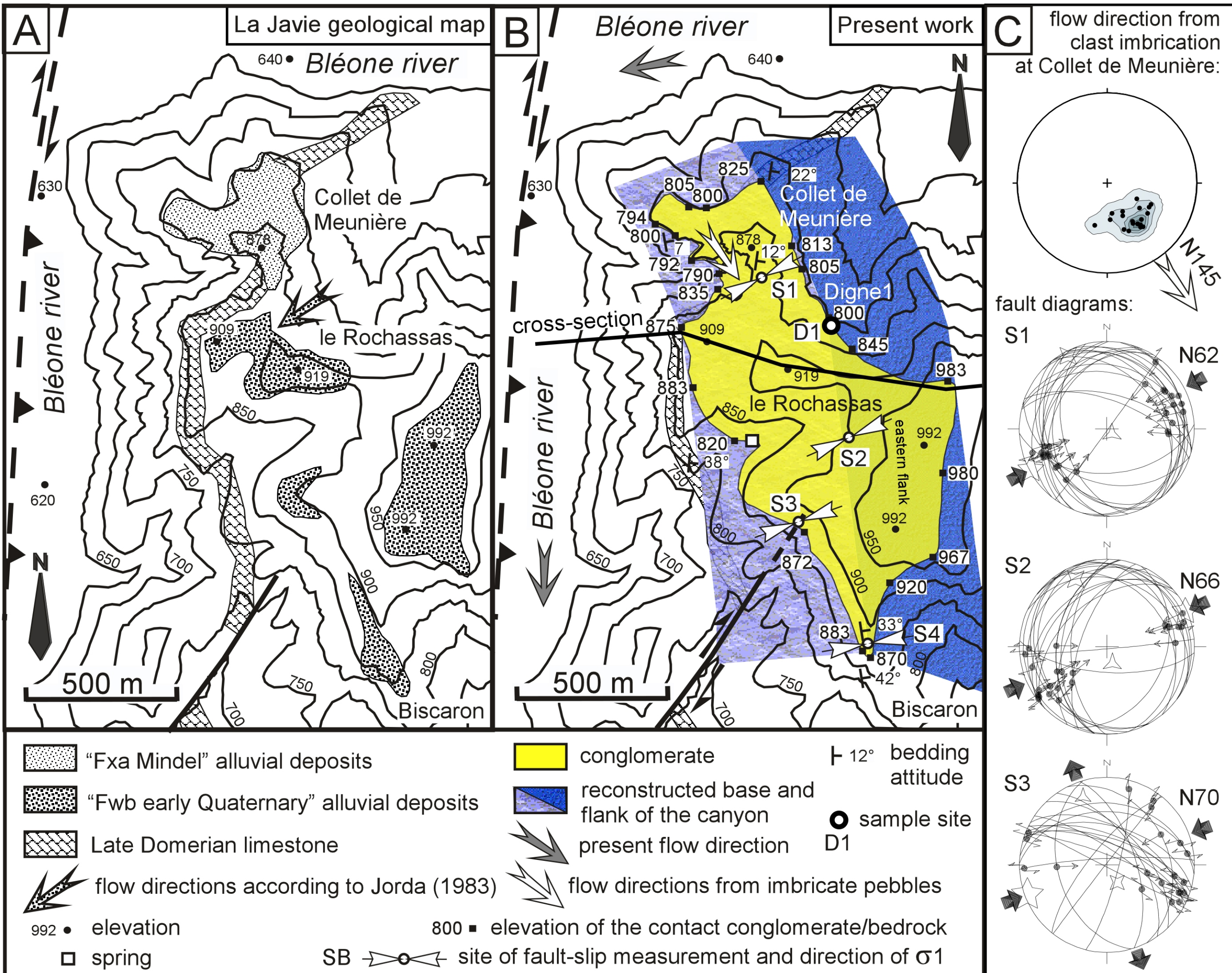
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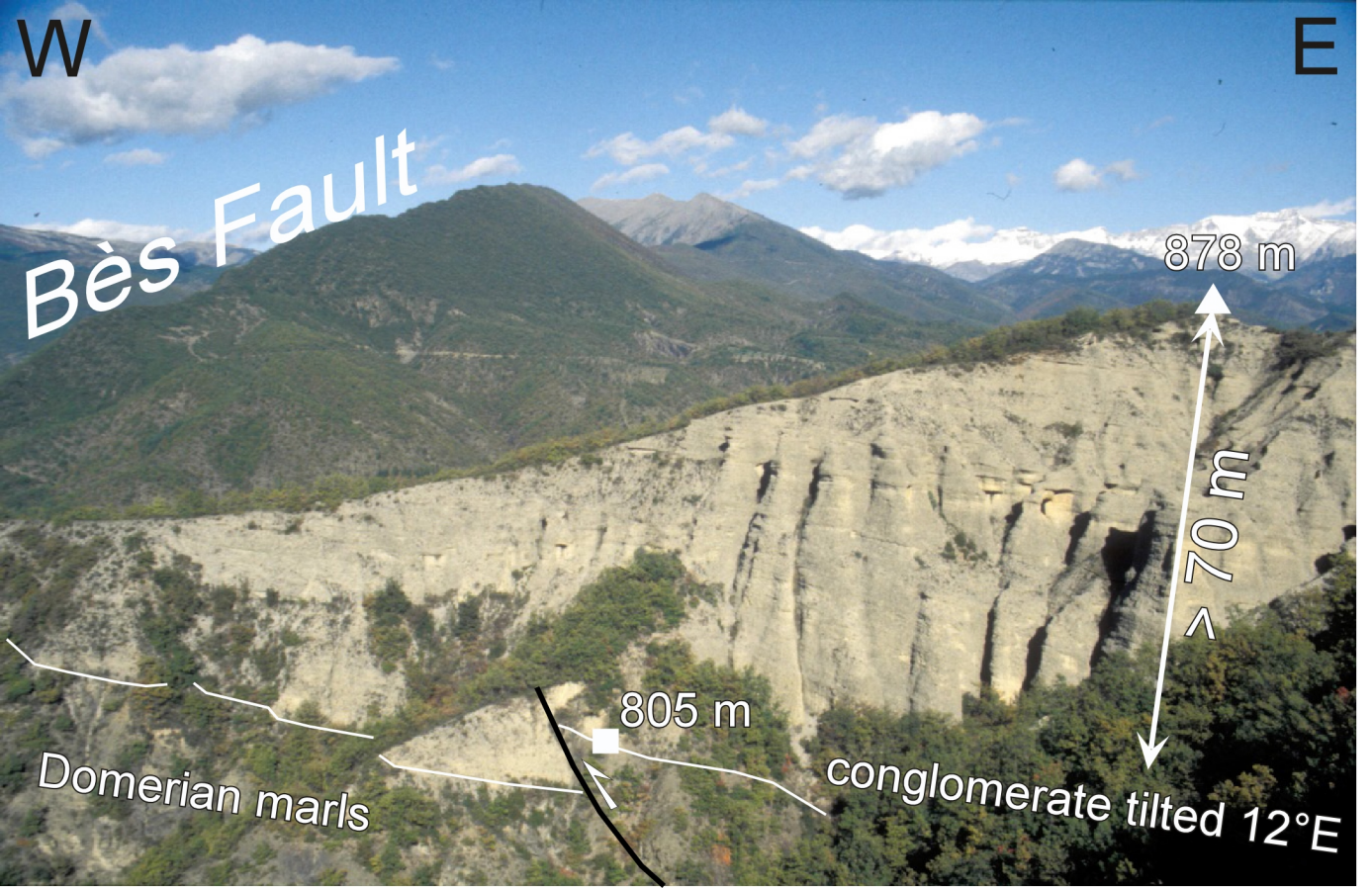
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