



The peri-Alpine Paleogene Red Molasse of southeastern France - I. Esparron syncline and Esclangon area (Alpes-de-Haute-Provence)

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Abstract: The Paleogene succession of the Esparron syncline consists of three superimposed stratigraphic units, in ascending order: (1) a lacustrine-palustrine-dominated basal unit (BU) bearing channels filled by limestone breccias at base, (2) fluvial deposits of the lower Molasse Rouge Formation (MR1), and (3) well-rounded polygenic conglomerates, bearing Alpine "green rocks" and radiolarites overlain by red clays in the upper Molasse Rouge Formation (MR2).

Breccia deposits of the basal unit represent a multi-channeled torrential system generally sloping to the northeast. However, the regional extent and character of the BU is difficult to determine due to its truncation by the basal surface of MR1. Around the northwestern termination of the Esparron syncline the succession is complete and 200 m thick. Basal breccias of the BU pass upward to reddish fluvial overbank mudstones, then to grayish lacustrine-palustrine limestones, and back to reddish silty claystones. Field data suggest that this unit cannot be proximal deposits of the "Nummulitic foreland basin", but is younger, just predating deposition of the MR1, likely in the late Rupelian. These also cannot be proximal deposits of MR1, as formerly suggested. They constitute a fully distinct tectono-stratigraphic sequence whose deposition cannot be understood without a broad regional synthesis (in preparation). Along the southern flank of the syncline, MR1 has a sheet geometry featuring amalgamated fluvial point bar deposits at the base, which are overlain by the deposits of a large fluvial fan prograding to the west. MR1 deposits abruptly pinch out along the northern flank of the syncline, and are interpreted as having filled a paleovalley that roughly matches the E-W orientation of the syncline.

South of the syncline, in the Esclangon and Hautes Duges areas, the same succession is found but the meandering fluvial deposits of Esparron are lacking at the base of MR1. Here, MR1 deposits are represented by fluvial fan deposits prograding to the west, but have a more proximal character than at Esparron. In this area, the MR1 unit is capped by the Molasse Grise (MG), which represents a flattening of the depositional profile after the progradation of the underlying fluvial fan.

Across the entire region, MR2 deposits are thin, and likely truncated by the main Digne thrust. They are deposited disconformably on top of either MR1 or directly on folded Mesozoic deposits, suggesting that erosion and tectonic activity occurred between deposition of MR1 and MR2. The occurrence of well-rounded pebbles of Alpine "green rocks" and radiolarites in the basal fluvial conglomerate of MR2 indicates that the system had a large watershed that encroached the inner Alps, probably during uplift of the latter.

In the Ainac area, the braided fluvial facies at the base of MR2 acquired a more distal character with channels filled by either conglomerates or a more sand-prone facies.

The vertical facies trend in MR1 and MR2 suggests that a low-gradient fluvial setting was followed by regional uplift responsible for the progradation of fluvial fans. The two stratigraphic units are therefore regarded as tectono-stratigraphic sequences, in response to changes in the Alpine stress regime. With unit 1 (BU), the Molasse Rouge is therefore composed of three independent sequences.

Finally, the ages of the MR1 and MR2 deposits are revised, both to Chattian and probably not extending into the Aquitanian, as previously reported for the MR2.

Geometric relationships suggest that the three continental Paleogene sequences record a changing depositional setting controlled by both active tectonics and intervening periods of quiescence in a time interval grossly bracketing the late Rupelian and the Chattian.

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Résumé : Les molasses rouges paléogènes péri-alpines du Sud-Est de la France - I. Synclinal d'Esparron et secteur d'Esclangon (Alpes-de-Haute-Provence).- La série paléogène du synclinal d'Esparron comprend trois unités stratigraphiques superposées : (1) une unité basale (UB), lacustre à palustre, débutant par des chenaux remplis de brèches calcaires, (2) les dépôts fluviatiles d'une molasse rouge inférieure (MR1), et (3) des conglomérats polygéniques à éléments alpins ("roches vertes" et radiolarites) surmontés par des argiles rouges constituant ensemble une molasse rouge supérieure (MR2). Les brèches de l'unité basale représentent un système de cônes torrentiels parallèles, pentés vers le nord-est. L'extension régionale de l'unité basale ainsi que sa signification tectono-stratigraphique sont difficiles à discerner en raison de sa troncature par la surface de base de la MR1. Dans la terminaison NW du synclinal, la succession est complète, épaisse de 200 m. Les brèches de base passent verticalement à des dépôts argilo-gréseux rouges de débordement puis à des calcaires gris lacustres à palustres, surmontés à nouveau par des argiles silteuses rouges. Les données de terrain excluent que cette unité puisse représenter le faciès proximal occidental du bassin nummulitique d'avant-chaîne. Elle est plus récente et constitue une unité juste antérieure au dépôt de la MR1. Elle ne peut non plus être considérée, comme on l'a parfois proposé, comme un faciès proximal de la MR1 car il s'agit d'une séquence tectono-stratigraphique à part entière mais dont la signification ne peut-être comprise que par une étude régionale plus vaste à venir.

Le long du flanc sud du synclinal, la MR1 est constituée d'une succession latéralement continue comportant un ensemble de barres de méandres emboîtées à la base, surmonté par les dépôts d'un vaste cône fluviatile progradant vers l'ouest. Les dépôts de la MR1 se pincent rapidement sur le flanc nord du synclinal, suggérant qu'ils ont rempli une vallée dont l'orientation coïncide à peu près avec celle du synclinal.

Au sud d'Esparron, dans le secteur des Haute-Duyes et d'Esclangon, une série semblable se retrouve mais le faciès méandrique manque à la base de la MR1. La MR1 est ici représentée par un faciès de cône fluviatile mais qui présente un caractère plus proximal qu'à Esparron. Dans ce secteur, la MR1 est surmontée par une molasse grise (MG) qui représente un aplatissement du profil général de dépôt après la mise en place du cône fluviatile progradant.

Sur l'ensemble du secteur, les dépôts de la MR2 sont minces, vraisemblablement en raison d'une troncature par le chevauchement de Digne. Ils reposent discordance sur la MR1, soit directement sur les dépôts mésozoïques plissés, ce qui suggère l'existence d'une phase de déformation et d'érosion entre le dépôt de la MR1 et de la MR2. La présence de galets bien arrondis de "roches vertes" et de radiolarites alpines dans le faciès conglomératique de base de la MR2 indique que ce système de dépôt avait un bassin versant étendu à l'intérieur de la chaîne alpine dont le relief vraisemblablement s'accroissait.

Dans le secteur d'Ainac, le faciès fluviatile en tresses de la base de la MR2 devient un peu plus distal car plus gréseux et moins conglomératique.

L'évolution verticale des faciès, à la fois dans la MR1 et la MR2, suggère qu'un profil de dépôt à faible gradient a été suivi par une augmentation des pentes, conséquence d'un soulèvement tectonique d'ensemble. Les deux unités MR1 et MR2 sont donc considérées comme deux séquences tectono-stratigraphiques successives résultant de changements dans le régime des contraintes alpines. Avec l'unité de base (UB), l'ensemble compréhensif des molasses rouges comporte donc trois séquences indépendantes. Enfin, l'âge des dépôts de la MR1 et de la MR2 sont révisés, toutes deux d'âge chattien et non partiellement aquitain pour la MR2, comme autrefois supposé.

Les relations géométriques d'ensemble suggèrent que les trois séquences continentales paléogènes enregistrent les changements du relief contrôlés par des pulsations tectoniques séparées par des phases de quiescence couvrant le Rupélien terminal (UB) et l'ensemble du Chattien (MR1, MR2).

Mots-clefs :

- molasse ;
- Rupélien ;
- Chattien ;
- Alpes ;
- France

1. Introduction

The sedimentary succession of foreland basins records the dynamic interactions between tectonic drivers and surface processes during orogenesis (CRAMPTON & ALLEN, 1995; DECELLES & GILES, 1996). The arcuate shape of the Western Alps resulted from a NNW-directed continental collision between the Adriatic and European plates from Eocene to earliest Oligocene (FORD & LICKORISH, 2004;

DUMONT *et al.*, 2008, 2011, 2012). This evolved into a W-directed motion driven by extrusion of the internal Western Alps, creating a radial arc geometry (DUMONT *et al.*, 2008, 2011). The late Oligocene is marked by foreland thrust-fold structures oriented NE-SW, associated with a change in compressional direction (LICKORISH & FORD, 1998; FORD *et al.*, 2006), and by a series of ~N-S thrust-sheet (piggy-back) basins characterized by a complex infill history (FORD *et al.*, 2006). The



study of syn-tectonic strata with a growth stratal pattern during contractional deformations is crucial for reconstructing the chronology of successive deformational events, including thrust propagation, depocenter migration and foreland basin evolution.

The Oligo-Miocene evolution of the Western European Alps entails foreland thrust propagation, hydrographic network reorganization and major climatic changes. Deciphering the possible interactions between these factors and establishing a precise tectono-stratigraphic framework of such interactions requires accurate sedimentological data. This paper is the first of a series aimed at providing a comprehensive and detailed field-based sedimentological reappraisal of "post-Nummulitic" Paleogene deposits in front of the southern French Alps. These deposits have long been included within a stratigraphic and sedimentological catch-all term called Oligocene *Molasses Rouges* or Red Molasses (GIGOT *et al.*, 1974; GRACIANSKY *et al.*, 1982; HACCARD *et al.*, 1989; HELD, 2011; HAMON, 2022; HUET, 2024), which has now been split into several distinct tectono-stratigraphic sequences encompassing the Rupelian and Chattian. Here we link different synclines yielding well-preserved successions of *Molasses Rouges* deposits (*i.e.*, Esparron syncline, Esclangon synclines, Hautes Duyes area) and propose a re-evaluation of the stratigraphic framework at the regional scale, based on correlations involving the evolution of sedimentary dynamics for each zone studied. We discuss (i) resulting depositional palaeogeographies for Paleogene sequences formed during contractional deformation and (ii) age of each sequence in the light of existing literature. A forthcoming regional synthesis will address how these successions record tectonic and peri-Alpine drainage network evolution during the late Paleogene (late Rupelian and Chattian) in front of the active Alpine thrusts.

2. Materials and methods

The study mostly focuses on scenic outcrops of the Esparron syncline (Fig. 1.B) although the nearby Esclangon and surrounding areas (Fig. 1.C) were also investigated, as it appears those locations were closely connected during deposition. The narrow Faucon-Turriers corridor (FT, Fig. 1.A) and the Devoluy area to the north will be addressed in forthcoming studies, as well as coeval deposits located westward of the Digne thrust (Manosque area). Included in the present study are a few scattered remnants of Paleogene deposits, farther to the SW within the Digne nappe or thrust *s.l.* (Hautes Duyes area and tectonic slices in front of the Robine thrust, Fig. 1.C). Molasse Rouge deposits are scarce east of the Rouaine fault within the fold-and-thrust belt of the Castellane Arc (Fig. 1.A).

This work relies mostly on new field investigations (2022-2024), including detailed log sections, facies sedimentology, and analysis of photographic panoramas for identifying depositional geometry. The well-exposed southern part of the Esparron syncline was investigated by a detailed drone survey.

The Esparron syncline represents a stratigraphic reference for the upper Paleogene, as the present study identified for the first time three successive, disconformable depositional sequences resting on folded Mesozoic deposits, whose areal extent is shown on Figure 1.B by the gray, pink and purple colors, in ascending stratigraphic order. Marine deposits of the "Nummulitic trilogy" sequence of the first Alpine foreland basin, namely the "Calcaire Nummulitique", the "Marnes Bleues" and the "Grès d'Annot", are lacking here since they were deposited in a more inner-Alpine location.

From a biostratigraphic point of view, most data regarding the local Paleogene deposits are longstanding, and summarized on a regionale scale by CAVELIER *et al.* (1984). New mammal discoveries are integrated in the local stratigraphic scheme. With respect to the latter, we rely on published studies combined with the Paleogene timescale of SPEIJER *et al.* (2023).

3. Results

3.1. ESPARRON SYNCLINE

Three areas are described in turn from the Esparron syncline, (a) its northwestern entrance (sections 1 and 2, Fig. 1.B), (b) its southern flank (sections 3 to 6, Fig. 1.B), and (c) its northeastern flank around the Garnaysse ravine (sections 7 to 9, Fig. 1.B).

3.1.1. NW entrance of the Esparron syncline

This area exhibits what appears to be a full expression of sequence 1 beneath the Molasse Rouge sequence 2 (MR1). Correlation of two measured sections (Fig. 2) demonstrates a drastic increase in the thickness of sequence 1 along the axis of the syncline (Pl. 1, fig. A), as well as onlap of breccia beds at the base of sequence 1 against its northern flank (Pl. 1, fig. B). Except for a brief description (HAMON, 2022), thickening of sequence 1 between sections 1 and 2 is not recorded in the literature. This relationship demonstrates that sequence 1 is often preserved only as a basal breccia beneath the truncational basal surface of sequence 2. It also explains why the lower breccia beds of sequence 1 were considered in the literature as merely a local basal facies of sequence 2.

Sequence 1 begins in both sections (Fig. 2) with limestone breccias resting on either a Valanginian bed-scale limestone-marl alternation (Esparron road) (Pl. 1, fig. C) or an Aptian marlstone (Patègue summit), revealing a disconformable relationship between sequence 1 and its substratum.

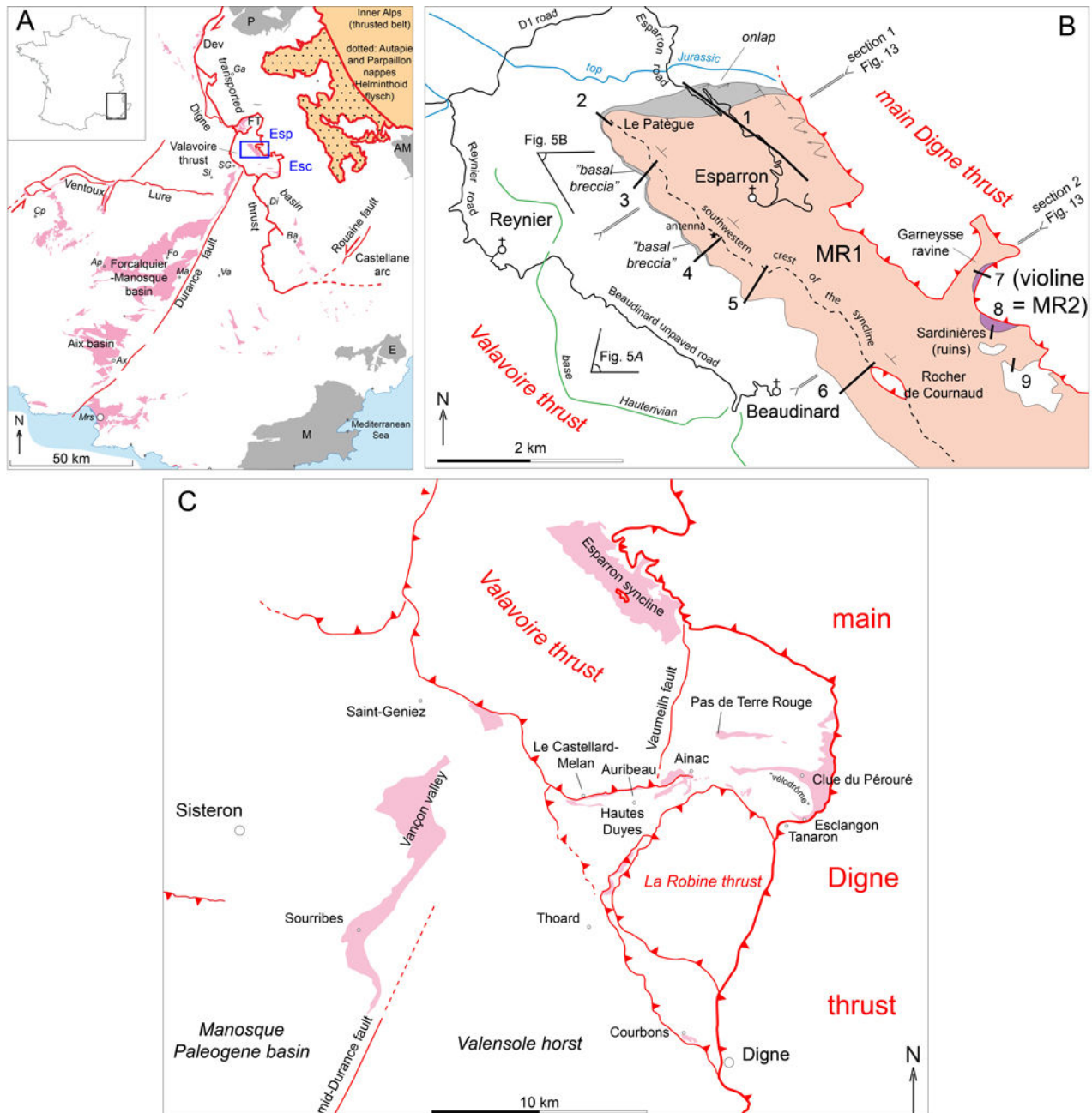


Figure 1: Location maps. **A**, outcrops of Oligocene peri-Alpine continental deposits in SE France (in pink), dark-grey: Paleozoic basement including Permian sedimentary rocks and volcanics, ESP (Esparron) and ESC (Esclangon). **B**, detailed map of the three continental sequences in the Esparron syncline, and location of the nine sections studied (gray, sequence 1; pink, sequence 2 or Molasse Rouge 1 [MR1]; purple, sequence 3 or Molasse Rouge 2 [MR2]). **C**, enlarged area of the Esparron-Hautes Duyes area, south of the Valavoire thrust. Abbreviations: AM, Argentera-Mercantour; Ap, Apt; Ax, Aix; Ba, Barrême; Cp, Carpentras; Dev, Dévoluy; Di, Digne; E, Estérel; ESC, Esclangon; ESP, Esparron; Fo, Forcalquier; FT, Faucon-Turriers; Ga, Gap; M, Maures; Ma, Manosque; Mrs, Marseille; P, Pelvoux; SG, Saint-Geniez; Si, Sisteron; Va, Valensole.

Along Esparron road, the lower part of sequence 1 is composed of thick channelized breccia beds (Pl. 1, figs. C, E). These are interbedded with reddish siltstone hosting minor channel-fills of similar coarse breccia (Pl. 1, figs. D, F). The upper part of sequence 1 comprises lacustrine light-gray limestone and dark-gray marlstone (Pl. 1, fig. G). Reddish siltstone occurs again in its uppermost part. The deposits of sequence 1 are sharply overlain (Fig. 2) by red fluvial deposits of MR1. These consist of sandstone and siltstone. Channel fills are usually coarse-grained at the

base and fining-upward (Pl. 1, fig. H). The MR1 at Esparron road appears to be capped by a homogeneous silty claystone; however, the upper contact is not observed.

Around the Patègue summit, the basal breccia beds are multi-storied and lack the interbedded mudstone that is found in the Esparron road section (Fig. 2; Pl. 2, figs. A-B). The breccia beds thin and disappear quickly to the W, indicating that they fill a south to north-oriented paleovalley. Clasts are angular to subangular (Pl. 2, fig. E)



and sometimes floating (Pl. 2, figs. D-E) in a reddish silty matrix, suggesting rapid deposition, possibly as debris flows. The middle part of sequence 1 is made of several prominent light-gray fine-grained limestone beds (Pl. 2, fig. C), showing closely spaced vertical features interpreted as root casts. This facies is interpreted as being deposited as stacked palustrine sequences that form the up-dip equivalent of the lacustrine limestone beds of the Esparron road section. The uppermost part of sequence 1 consists of a succession of reddish siltstones intercalated with light-gray palustrine deposits (Pl. 2, figs. F-G). Only the lower part of sequence 2 (MR1) is visible at the Patège summit. Its basal sandstone beds infill large channels (Pl. 2, fig. B) in which lateral accretion surfaces indicate point-bar deposition. This relationship was not seen in the Esparron road section, possibly due to limited outcrop.

The vertical succession of sequence 1 therefore shows the same vertical trend at both locations, from the basal breccia to lacustrine-palustrine deposits capped by reddish siltstones, though thicknesses are much greater in the Esparron road section. This suggests that subsidence drastically increased to the north during the deposition of all the units of sequence 1. The vertical trend also indicates an overall flattening of the depositional gradient as the system transformed from a debris-flow-dominated setting to a lacustrine system that filled remaining accommodation.

3.1.2. Southern flank of the Esparron syncline

The southern flank of the syncline provides a spectacular, laterally continuous exposure (Pl. 3) allowing a detailed analysis of depositional sequences 1 and 2. In addition to the Patège section, four other sections have been logged along this slope (Fig. 1.B), and a large number of photographs and panoramas have been obtained by drone survey.

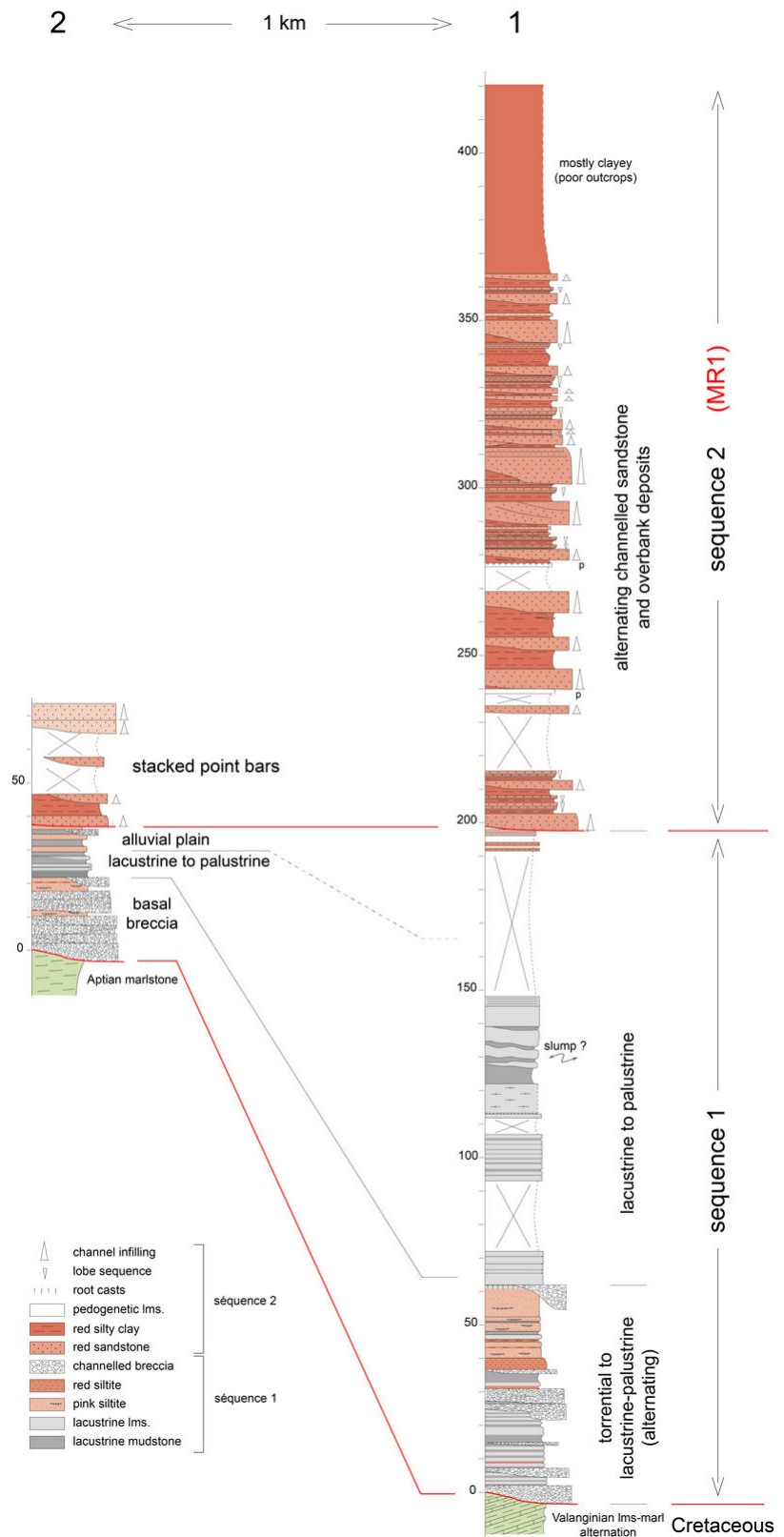


Figure 2: The Paleogene Molasse Rouge (MR) succession at the NW termination of the Esparron syncline. 1, Esparron road section; 2, Patège section (location on Fig. 1.B).