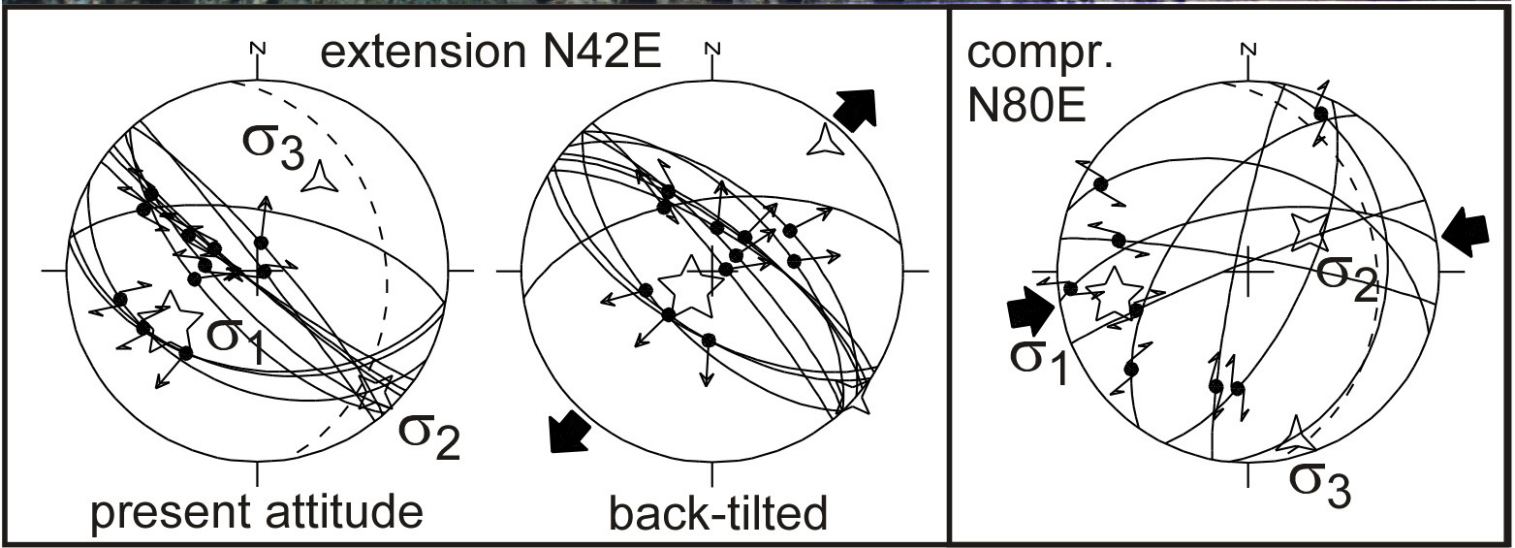
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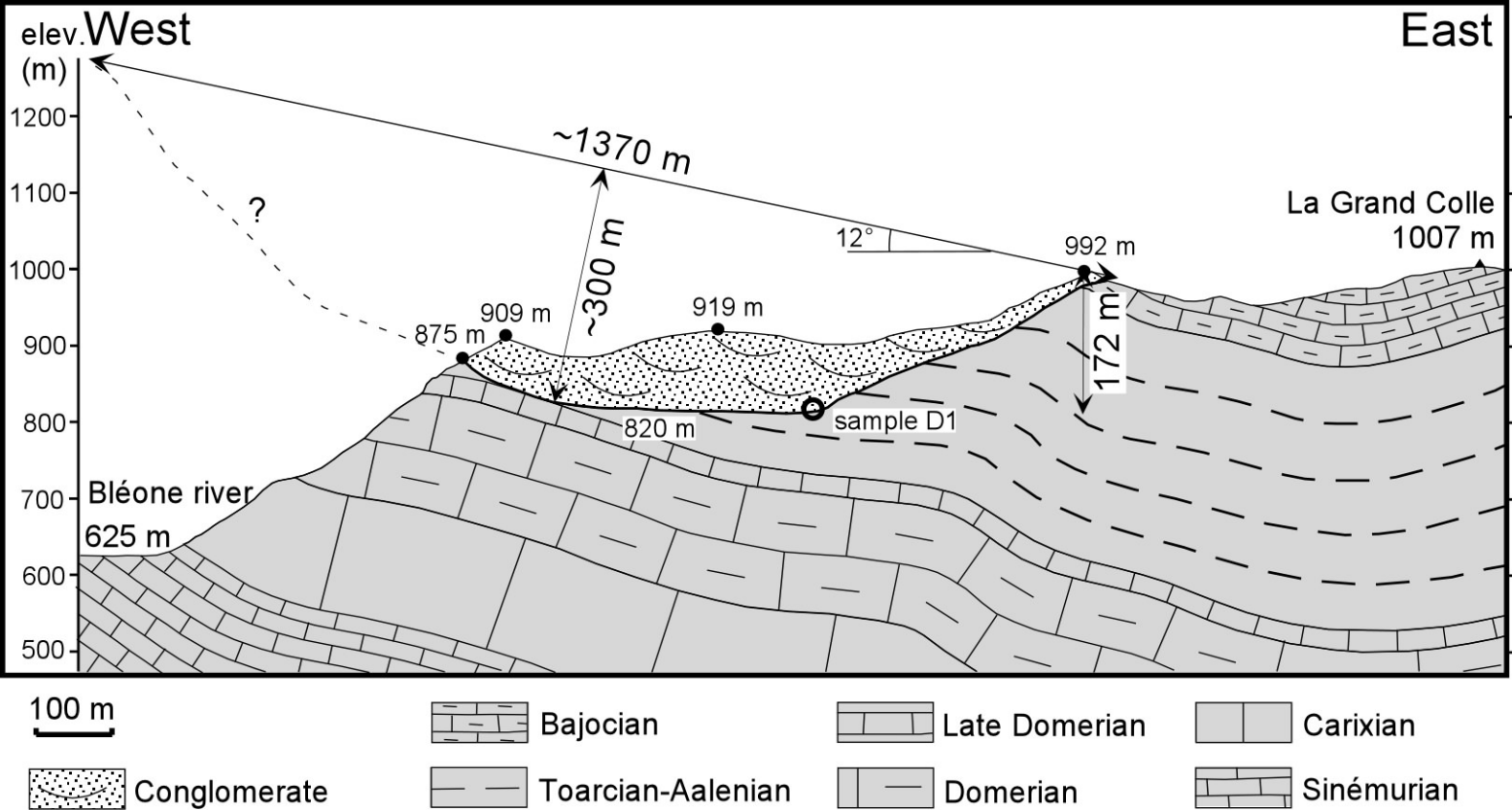