Figure 3: Point bar deposits at base of the MR1 along the southern flank of the Esparron syncline. **A**, view of the stacked point bars showing internal lateral accretion, alternating with laterally continuous thickening-up overbank deposits; **B**, closer view of a laterally accreting point bar; **C**, view of the sole of the channel showing current casts oriented perpendicular to the lateral accretion; **D**, stacked point bars at the SE termination of the syncline.

Sequence 1 has been truncated by subsequent erosion and consist only of a breccia preserved at its base. The breccia thickness diminishes along the syncline length to the SE, before disappearing (Fig. 2; Pl. 3, fig. B). A narrow, isolated channel fill within the basal breccia extends SW to the Rocher de Cournaud summit. In contrast to channel fills found in the breccia along the Esparron road, here the basal breccia beds may be more laterally continuous (Pl. 3, fig. C) with complex internal geometry (Pl. 4, figs. B, E) indicating concurrent incision and deposition typical of braided stream systems. In places (Pl. 4, figs. A, E-F)

basal breccias are overlain by finer-grained reddish deposits, suggesting vertical evolution to a fluvial plain setting similar to that observed around the Esparron syncline's NW entrance. Breccia clasts are angular and unsorted (Pl. 4, figs. C-D), and the unit can be either clast- or mud-supported, suggesting rapid deposition and possible subsequent winnowing. It consists of a mixed provenance of nearby Mesozoic (Tithonian to Cenomanian) carbonates indicating the region had been folded and eroded prior to the deposition of the breccia. The matrix of the breccia is reddish or pale siltstone, as commonly observed

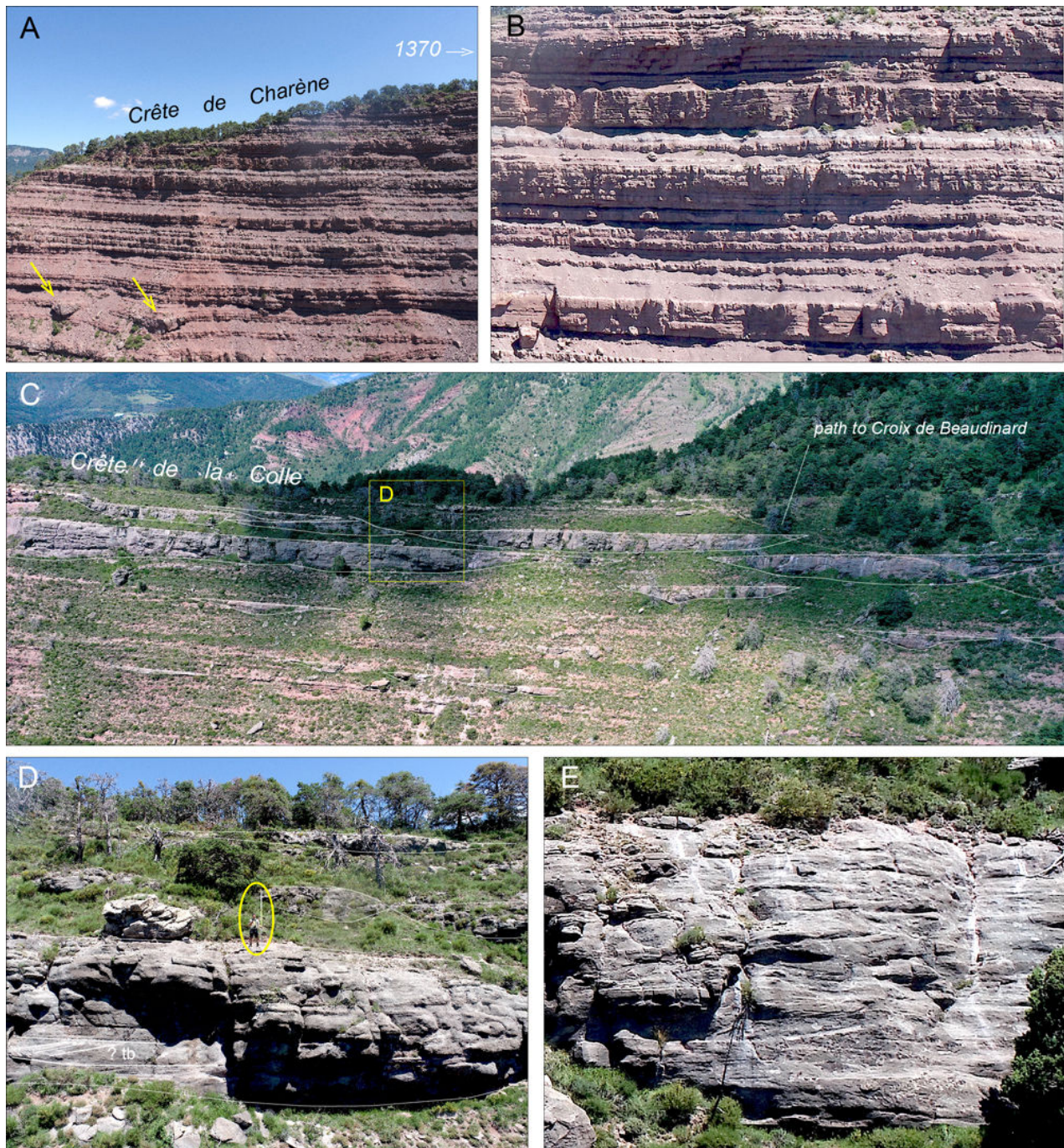


Figure 4: Distal to mid alluvial fan deposits in the middle part of the MR1 along the southern flank of the Esparron syncline. **A**, thick succession of evenly bedded, fine-grained sandstone beds close to the Patègue section (note the few narrow channels, yellow arrows); **B**, closer view of the same; **C**, view of the large channels occurring along the crest of the syncline's flank, atop the well-stratified mid-MR1 subunit (channel infillings are 6 to 9 m thick); **D-E**, closer views of the channel infillings showing quasi-planar lamination and dune cross lamination throughout (circled, P. SORREL with 3 m long rule, for scale).

in modern torrential debris-flow beds (Pl. 4, fig. G). Overall, the paleogeographic picture is one of a belt of coalesced alluvial fans. The fans are composed mostly of stacked and interfingering pebbly to blocky debris flows, the tops of whose depositional lobes were incised by continuing stream flow after the surges. This complex system is fully torrential and channelized at the base, passes upward to a stack of lobes, and ultimately grades into a clay-prone distal facies. This trend is reminiscent of that observed at the syncline's

northern entrance and therefore is likely to be laterally continuous along depositional strike. It suggests a retrogradational pattern associated with a flattening of the depositional profile with time.

Deposits of the MR1 are organized into three parts: (a) a basal section of multi-storied channelized, coarse-grained sandstone (Pls. 4-5), (ii) a thick well-stratified middle unit where beds are laterally continuous, and (iii) an upper part composed of thick sandstone-filled channels interfingering with laterally continuous overbank fine-

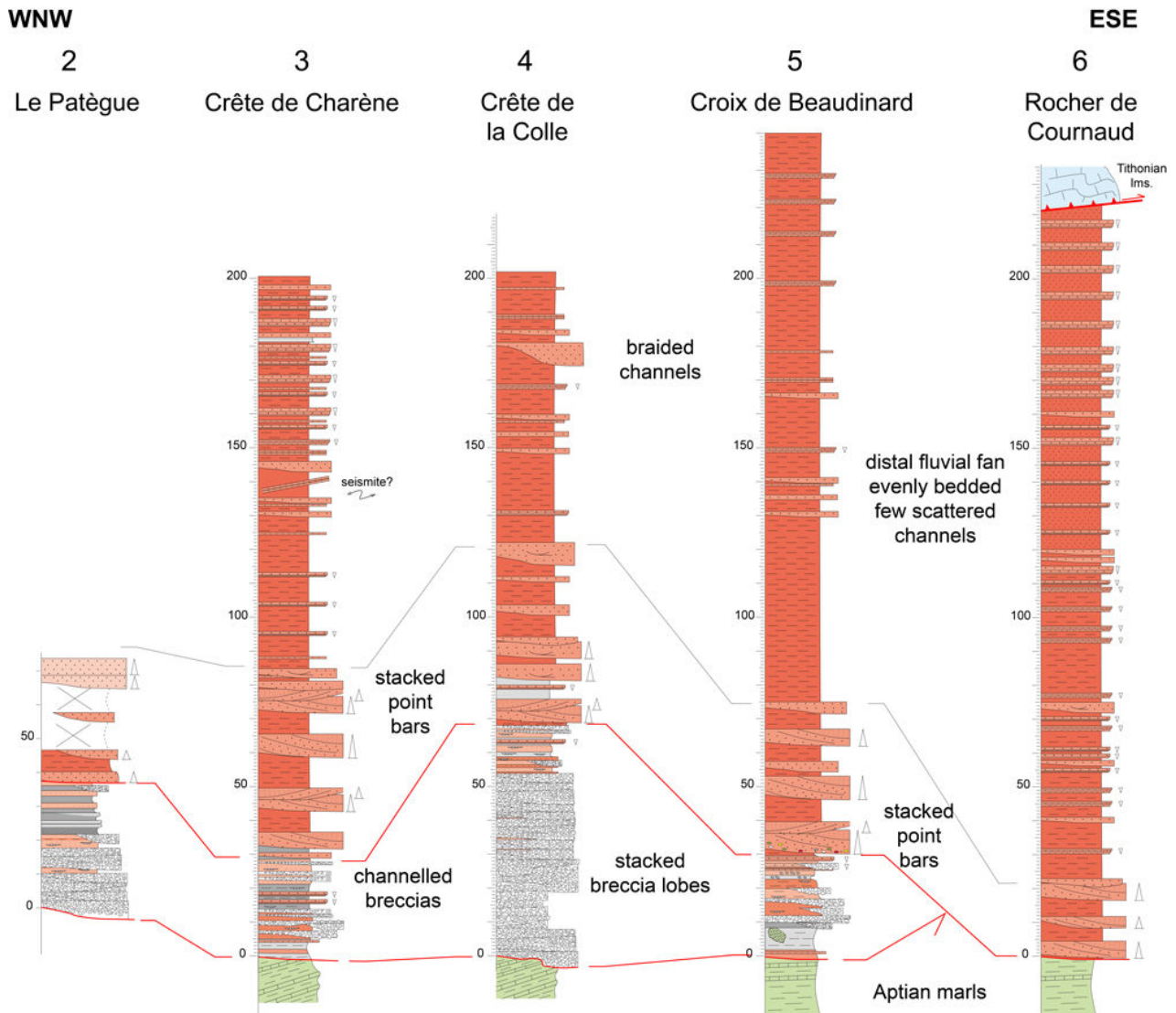


Figure 5: Correlation of sections along the SW flank of the Esparron syncline (location, see Fig. 1.B).

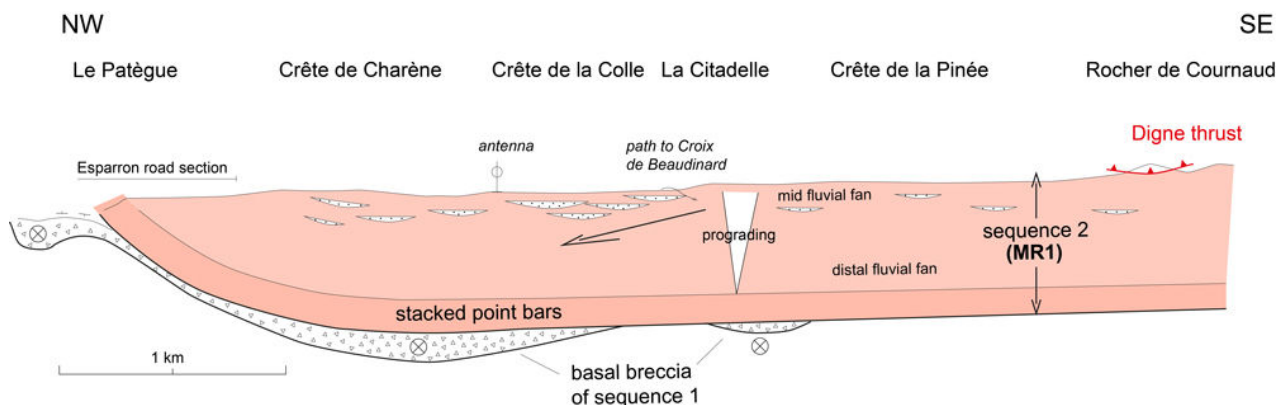


Figure 6: Cartoon depicting the internal organization of the MR1 along the southern flank of the Esparron syncline.

grained sandstones and siltstones. The basal channel fills (Fig. 3) are characteristic of a meandering stream system, including prominent lateral accretion features characteristic of point bars (Fig. 3.A), sole marks at the base of channel fills that are perpendicular to the direction of lateral accretion (Fig. 3.B-C), and clay plugs filling abandoned channels (Fig. 3.A). Fining-upward point-

bar deposits alternate with thin, coarsening-upward overbank deposits (Fig. 3.A).

The multi-storied channel interval (Pl. 3, figs. B-C) thickens from SE (≈ 20 m) to NW (≈ 50 m). It indicates a more moderate accommodation rate with respect to the upper deposits of the MR1. Point bar deposits are composed mostly of sand with common lag gravels at the base. These lag

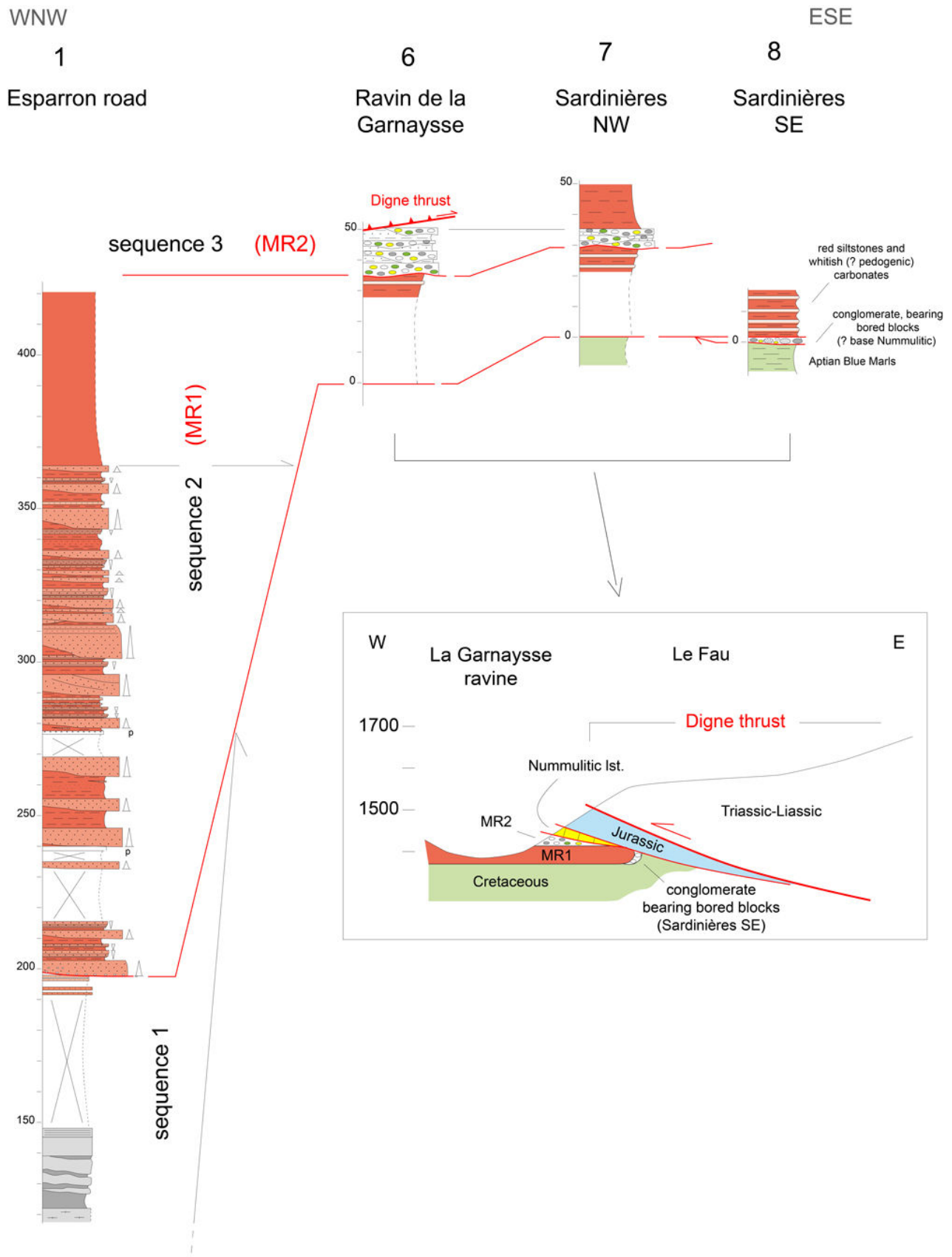


Figure 7: Correlation of the sections along the NE flank of the Esparron syncline showing the rapid pinching of sequence 2 to the east and the disconformable stratigraphic relationship of sequence 3 (location of sections, see Fig. 1.B). Box, cross-section showing the location of the lens of bored boulders at base of sequence 2.

gravels include a wide range of lithologies including Alpine "green rocks" and occasional radiolarites, indicating a partial provenance from the inner

Alps; however, that most clasts are subrounded suggests a short transport distance.



Figure 8: Facies of the thin Molasse Rouge succession in the Garnaysse-Sardinières sections 7 to 9, which sharply rest on Cretaceous deposits. **A**, overturned lenticular conglomerate bed sandwiched between Aptian marlstone and upper MR1 deposits (sequence 1 and lower MR1 both lacking), pen (circled) for scale; **B**, Closer view of the conglomerate bed showing a mixture of lithologies (coarse-grained sandstone, microbreccia, limestones), some of the limestone cobbles being slightly weathered (reddened) and bored (arrows); **C**, sharp contact between the uppermost, clay-dominated part of sequence 2 (MR1) and the conglomerate beds of sequence 3 (MR2) in the Garnaysse ravine (section 7, Fig. 1.B); **D**, Close view of the basal conglomerate of sequence 3 in section 8 (Sardinières ruins) showing interbedded well-rounded channelized conglomerate and greenish-grey laminated or cross-bedded sandstone (hammer for scale); **E**, close-view of a conglomerate bed showing pebble imbrication to the SW (pen for scale); **F**, close-view of the polygenic conglomerate showing pebbles and gravels of inner Alpine "green rocks", Garnaysse ravine (section 7, Fig. 1.B).

The middle part of the MR1 is a thick, laterally continuous interval of interbedded reddish silty claystone and medium- to fine-grained sandstone with planar contacts (Fig. 4.A-B; Pl. 3, fig. D). Some narrow channel forms may be present (Fig. 4.A). Higher in the section, along the Crête de la Colle (Fig. 4.C), large sandstone-filled channels occur. The geometry of their infilling (Fig. 4.D-

5.E) does not indicate point bars as at base of the MR1, because lateral accretion is lacking. Bedding structures consist of thin irregular beds filled by planar to wavy lamination and small-scale trough and planar cross bedding, implying a sandy riverine system where channel infillings are formed by laterally shifting dunes and bars, including low-stage transverse bars showing tabular oblique



lamination. These channel infillings were interpreted as point bars by HELD (2011), but they lack most of the characteristics of such a facies. Channel fills are up to 150 metres wide in slightly oblique sections and up to 9 metres in depth (Fig. 4.D-E), indicating a powerful stream carving laterally continuous overbank deposits made of sequences up to several metres thick (Fig. 4.B). The vertical trend from base to top of the upper MR1 is therefore overall prograding. It represents a fluvial system different from the underlying meandering system. Its architecture shows the dominance of overbank deposits in contrast to the thick scattered sandstone-filled distributaries at its top. The global picture is one of a large distributive fluvial system (*i.e.*, VENTRA & CLARKE, 2018; MOSCARIELLO, 2018) rather than of an alluvial fan proper, which is of more limited extent and more coarse-grained, like deposits of sequence 1.

Correlation of the five sections (Fig. 5) logged along the southern flank of the syncline (Fig. 1.B) shows the lateral architecture of sequences 1 and 2. The organization of the upper part of the MR1 is illustrated in Figure 6. Upper sand-filled channels occur in the south-eastern and central parts of the syncline's flank. The northwestern part is devoid of channels. It indicates an overall updip-to-downdip direction of the depositional system to the NW; however, because the upper channels are concentrated in the central part of the syncline's flank, the actual direction is judged to be slightly oblique to the west (Fig. 6).