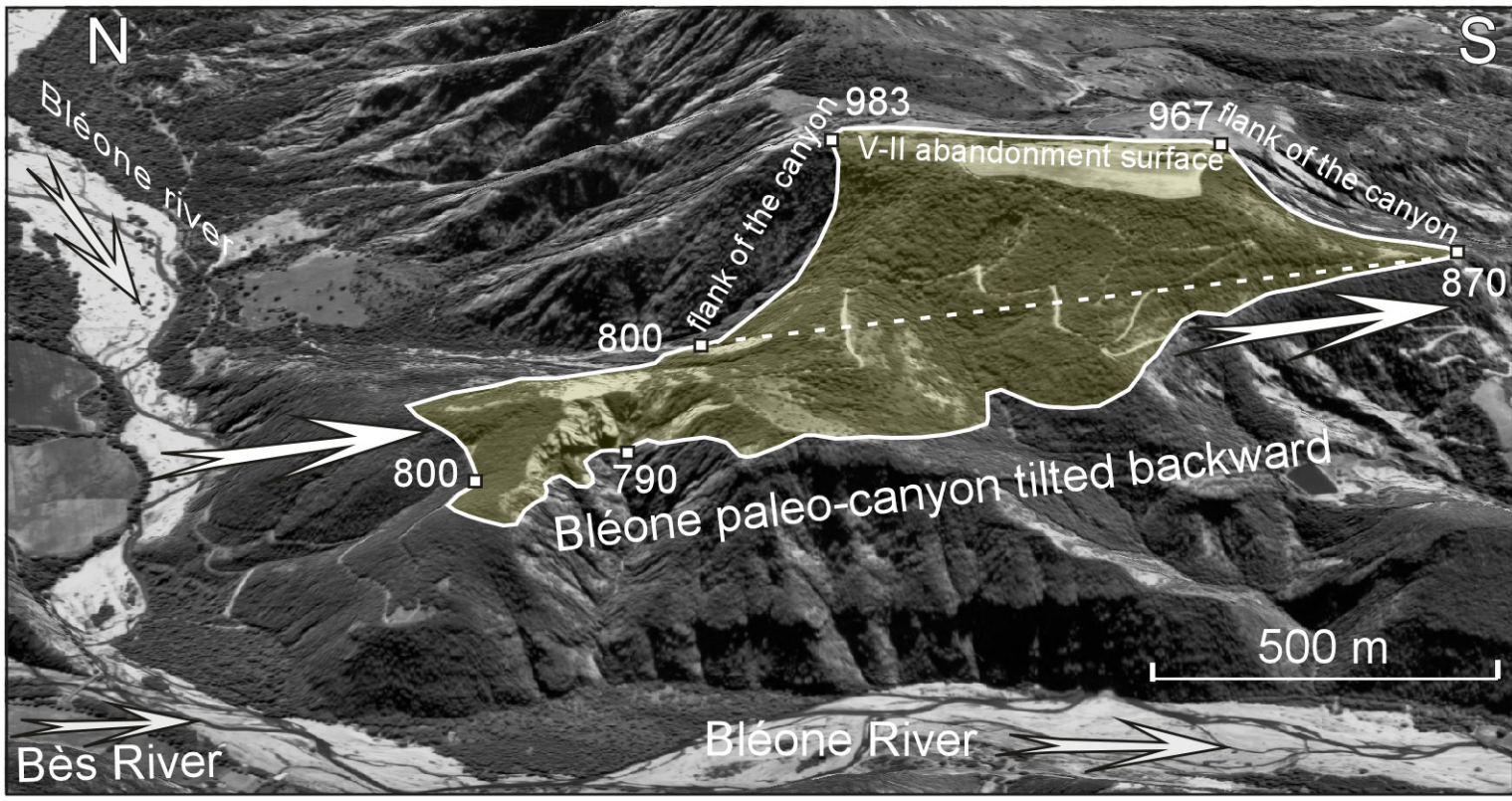


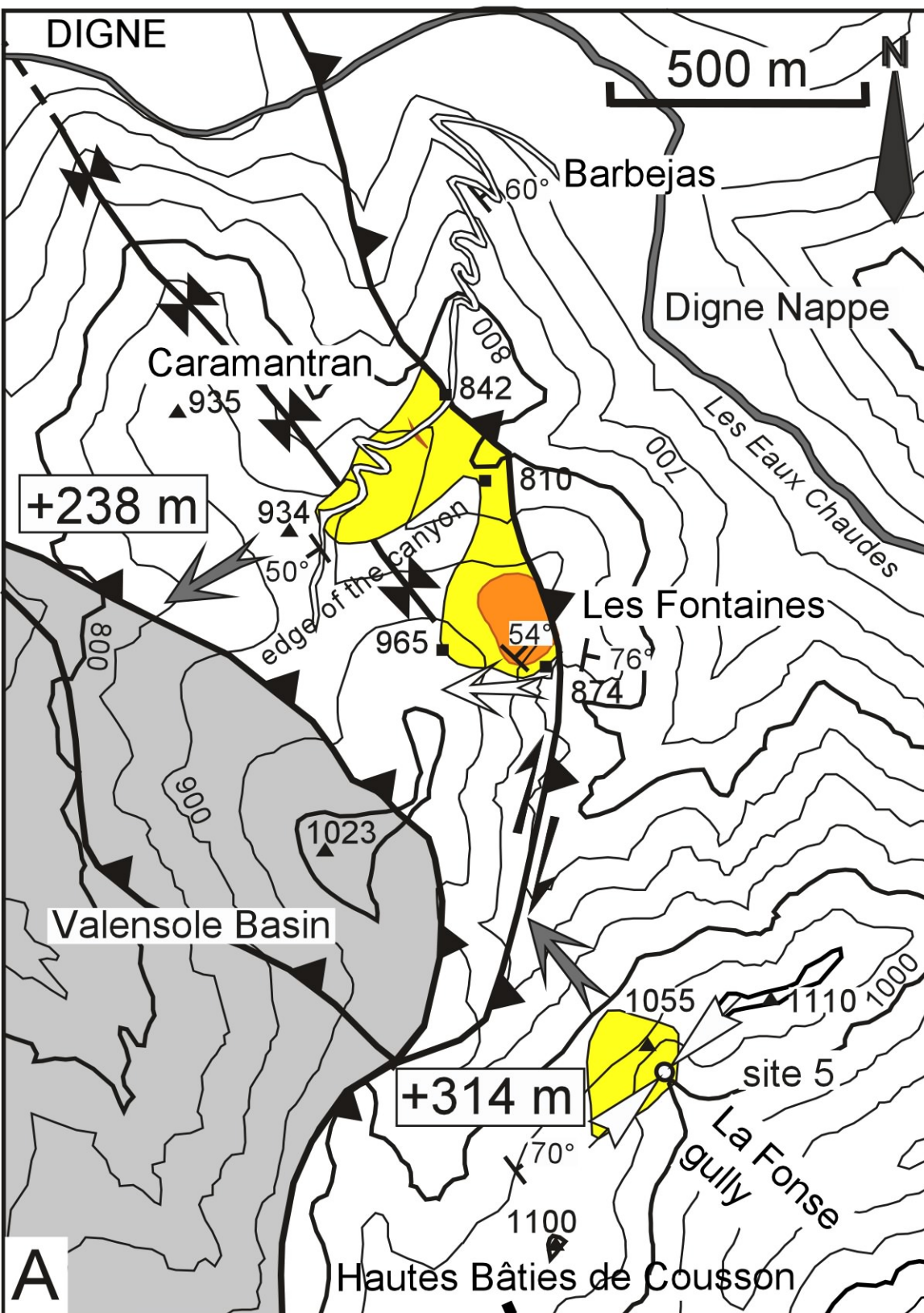






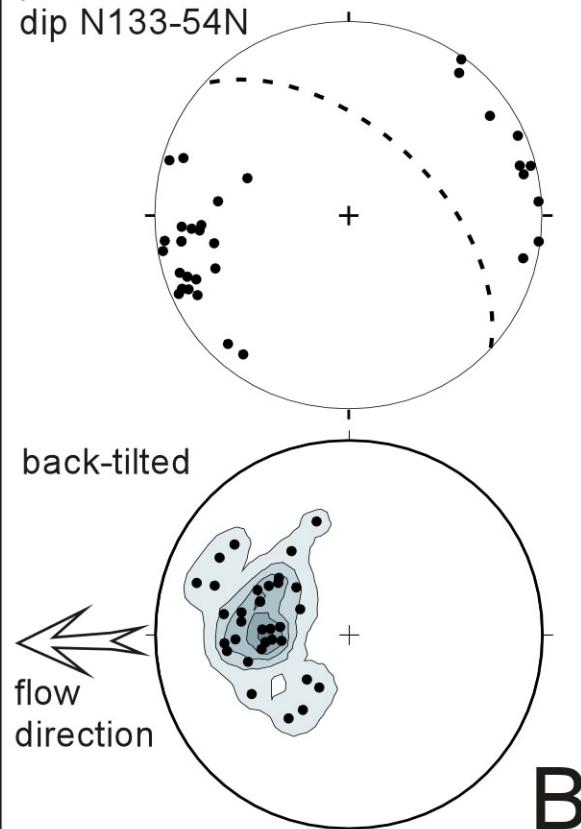




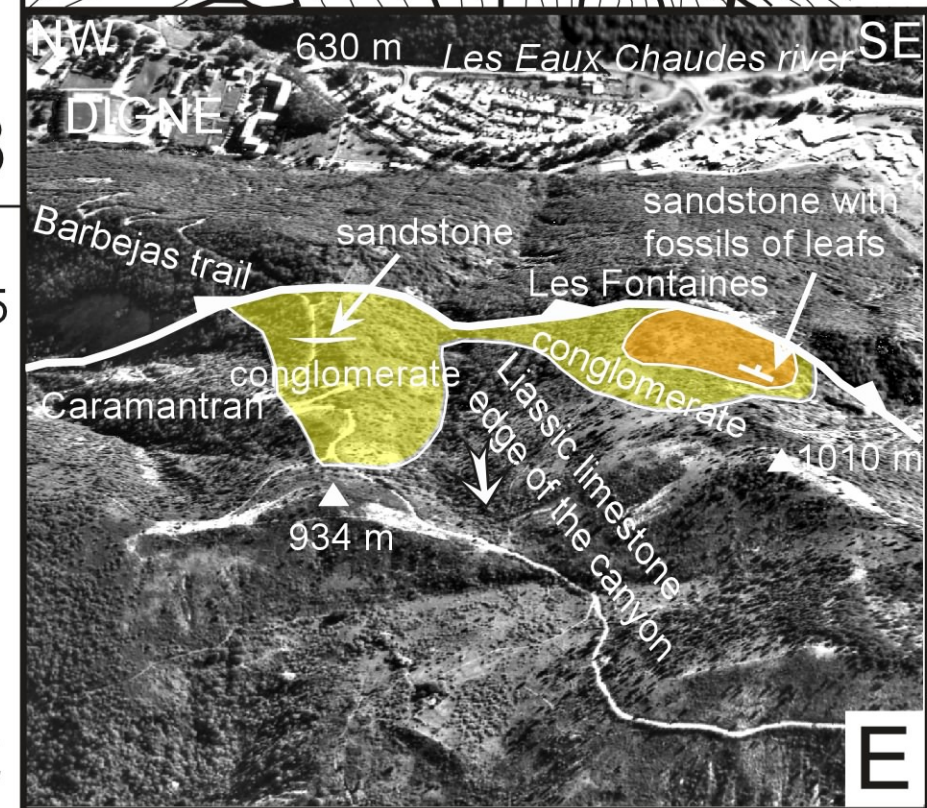