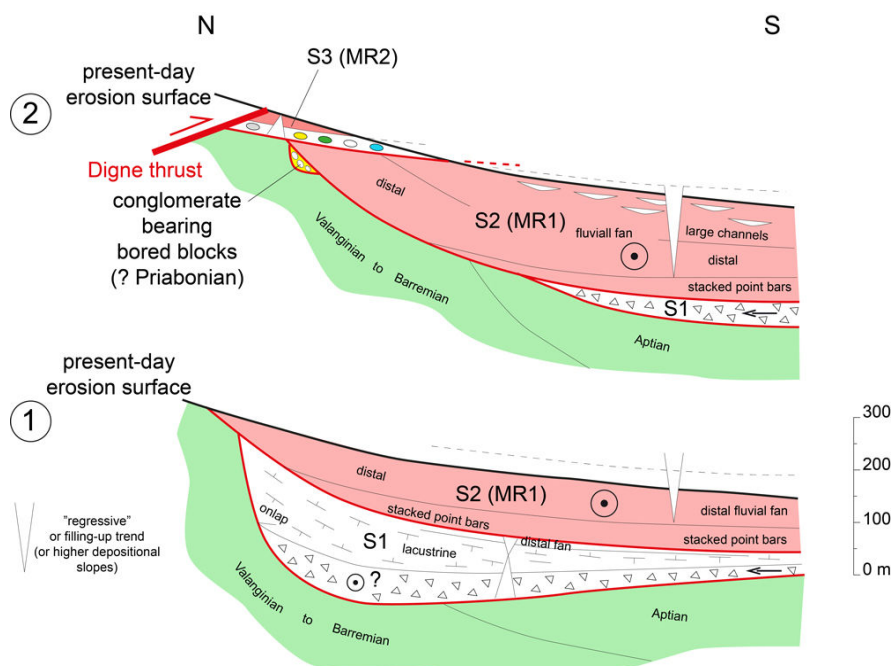


Figure 9: Stratigraphic relationships between the three Paleogene sequences in the Esparron syncline. 1 and 2, Patègue and Garnaysse cross-sections, respectively (location, see Fig. 1.B).

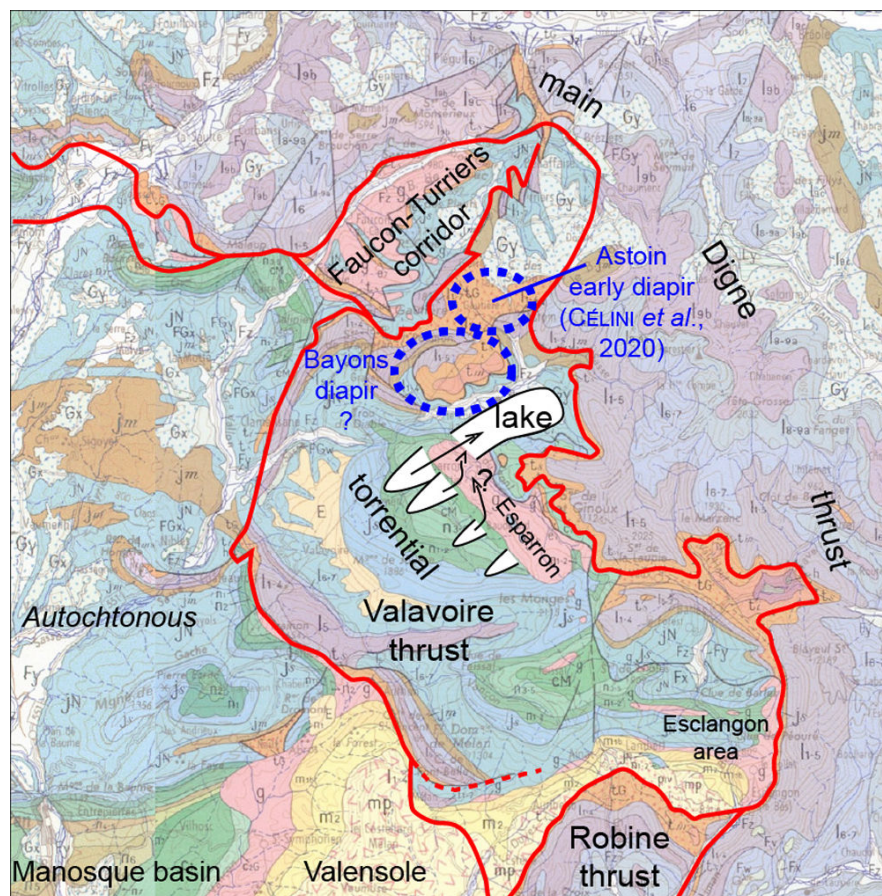


Figure 10: Possible early diapirs in front of the main Digne thrust whose early play could have influenced the internal organisation of sequence 1. Background, 1 : 250,000 geological map (BRGM edit.); red lines, main thrusts.

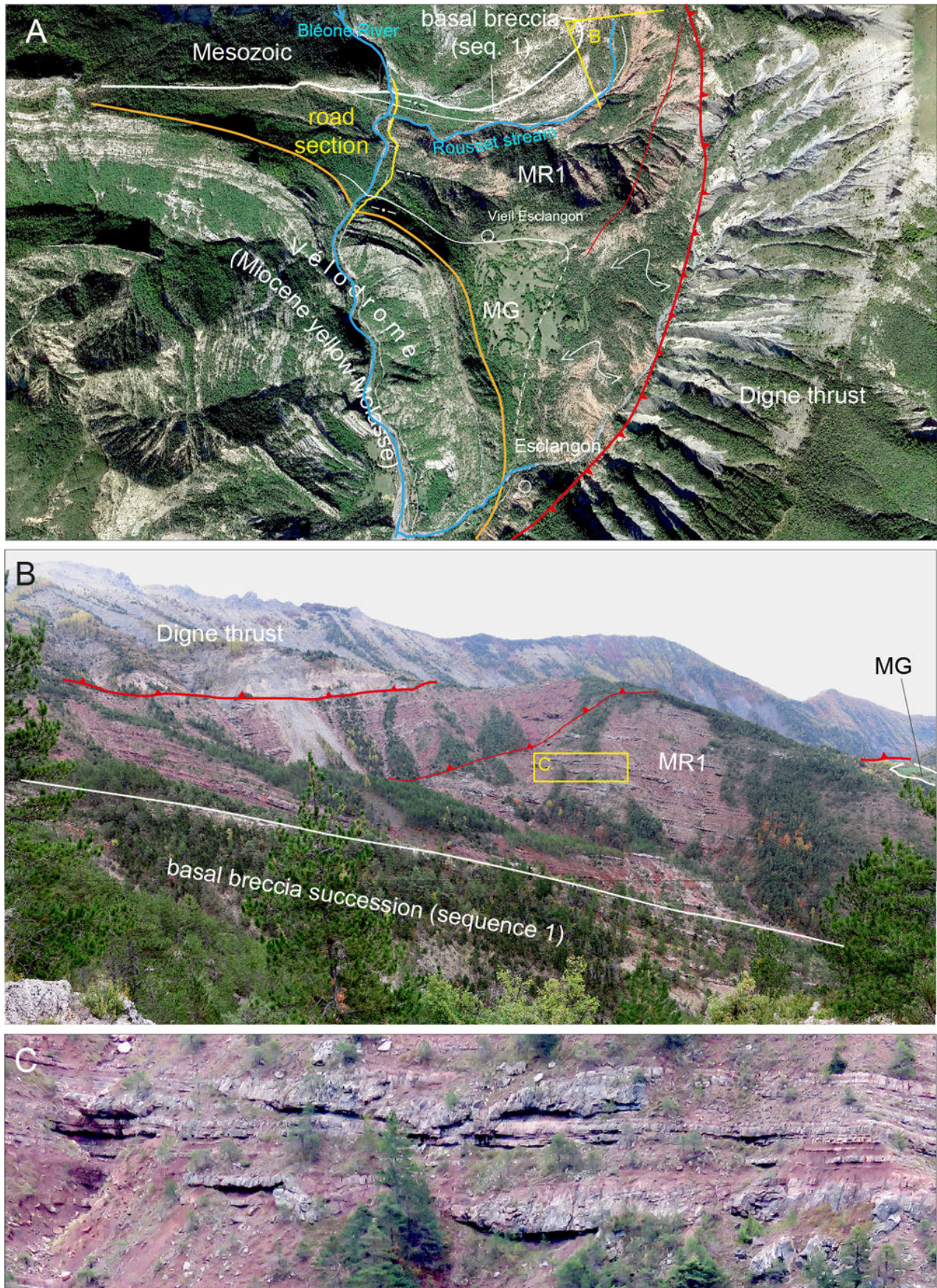


Figure 11: Esclangon area. **A**, aerial view; **B**, panoramic view from the Rousset stream; **C**, Enlarged view of the channelized sandstone beds within the alluvial fan of the MR1.



3.1.3. Northeastern flank of the Esparron syncline

The northern flank of the Esparron syncline shows how abruptly the thick succession of the previously described section 1 is truncated at its base, as it onlaps onto Mesozoic deposits to the SE (Fig. 7). The thick sequence 1 of the Esparron road is the first to disappear, followed by the large sandstone-filled channels of the MR1. Going farther to the SE (Garnaysse ravine), only the uppermost, claystone-dominated part of the MR1 is still encountered, resting on Aptian marlstone, where it interfingers with light-gray limestone beds, likely representing palustrine paleosols.

In section 8 (Sardinières ruins), close to the Digne thrust, a bed of polygenic, well-rounded boulder conglomerate is found at base of the MR1, in the Esparron tectonic compartment (Fig. 8.A-B), but not in thrust slices. Some boulders have been bored, indicating deposition along a marine shore-face. Such a facies, previously unknown in an external location in Paleogene deposits, is of great importance for determining the age of sequence 1 and its relationship, if any, to the Molasse Rouge proper (Discussion). Interestingly, the marine yellowish "Nummulitic Limestone" is found (Fig. 7, box) in tectonic slices in front of the Digne thrust in the Garnaysse ravine. It is likely that the bored boulders represent its shore facies.

The molasse deposits resting on the MR1 are quite different. In the Garnaysse ravine (Fig. 7) they consist of a well-rounded, pebbly, polygenic conglomerate whose internal geometry suggests deposition by a braided fluvial system at the base (Fig. 8.C-D). The conglomerate has been truncated by the Digne thrust. Imbrication of pebbles indicates flow to the west or south-west. Laterally (section 7, Fig. 7), a red, claystone-dominated succession, several tens of metres thick, is preserved above the polygenic fluvial deposits and beneath the Digne thrust. This conglomerate and the upper claystone make sequence 3, or MR2, constitute an upper Molasse Rouge sequence representing a fluvial system different from that of the MR1. Among the pebbles are found Alpine metamorphic quartzites, radiolarites and "green rocks" (Fig. 8.E-F) indicating that the formative river system drained the inner Alps. The sequence is thin in the Esparron syncline but dramatically thickens to the NW in the Faucon-du-Caire area (in preparation). Mapping shows that MR2 rests unconformably on the MR1 in the Garnaysse area.

The MR2 is therefore made of a succession of two fluvial systems, a pebbly braided deposit at the base draining a distant Alpine watershed, and a distal, clay-dominated fluvial or alluvial fan at the top, likely coming from a closer source. This succession is somewhat similar to that of the MR1, with multi-storied point bars at the base, representing a low-topography river profile, overlain by a slightly steeper prograding fluvial fan at top.

3.1.4. Summary of the Esparron syncline

The above descriptions are depicted in two north-south-oriented cross sections (Fig. 9) that cross the Esparron syncline at its northwestern entrance and traverse its middle part at the Garnaysse ravine (location on Fig. 1.B). Both cross sections show the onlap of sequences 1 and 2 against the northern flank of the syncline, and highlight the disconformable relationship between the MR2 and the MR1, as mapped in the Garnaysse area.

If the lens of bored cobbles preserved near the Sardinières ruins truly represents the shoreface of the Calcaire Nummulitique, its proximity in the same tectonic compartment to a torrential system that evolved into a lacustrine setting in sequence 1 would preclude these two facies from being coeval.