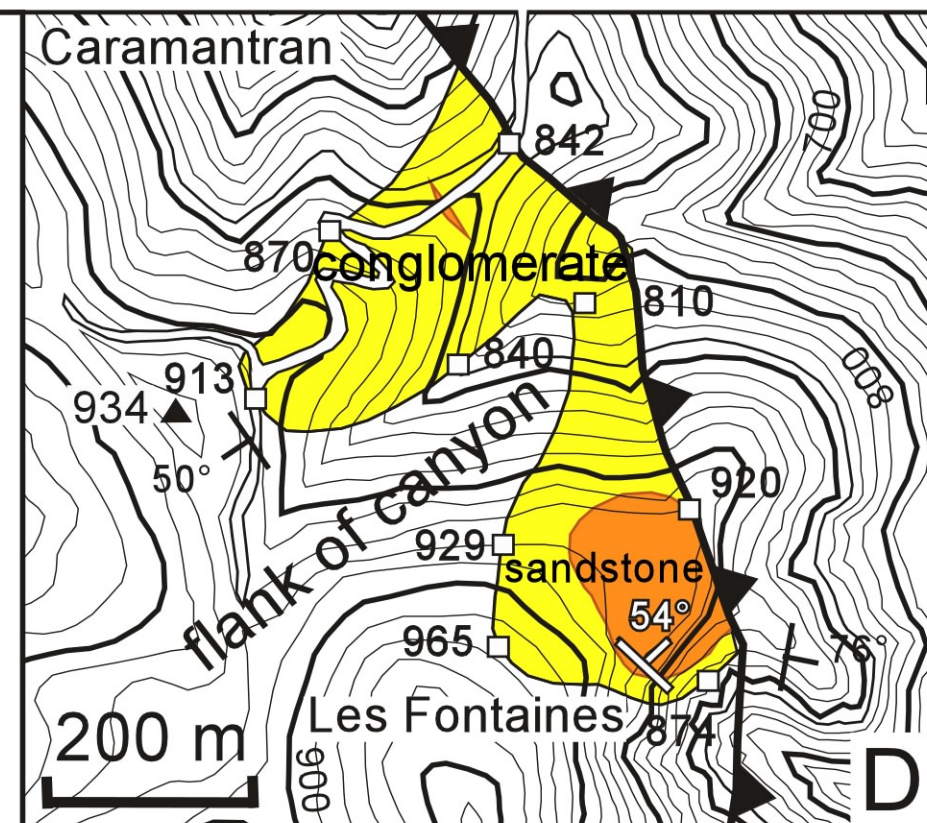
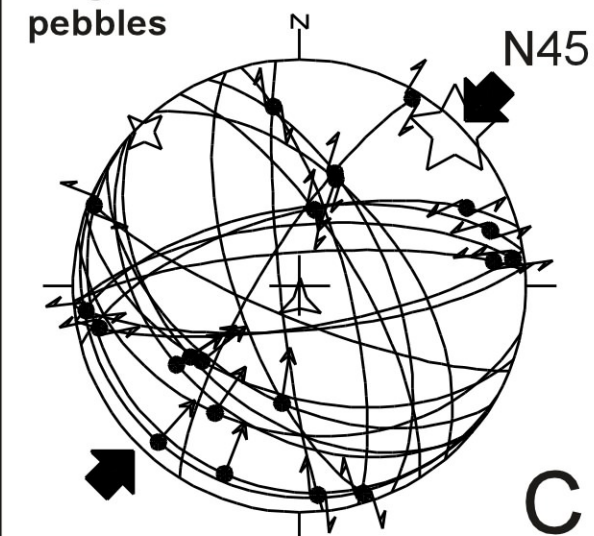


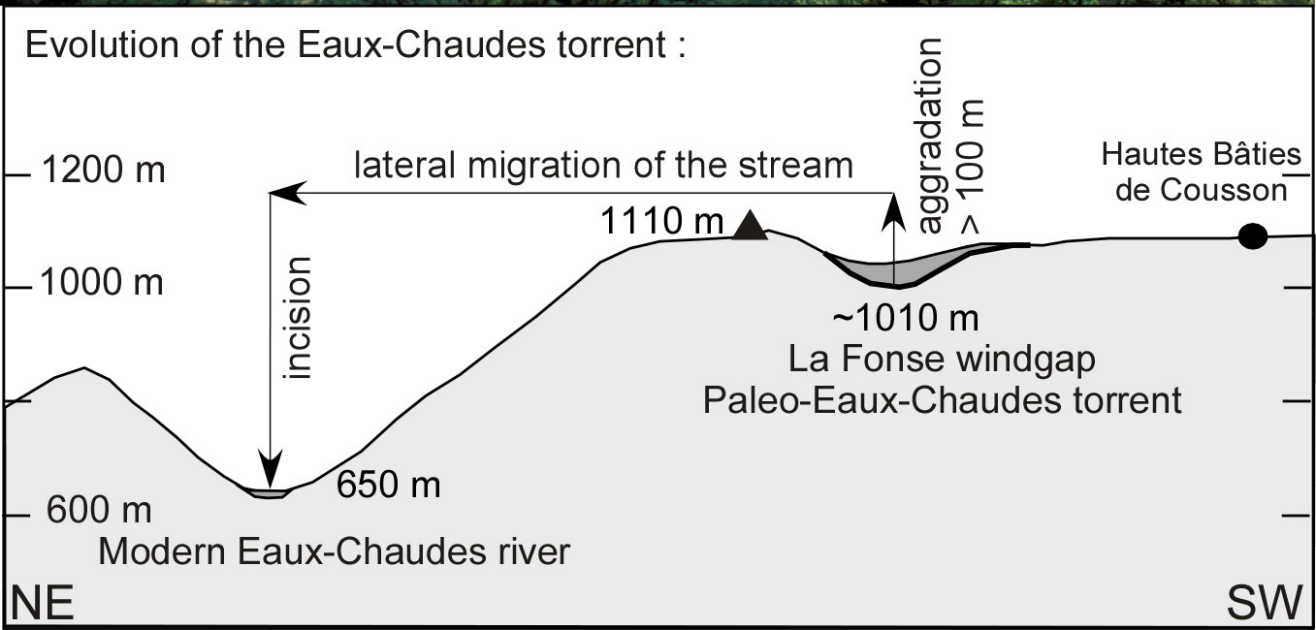
**poles of imbricated pebbles
at site Les Fontaines**

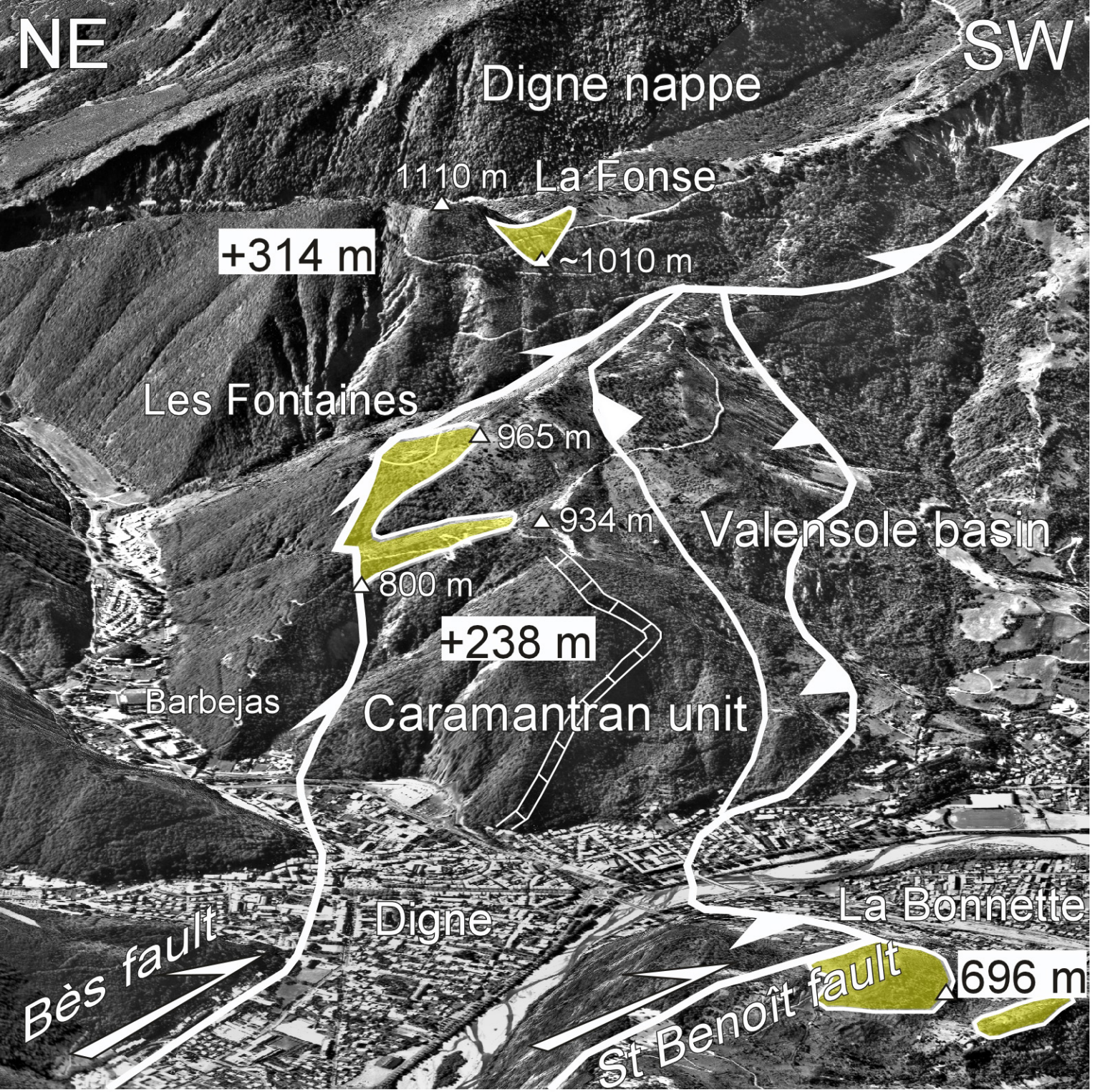
present attitude:
dip N133-54N

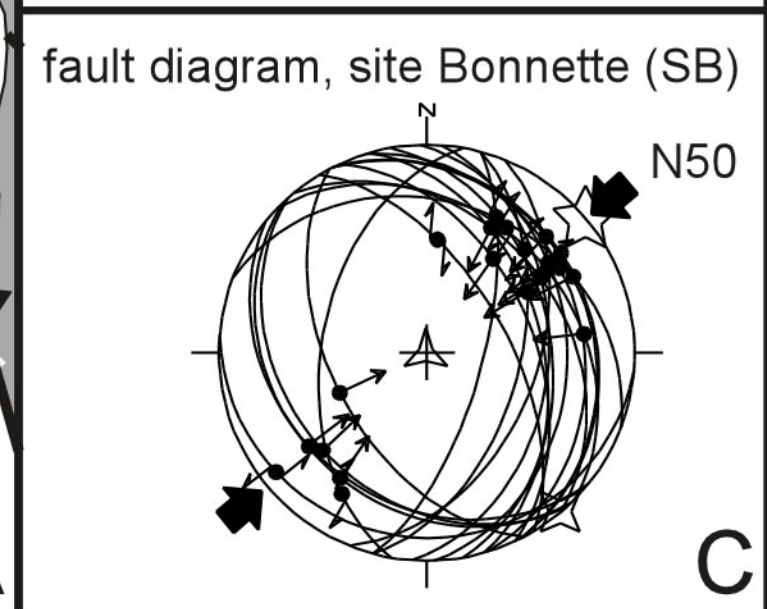
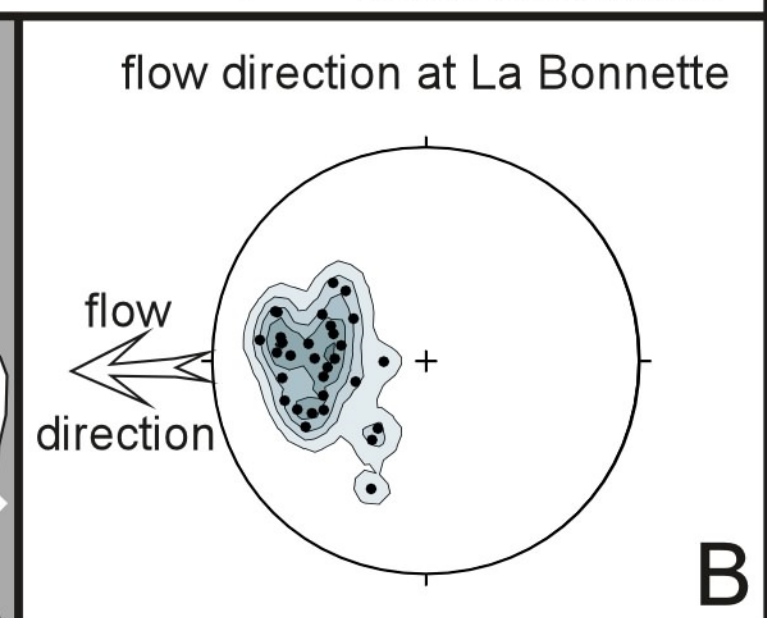
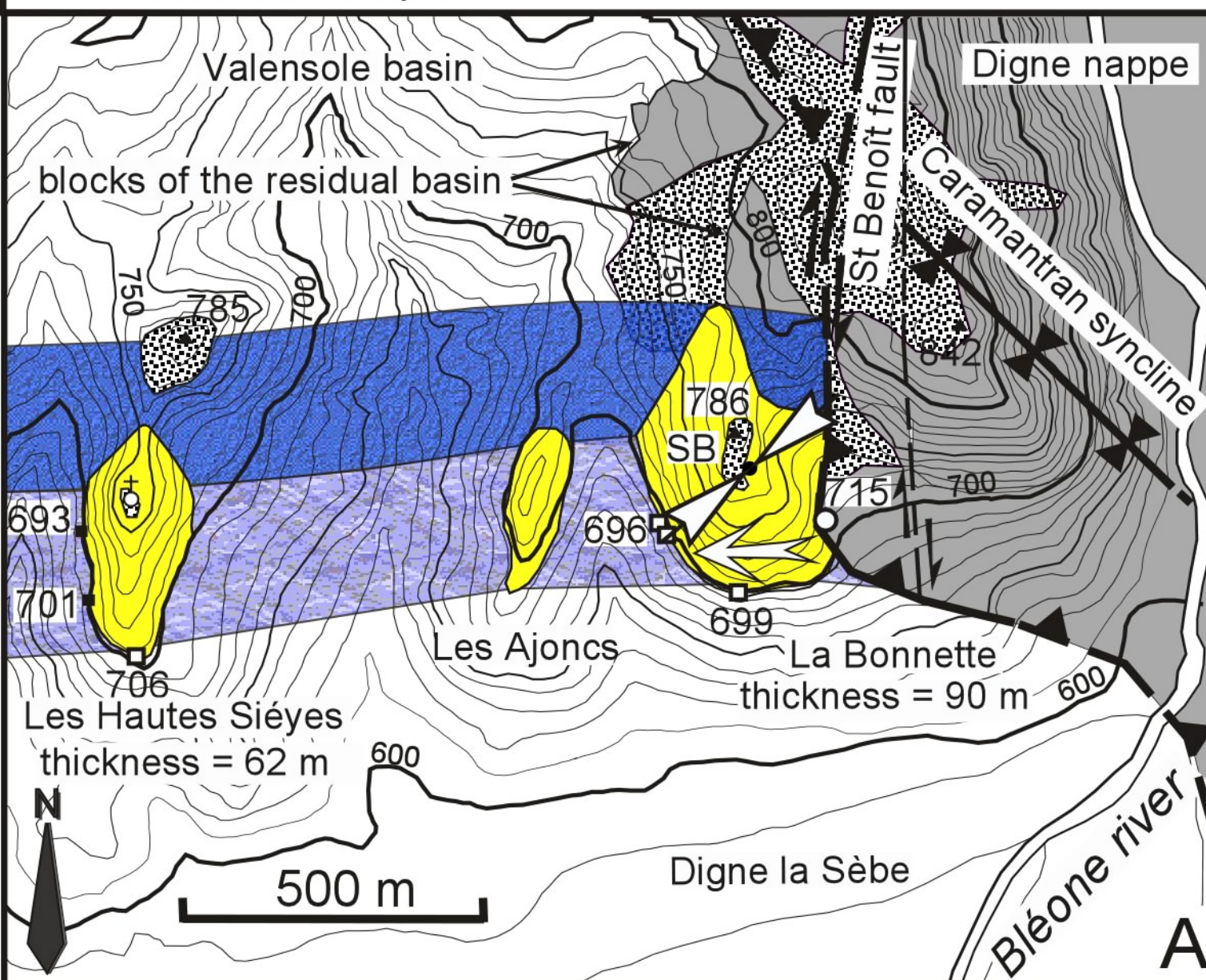
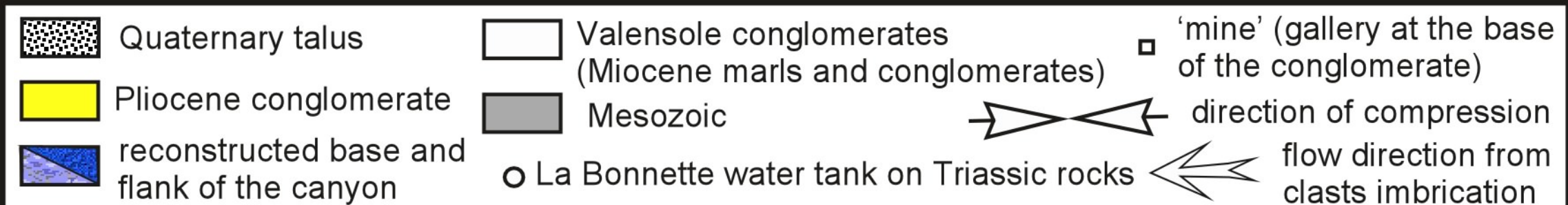