Clast provenance indicate that the torrential system of sequence 1 is directed toward the Alps, whereas deposits of the MR1 and MR2 come from the inner Alps. However, the paleogeography of sequence 1 remains unclear. The NE-directed breccia channels seen on the southern flank of the syncline disappear on its northern flank, except for the Patègue channel which quickly evolves to a lake system in the NE. CÉLINI *et al.* (2020, 2021) and HAMON (2022) suggested the possible role of early diapirs in controlling the areal deposition of continental deposits in the local upper Paleogene. The circular structure of Bayons (Fig. 10), or the nearby Astoin diapir (CÉLINI *et al.*, 2020) could possibly represent such an early diapir having controlled the occurrence of a lake through lateral subsidence. Such diapirs would likely have been beheaded by the translation of the Digne thrust and its frontal tectonic units (Valavoire thrust).

The fact that the basal breccia channels of sequence 1 onlap the northern flank of the syncline (Pl. 1, fig. B) may suggest that a lateral (tributary) valley already existed at that time, which would possibly have redirected the other NE-oriented channels seen on the southern flank of the syncline (Fig. 10). The tectonic deformation pre-dating deposition of the MR1 could also have masked an earlier topography oriented to the NE.

It is difficult to determine the average direction of the meandering river at the base of sequence 2 from current features in deposits, which is a common problem in such facies. The spatial organization of deposits in the upper fluvial fan (Fig. 6) clearly indicates a flow overall directed to the west that roughly follows the syncline's axis. Therefore, onlap of the MR1 on the northern flank of the syncline (Fig. 9) implies that the paleovalley was likely a protosynclinal valley.



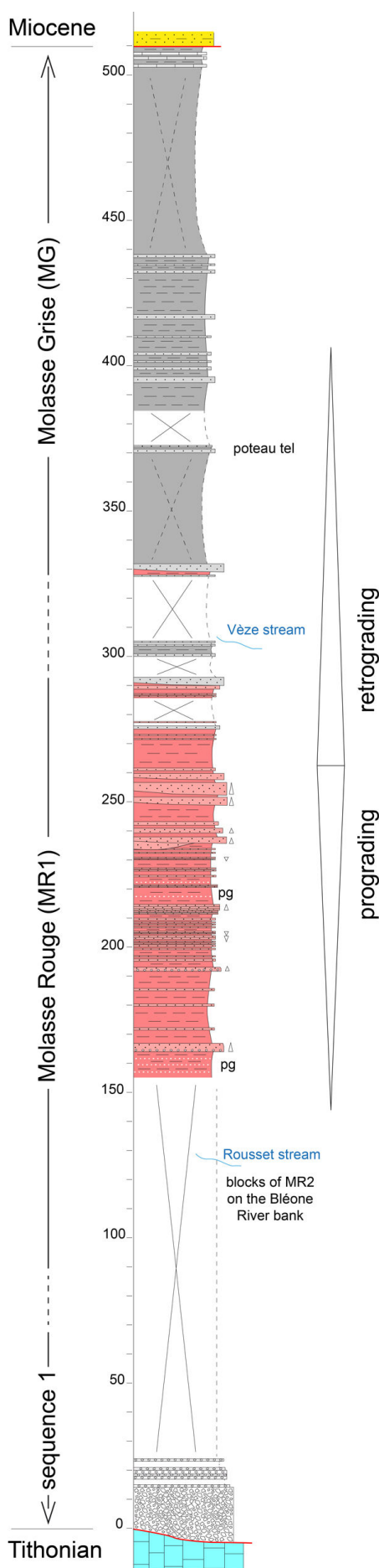


Figure 12: Esclangon road section.

3.2. ESCLANGON AREA

The Esclanton "Vélodrome" area is a landmark for the geology of perialpine Cenozoic Molasses in SE France. The superimposed red Paleogene and yellow Neogene molasses are well-exposed, and follow a famous curved path in a scenic landscape (Fig. 11.A). The area is situated about 12 km to the SE of the Esparron syncline (Fig. 1.C).

To image the depositional architecture, a road cutting was logged (Fig. 12) and photographic panoramas (Fig. 11.B-C) were taken uphill from a path roughly following the Rousset stream to the contact with the Digne thrust. Basal breccia of the same facies as that seen in the Esparron syncline (sequence 1) pinches out to the west (Fig. 11.A). The unit's thickness expands to the east. Breccias either fill channels (Pl. 5, figs. A, C) or constitute laterally continuous unsorted debris flow frontal lobes (Pl. 5, fig. B). They represent exactly the same kind of alluvial fan debris flow deposits found in the Esparron syncline. Channels are W-E oriented, flow being to the east or north-east, as indicated on the 1:50,000 geological map (sheet #918, La Javie). Clasts are angular, and composed of locally reworked Mesozoic limestones, as seen in the Esparron syncline.

The lower part of sequence 2 (MR1) is poorly exposed in the succession logged along the D 900A road (Fig. 10). Depositional geometry can be interpreted using observations from photographic panoramas (Fig. 11.B) taken on the slopes below the Digne thrust a long the Rousset stream (Fig. 11.A), where the contact with the basal breccia of sequence 1 can be traced. HELD (2011) reported the occurrence of point bars in the lower part of the MR1; however we did not find evidence of heterolithic geometries within the MR1 deposits of Esclangon. Instead, slopes of the cirque show relatively narrow, sandstone-filled channels (Fig. 11.C; Pl. 5, fig. C) cut into laterally continuous overbank deposits (Fig. 11.C; Pl. 5, fig. D) and paleosols bearing carbonate root casts (Pl. 5, fig. F). The sandstone infilling of channels is in general vertically accreting, showing complex cross lamination (Pl. 5, fig. E). The overall picture for the MR1 is one of an alluvial fan, not a meandering stream. This alluvial fan is different from the large distributive fluvial fan of Esparron, where the thickness of channels (up to 8 m) in the upper part of sequence 2 suggests a more powerful stream. An additional difference is the lack at Esclangon of point bars, as encountered at Esparron, in the lower part of MR1.

The red mudstone deposits of the MR1 are overlain by a thick grayish marlstone-dominated succession (mostly lacustrine and palustrine deposits) called Molasse Grise (MG), which was deposited abruptly but conformably over the underlying red mudstone deposits. The lack of an unconformity between the MR1 and the MG is used to place the MG as the upper part of sequence 2 at this locality. The absence of MG in the Esparron area indicates it was either not deposited or it was eroded before deposition of the MR2 in that area. This succession is very similar to that observed in the Barrême syncline, farther to the south, where the Molasse Grise was ascribed a Chattian age (CARBONNEL *et al.*, 1972).

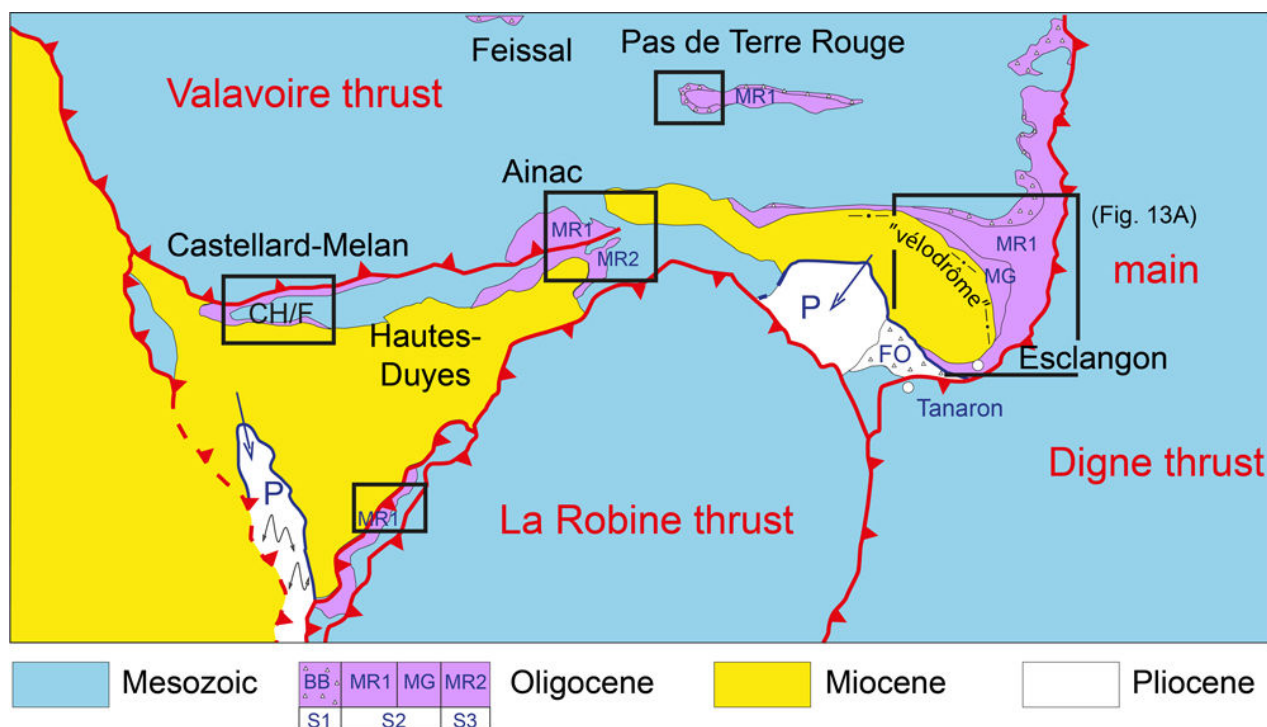


Figure 13: Map of the surroundings of the Esclangon area to the Hautes Duyes showing the other localities discussed in the text. What is mapped as Molasse Rouge in the Castellard-Melan area is to be revisited as basal Miocene sandstone (see text, and Fig. 22.A).

The deposits of sequence 3 (MR2) were not observed, but were identified by TREMBLAY (2000) in some remote places immediately in front of, and possibly truncated by, the Digne thrust. Their occurrence is also verified by some blocks (Pl. 5, fig. G) carried downslope by the Rousset stream, where they are found in the Bleone River bank at the confluence with the stream, but have not been found farther upriver. The material is a well-rounded, highly diversified, varicoloured polygenic conglomerate (Pl. 5, fig. H), in which Alpine green rocks are scarce, unlike in the Esparron syncline, meaning the paleostream had a geologically different catchment area from that supplying the Esparron area.

The succession observed at Esclangon is also found, though strongly truncated by recent erosion, in the Pas de Terre Rouge area (Fig. 13), an intermediate position between Esparron and Esclangon (Fig. 1.C). The basal breccia of sequence 1 (BB, on Fig. 14.A) is overlain by red claystone (Fig. 14.A), revealing a vertical trend (retrograding, or flattening of the depositional profile) similar to that observed at Esparron. The thickness of the basal breccia diminishes to the NE (Fig. 14.A), which suggests a torrential fan oriented to the NE, as in the Esparron syncline.

MR1 deposits rest conformably on sequence 1. They bear a stack of channelized sandstone beds at the base, overlain by a more clay-prone succession (Fig. 14.B). The succession overall appears more distal than that of Esclangon.

3.3. HAUTES DUYES AREA

The area (Fig. 13) encompasses a strip of outcrops in front of the southern branch of the Valavoire thrust in the Castellard-Melan area (Col de l'Hysope, Fontbelle) to the upper reaches of the Hautes Duyes streams close to Ainac/Le Château. Tectonic slices in front of the Robine thrust, close to village of Thoard, are also investigated. All outcrops are within the Digne thrust *lato sensu*, including the Valavoire and Robine frontal tectonic units. The allochthonous Hautes Duyes area is bounded to the west by a blind thrust within Miocene deposits marked by folded breccia deposits infilling a crushed Pliocene paleovalley (Fig. 13) cut into the upper Miocene Valensole Conglomerate [not indicated as such on the 1 :50,000 geological map (sheet #918, La Javie)].