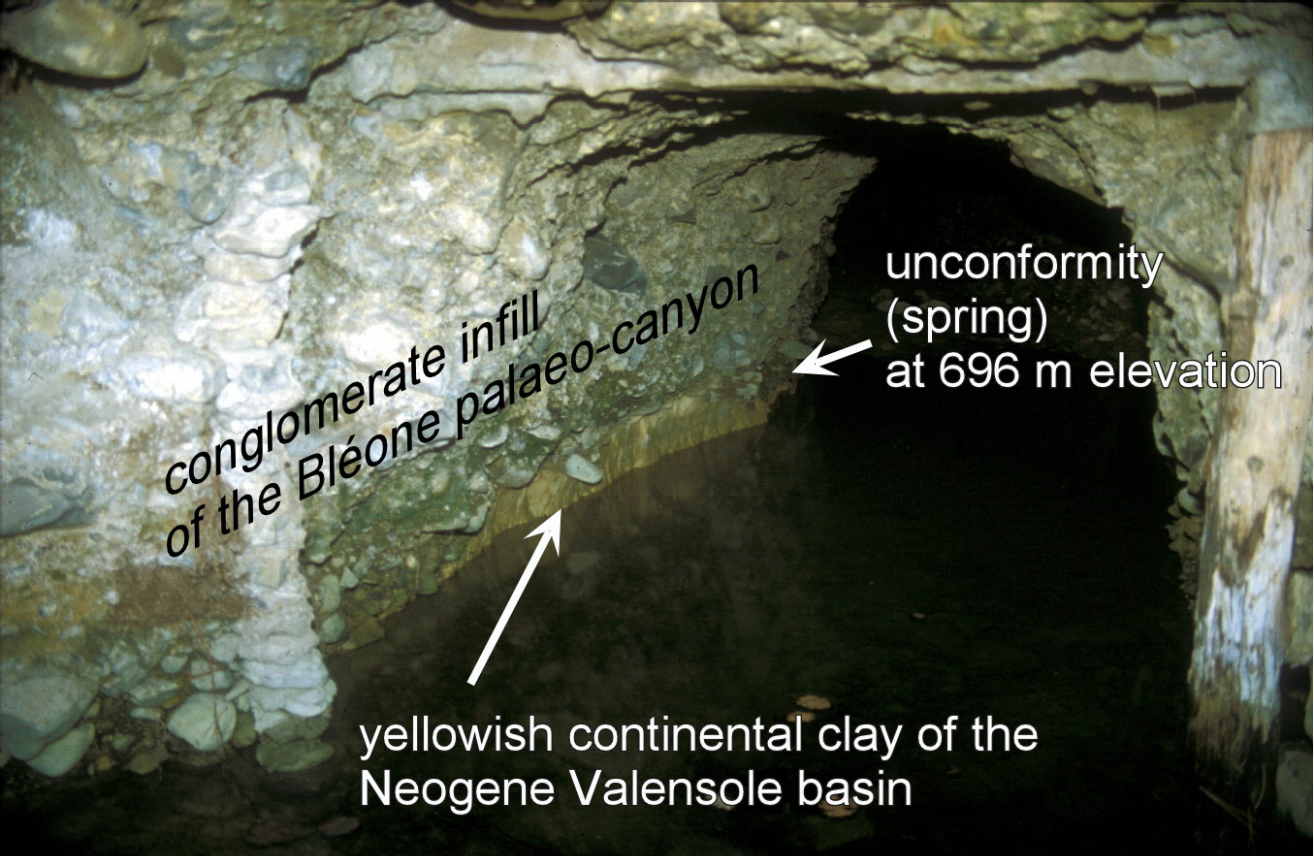
**Diagram of La Fosse striated
pebbles**











conglomerate infill
of the Bléone palaeo-canyon

unconformity
(spring)
at 696 m elevation

yellowish continental clay of the
Neogene Valensole basin

NW

SE

Quaternary talus

Digne Nappe

Digne

755 m

La Bonnette
conglomerate

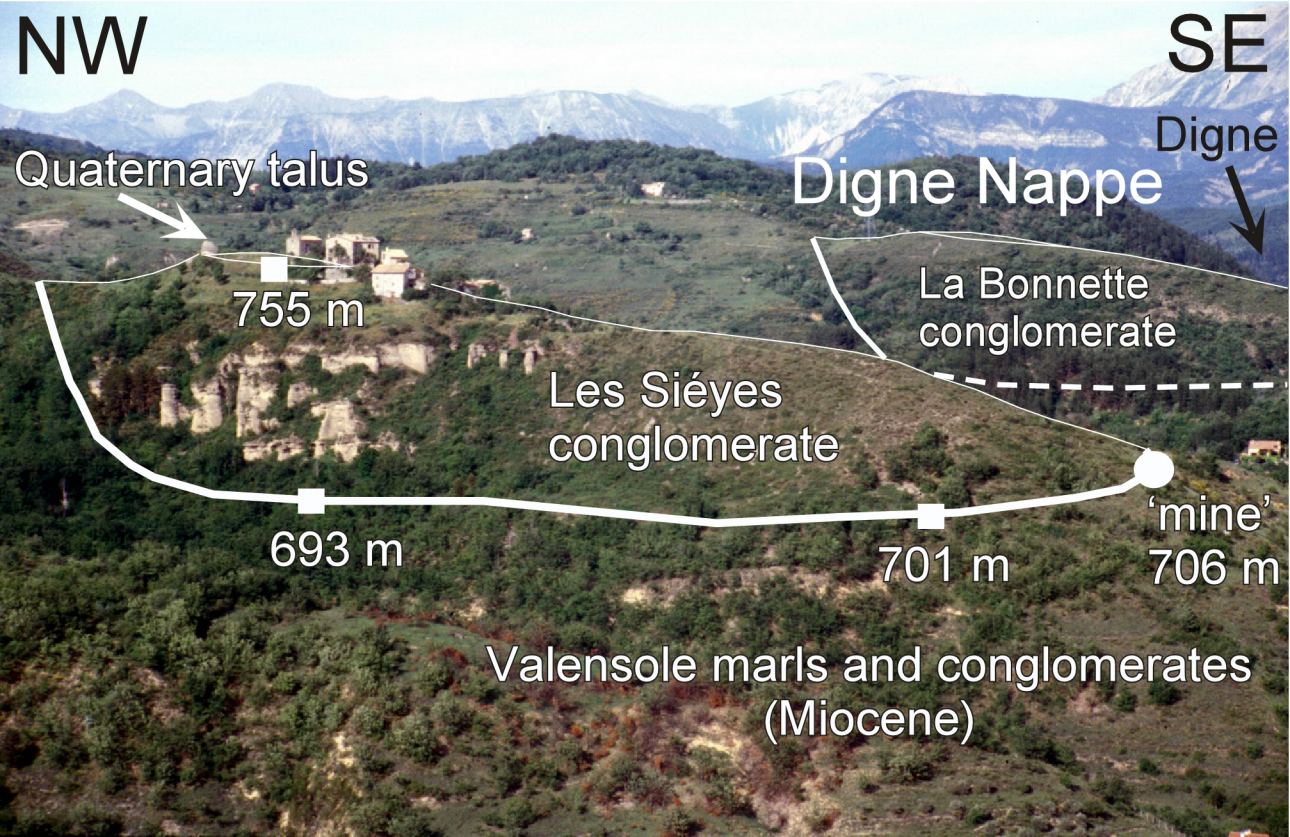
Les Siéyes
conglomerate

693 m

701 m

'mine'
706 m

Valensole marls and conglomerates
(Miocene)



Hautes Sieyes
conglomerate

786 m

La Bonnette
conglomerate

'mine'
at 699 m

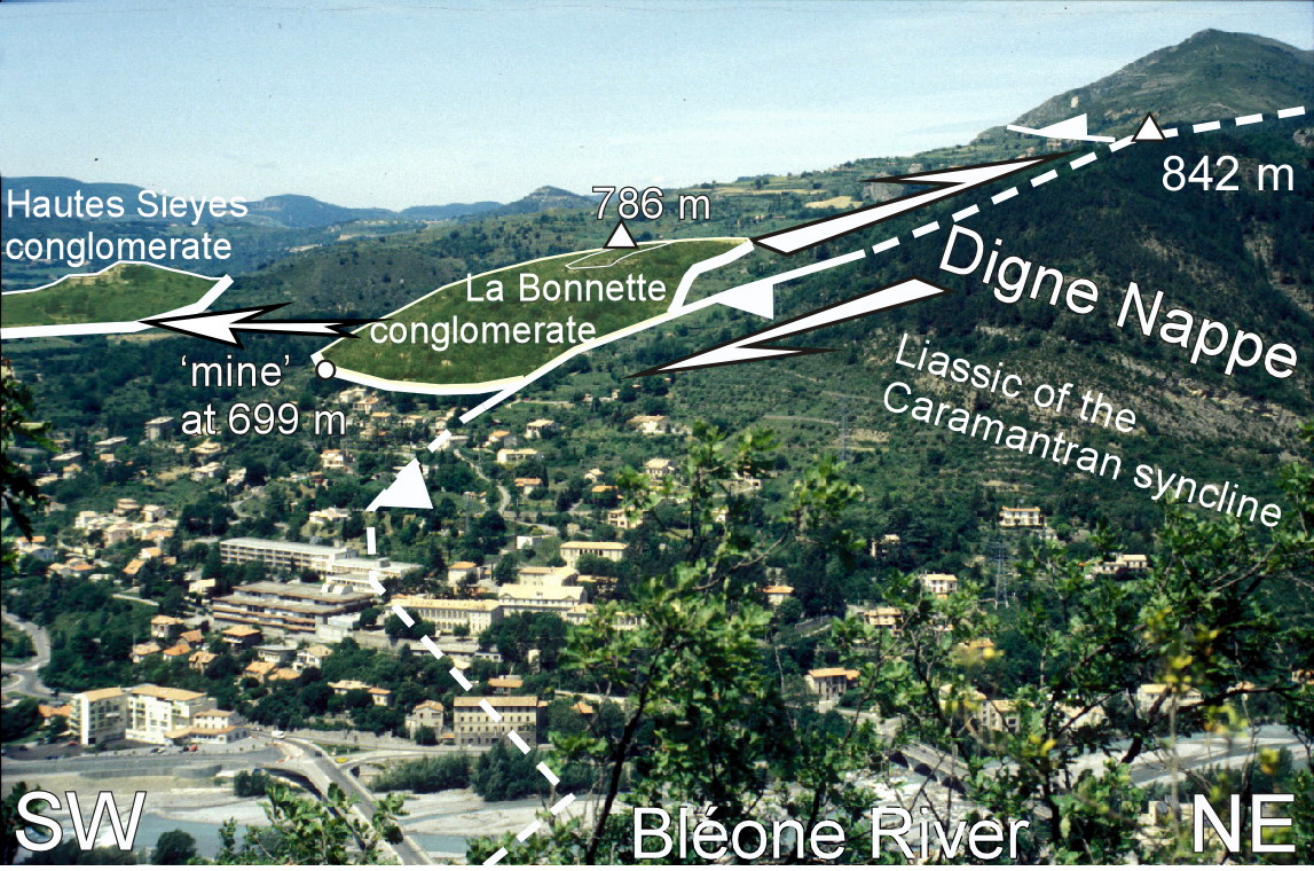
842 m

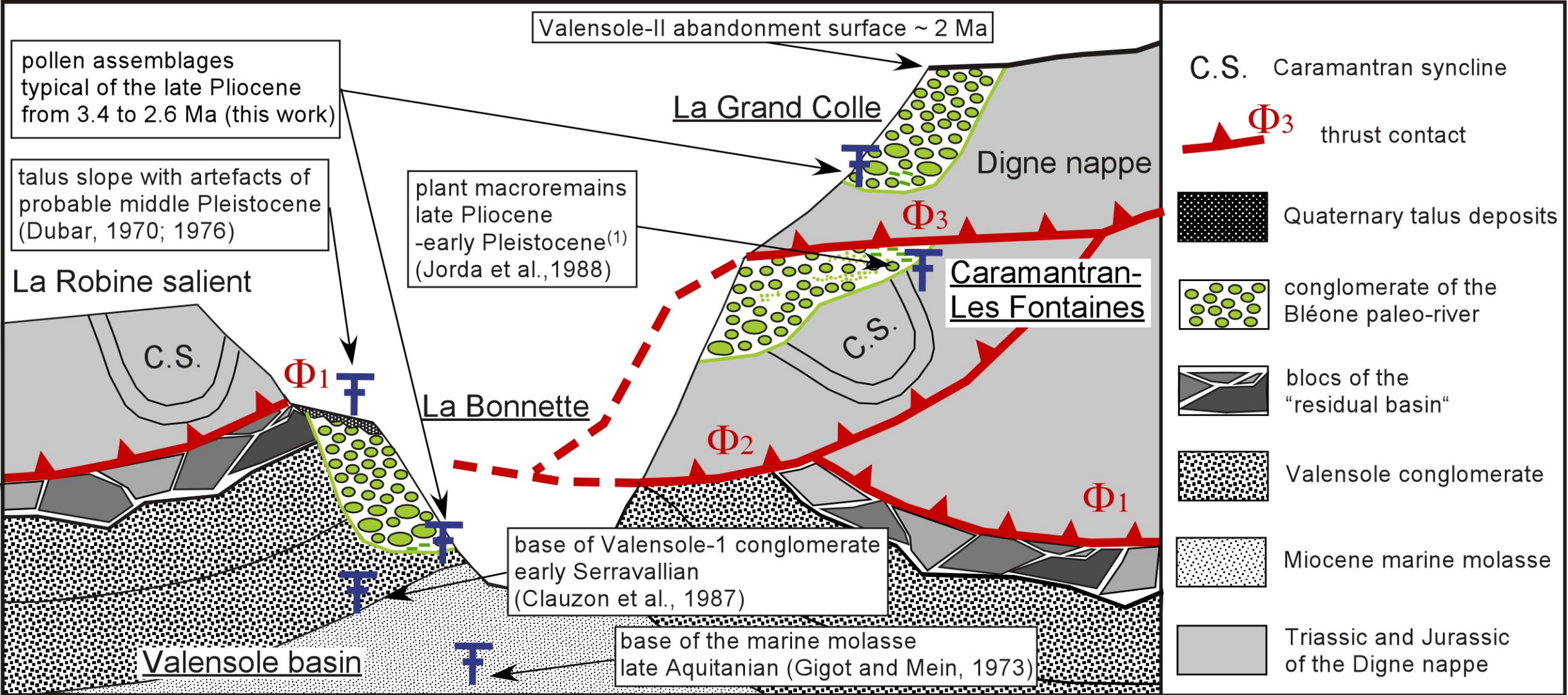
Digne Nappe
Liassic of the
Caramantran syncline