In the Ainac-Le Château vicinity, three stratigraphic units belonging to the Molasse Rouge *s.l.* are recognized on the geological map (sheet # 918, La Javie): (i) basal breccias (e7-gBr) showing a paleoflow direction to the NE, and which are considered as a lateral equivalent of the Nummulitic deposits on the basis of reworked *Microcodium* found in the breccia material, (ii) an alternation of reddish to greyish claystone and channelized grayish sandstone (g-m), and (iii) a polygenic conglomerate unit (g-mC) possibly a lateral equivalent of the Miocene marine molasse. Given the facies similarities, these three units can be regarded as correlates of the three sequences of Esclangon and Esparron, namely the basal breccia

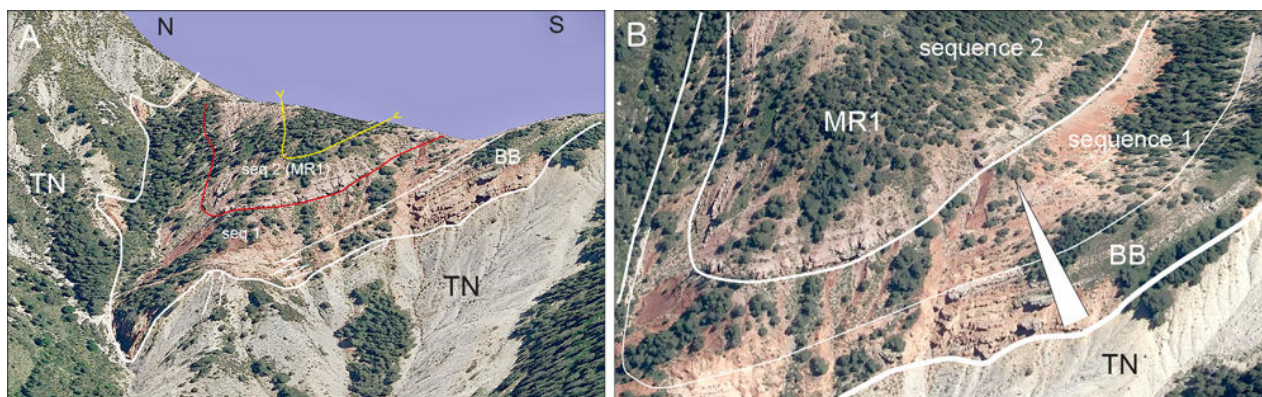


Figure 14: Oblique aerial views of the Pas de Terre Rouge perched syncline (location on Fig. 18), showing both the fining-up trend (triangle) of sequence 1, similar to that in the Esparron syncline, and the overall thinning to the north of its basal torrential breccia (BB) as at Esparron. TN, Jurassic Terres Noires Fm. 3D aerial views from the Iphigénie @ Application.

of sequence 1, the MR1 (sequence 2) and the MR2 (sequence 3), respectively. MR1 deposits are interbedded pink to red claystone to siltstone and grayish sandstone filling both broad (Fig. 15.A) and narrow (Fig. 15.B) and interpreted as mid to distal alluvial fan deposits. Deposits ascribed to the MR2 are channel-filling polygenic conglomerate whose lithological assemblage is close to that of the MR2 (Fig. 15.C), or sandstone-hosting lenses of polygenic pebbles of the same composition (Fig. 15.D).

An important observation is made, close to the Ainac chapel (Fig. 16), where the deposits of sequence 1 and the MR1 are found disconformably overlying the Jurassic "Terres Noires" Formation north of a fault which is in fact the SE termination (Castellard-Melan) of the Valavoire thrust (Fig. 13). South of the fault, only deposits of the MR2 are found overlying the Jurassic marlstone (Fig. 16). It suggests that thrusting was active between the deposition of the MR1 and that of the MR2.

Along the Crête de l'Hysope/Fontbelle (CH/F, Fig. 13), in front of the Castellard-Melan thrust, a band of Molasse Rouge deposits was incorrectly mapped around a pericline of Jurassic Terres Noires on the La Javie geological sheet. These deposits are actually the basal sandstone of the Miocene marine transgression. In good exposures, the succession shows an overturned package of laterally continuous sandstone beds (Fig. 17.B), likely a beach system containing marine shell accumulations (Fig. 17.C), and overlain by thick grayish marlstone. Laterally, in poor outcrops, the basal Miocene sandstone was most probably confused with the gray sandstone infilling the channels of the MR1 between Esclanton and Ainac. The genuine MR1 is preserved only in a local inlier on top of the anticline of Jurassic deposits (Fig. 17.A). This implies very strong post-Miocene deformation of the Valavoire thrust.

In front of the Robine thrust, upslope of Thoard village (Fig. 13), limited outcrops of grayish sandstone bodies and pinkish claystone are found within tectonic slices in front of the thrust. They are interpreted as the distal facies of the MR1, comparable to the sequence at Ainac and Esclanton.

4. Discussion

The discussion focuses on two issues, (i) the paleogeography interpreted from the deposits of the three upper Paleogene sequences, and (ii) the age of the sequences.

4.1. PALEOGEOGRAPHY

4.1.1. Sequence 1

Earlier studies have reported that the breccias beneath the subalpine Molasse Rouge belong to a depositional system oriented toward the Alps, in contrast to the Molasse Rouge whose transporting agent flowed in the opposite direction to the west (GIGOT *et al.*, 1974; GRACIANSKY *et al.*, 1982; HACCARD *et al.*, 1989) (Fig. 18).

A priori, the breccias of sequence 1 can be interpreted in two ways. In the first interpretation, in the context of active deformation of the Molasse Rouge fluvial basin along its western border, the breccias could be torrential breccias progressively blocked and retreating to the west as Alpine deformation proceeded and the fluvial basin in front of the Alpine thrusts widened. In this respect, the breccias may be interpreted simply as basal deposits of the MR1, without other significance.

Another interpretation is that they are proximal-margin deposits of a large flexural basin predating the deposition of the MR1. The discovery of an expanded lacustrine succession in the north-western termination of the Esparron syncline could suggest that the bordering torrential fans plunged onto a flat topography extending toward the Alps. However, as stated earlier, the possible emplacement of a synsedimentary diapir (Fig. 10) undermines the regional significance of such topography which could be purely local. Similarly, the pinching of the deposits of sequence 1 against the northern wall of the Esparron syncline (Fig. 9) is difficult to interpret. Were the streams reoriented along a valley following the future syncline axis (Fig. 10), or was the Patègue sequence (Fig. 2) really laterally continuous along the strike of the basin margin, and later eroded after tectonic deformation predating the truncation by the MR1?



Figure 15: **A-B**, large (A) and narrow (B) sandstone-filled channels scattered within pink to red claystone in the MR1 (more distal facies than at Esclangon) at Ainac (see Fig. 18 for location); **C**, conglomerate-filled channel at base of the MR2 at Ainac; **D**, more sand-prone facies of the MR2, Ainac chapel, red knife (center) for scale.

It is not possible to go further without additional stratigraphic data, and, above all, without a broader regional examination of the question.

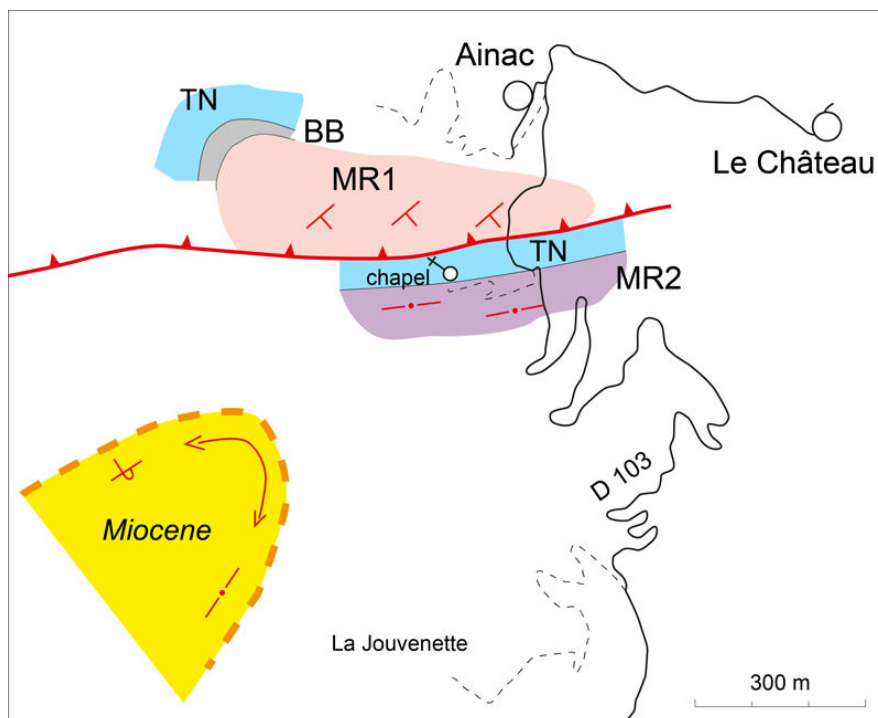
Yet, it has become clear that the torrential fans of sequence 1 encroached onto a continuous line of high-relief features to the west, if we compare the facies of the basal breccia with modern mountainous torrential fans (Pl. 4, fig. G).

4.1.2. Sequence 2

Sequence 2 comprises the MR1 at the base, and the Molasse Grise (MG) at the top. The MG is present only in the Esclangon area (Fig. 12), possibly due to a lack of preservation elsewhere. Several lines of evidence (Figs. 9, 16) show that intense tectonic deformation and erosion preceded the deposition of the MR2.



Figure 16: Revised geological map close to Ainac chapel showing the different Molasse Rouge successions on both sides of the Valavoire thrust fault. BB, basal breccia of sequence 1, TN, Jurassic Terres Noires Fm.



With respect to depositional profiles, the MG indicates a flattening of relief after the prograding pattern (steeper slopes) represented by the MR1. The MR1 of the Esparron syncline has been divided into two parts (Fig. 18), best seen in the Esparron syncline: (i) a meandering stream system represented by multi-story point-bar deposits (Fig. 5) indicative of a very low-gradient topography, and (ii) a middle- to distal fluvial fan system in the upper part deposited on a slightly higher gradient. Both thickening of the point-bar stack to the NW (Fig. 5) and the architecture of the upper alluvial fan deposits (Fig. 6) indicate deposition to the NW (Fig. 18). Pinching out of the MR1 deposits on its northern flank (Figs. 7, 9) also indicates that the paleovalley formed within a syncline in front of an active fold or thrust (Fig. 18).

The large braided channels in the upper part of the MR1 (Fig. 4) are different from those of the Esclangon alluvial fan. Those of the Esclangon fan may be better connected, on the basis of sedimentological characteristics (grain-size, channel width), with those of the Hautes-Duyes-Ainac area. Therefore, development of the Esparron and Esclangon fans are regarded as separate systems (Fig. 18). Progradation of the Esclangon alluvial fan may have started when a meandering stream flowed from a distant location in the Esparron area. Later, gradients increased in both areas, and the two fan systems likely merged (Fig. 18).

4.1.3. Sequence 3

Outcrops of sequence 3 (or MR2) are limited. It is found only in the Garnaysse area of the Esparron syncline (Figs. 1.B, 7, 9). Here, basal MR2 deposits were laid down in a relatively low-gradient, pebbly braided fluvial system and which changed rapidly upward to a clay-dominated, distal alluvial fan. This succession somewhat re-

sembles that of the MR1, with a fluvial system likely sourced from deep within the Alps and later covered by local alluvial fans. Such successions experienced recurrent tectonic deformation that induced significant changes in local and regional topography during the deposition of the MR1 and MR2 sequences.

Due to limited outcrop, however, it is difficult to trace precisely the path of the primary streams (Fig. 18).