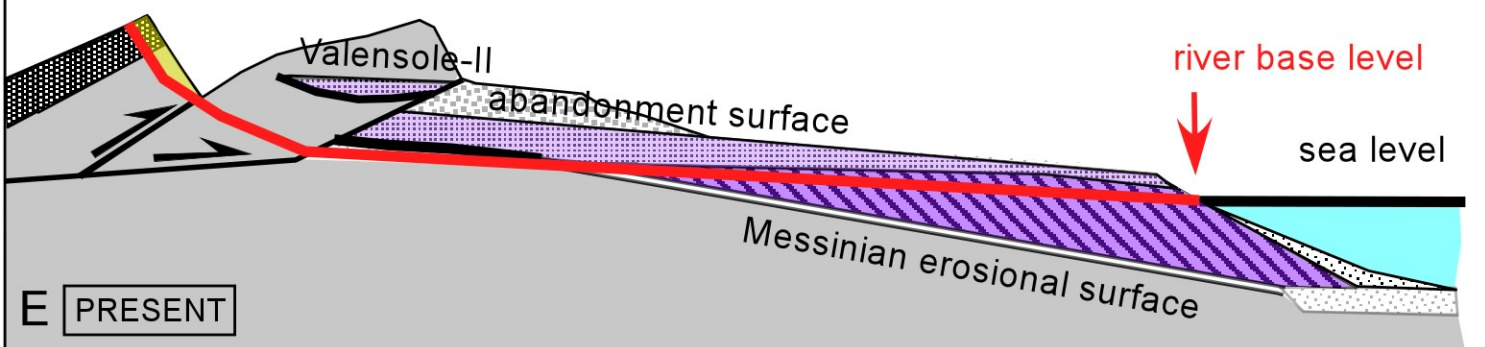
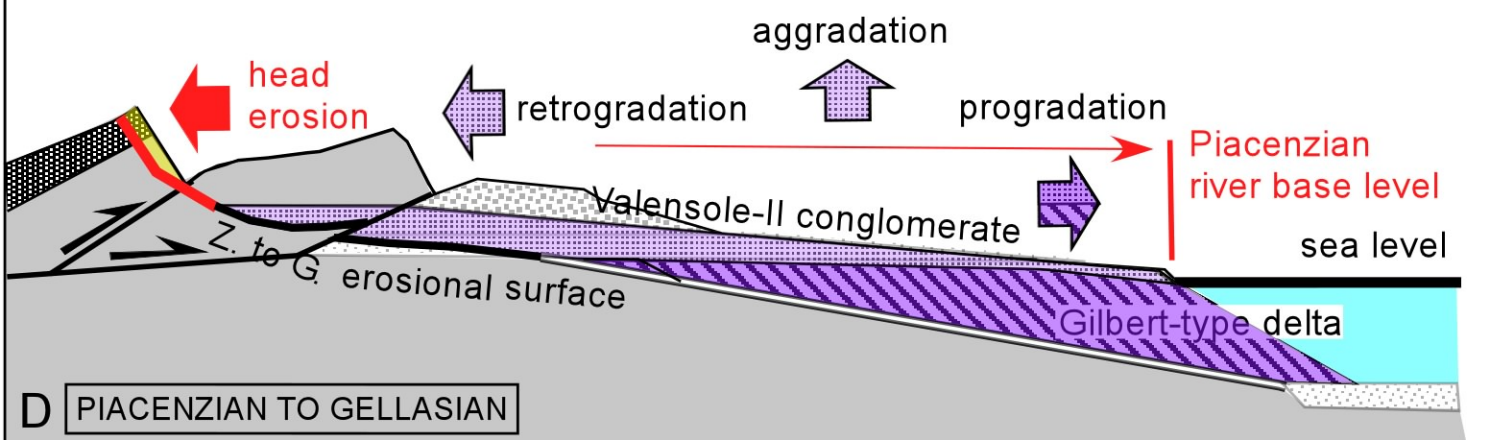
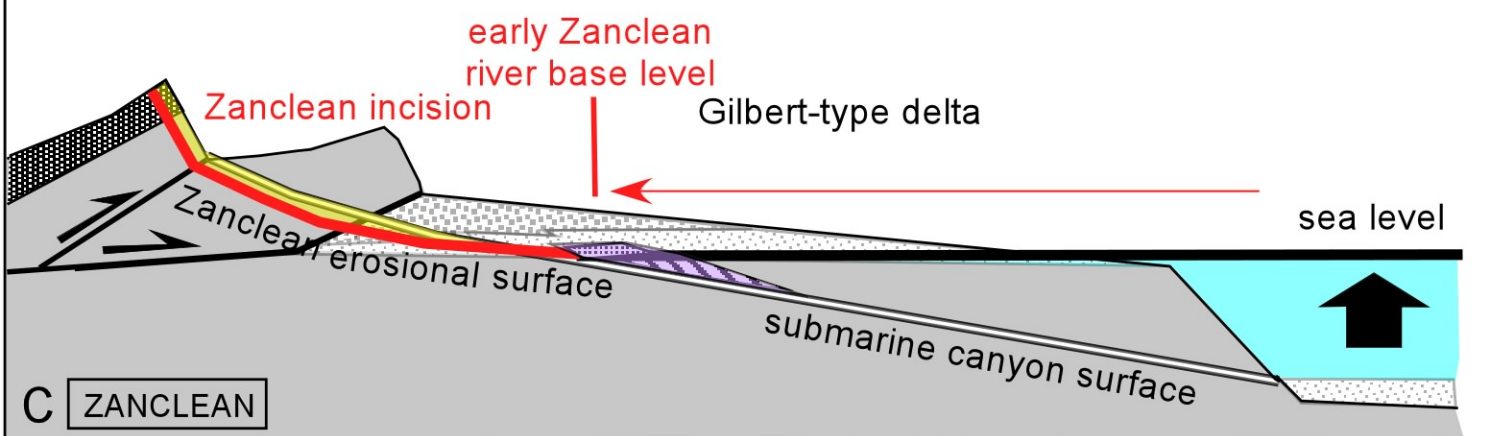
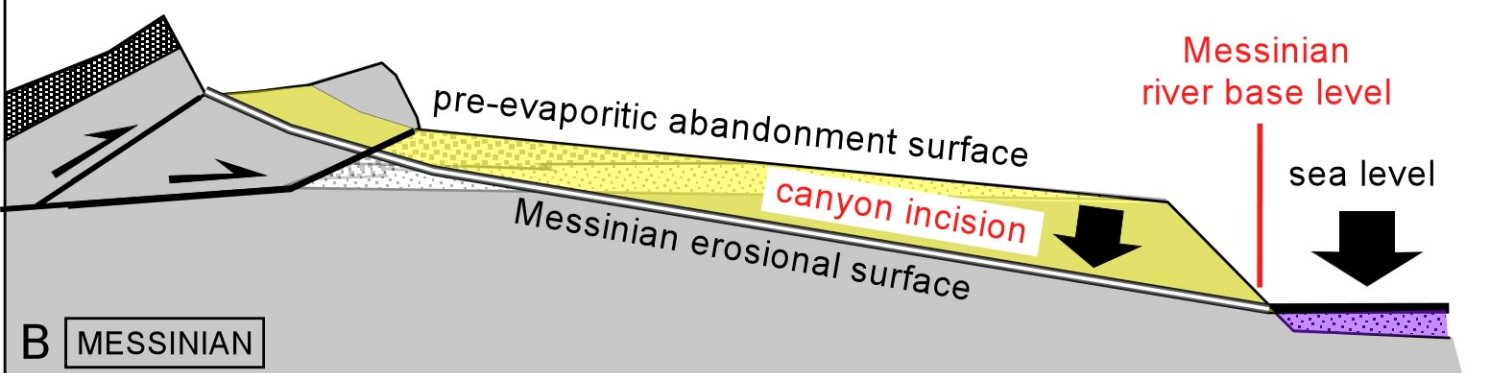
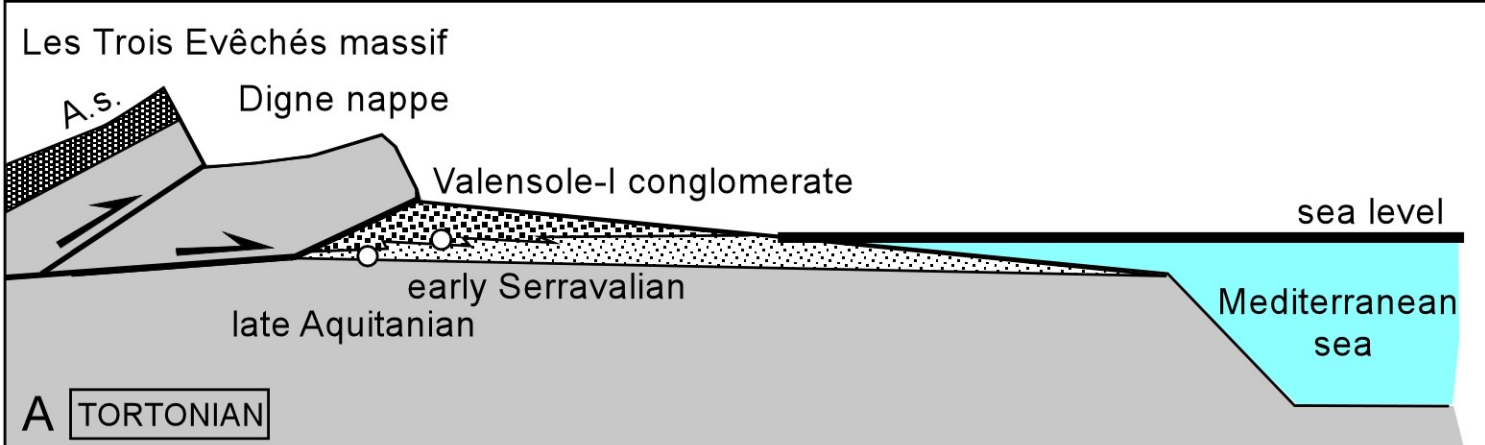
SW

Bléone River

NE







NE

Les Plaines

SW

conglomerate

■
702 m

Neogene sandy clays
of the Valensole Basin

1326 m Escuichière windgap

126 m

1242 m

~1200 m

Paleo-Bès canyon
and conglomerate

Paleo-Bléone conglomerate at Chauvet