4.1.4. Relationships with coeval deposits outside the Digne nappe

Fieldwork in progress shows that in the Sisteron area (Saint-Geniez, Vançon Valley, Sourribes, Fig. 1.C), upper Paleogene deposits also include local equivalents of the MR1 and MG. Deposits of the MR1 correspond, at least in part, to the "Conglomérats duranciens" *auct.* deposited along the mid-Durance fault (Fig. 1.C). In the upstream area (Sourribes, Fig. 1.C), the red succession hosting these channel-filling conglomerates is overlain by a thick succession of gray marlstone representing the lateral equivalent of the Molasse Grise of Esclangon. However, the sedimentary material filling the channels of the red deposits is totally different in composition, being derived mostly from local limestones, and thus of different provenance from finer-grained subalpine MR1 gravels originating from the inner Alps. Their characteristics suggest that a former large river catchment would now be hidden beneath the Digne thrust, and that the Digne nappe corresponds to a transported basin whose displacement may be underestimated. It is possible that the high relief indicated by the breccia of sequence 1 marks the western border of this transported basin.

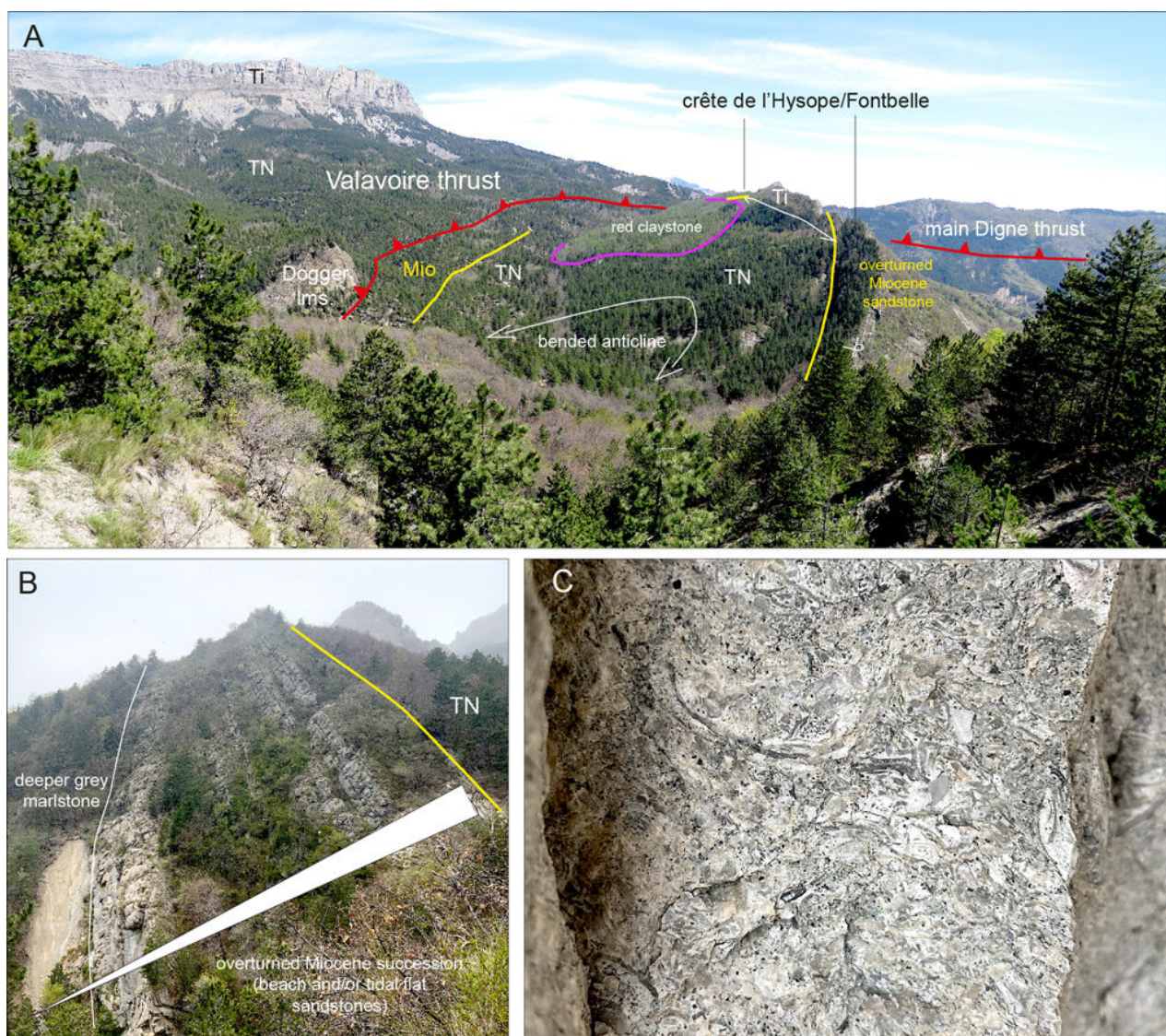


Figure 17: Revised Molasse Rouge deposits in the Castellard-Melan area (see Fig. 18 for location). **A**, view of the arcuate anticline in front of the Valavoire thrust. What is mapped as Molasse Rouge is in fact the basal Miocene sandstone. **B**, closer view of the overturned basal Miocene sandstone showing the laterally continuous beds which therefore cannot be fluvial (triangle depicting the deepening-up trend in marine deposits); **C**, detail of the shell accumulations within the Miocene sandstone of picture B.

The relationship with Paleogene deposits in front of the Ventoux-Lure thrust (Fig. 1.A) is not clear. The "Conglomerats de Montfroc", first assigned to the Oligocene (FLANDRIN, 1964), were subsequently given a Miocene age (MONTENAT *et al.*, 2000); however, the facies of the limited Montfroc outcrops as interpreted by this study are similar to those of the polygenic conglomerate at the base of the subalpine MR2, with radiolarites and Alpine green rocks among the pebbles filling narrow channels cut into red claystone.

Hence, the problem of outlets of the subalpine MRs outside the Digne nappe requires further investigation.

4.2. AGE OF THE SEQUENCES

The precise age of the Molasse Rouge *s.l.* has been an open question over the last few decades. This is mostly due to (i) the lack of reliable biostratigraphic data, (ii) uncertain lithological correlation between distant successions, and (iii) ques-

tionable paleontological determinations. Also, the existence of two disconformable successive sequences (MR1 and MR2) within the Molasse Rouge has not been reported so far. In addition, previous studies were not conducted in accordance with modern concepts of facies analysis for fluvial systems. Boundaries between successive sedimentary units with facies that were unlikely to be associated in space and time should be regarded as distinct unconformable or disconformable stratigraphic surfaces of regional significance. The subalpine term Molasse Rouge has long remained a lithological catch-all without sedimentological consistency.

GIGOT (1973) assigned a late Eocene age to the basal breccia in the St Geniez area (Fig. 1.C) outside the Digne Nappe. This age was later applied (GIGOT *et al.*, 1974) to the breccia deposits (*i.e.*, sequence 1 in the present work) at base of the Molasse Rouge within the Digne nappe (Es-

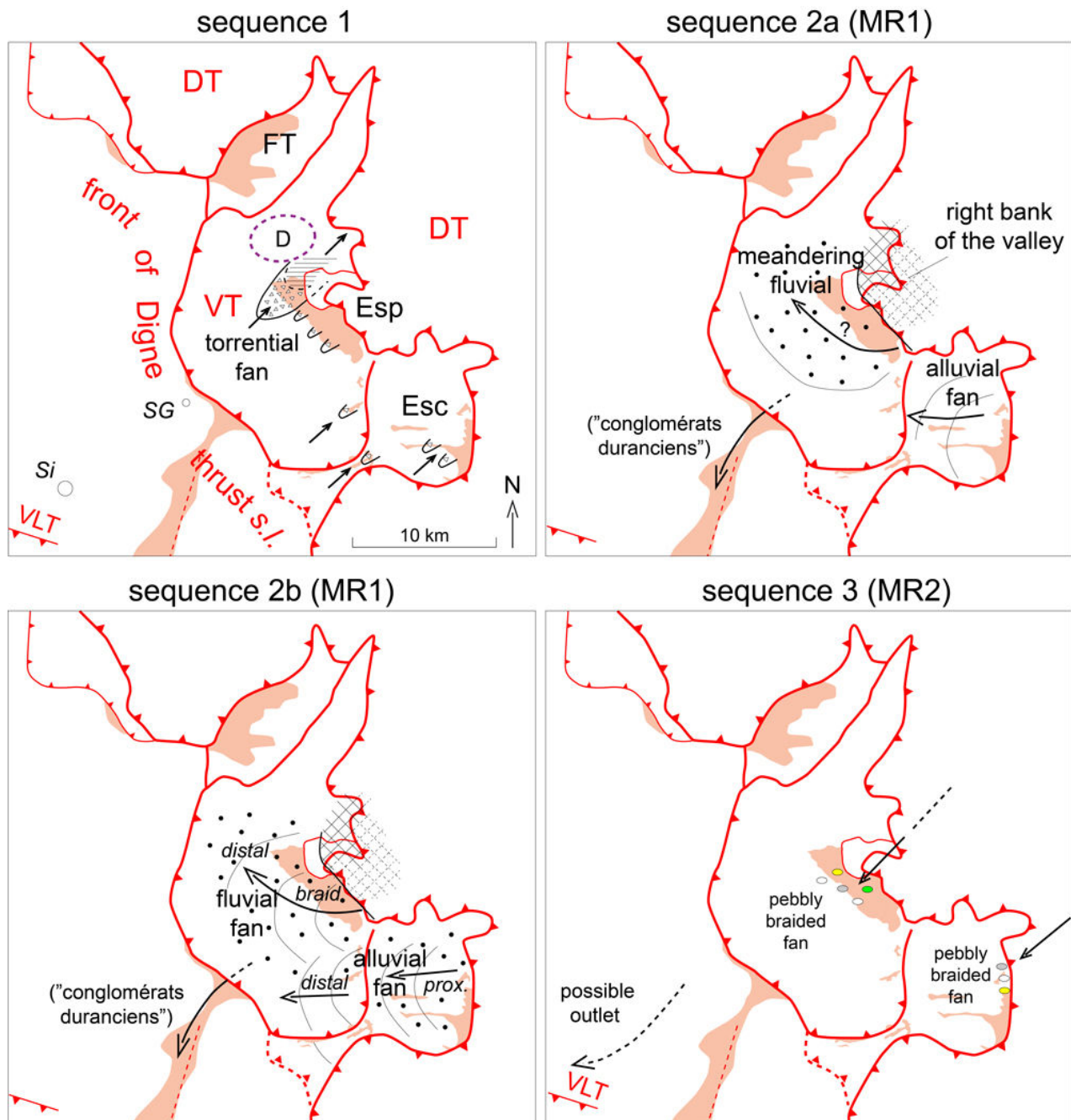


Figure 18: Evolving paleogeography for sequences 1 to 3. Abbreviations: DT, Digne thrust; ESC, Esclangon; ESP, Esparron; SG, Saint-Geniez village; Si, Sisteron city; VLT, Ventoux-Lure thrust.

parron syncline and Esclangon area) in the explanatory notices of the geological maps of Digne (GRACIANSKY *et al.*, 1982) and La Javie (HACCARD *et al.*, 1989). The St-Geniez breccia is the northern, proximal equivalent of Eocene fluvial deposits hosting large debris-flow units (klippes sédimentaires). The latter can be traced from Sourribes (location on Fig. 1.C) southward to the Forcalquier-Manosque basin at the base of a mostly lacustrine succession beginning in mammal zone MP18 (TRUC & DEMARCO, 1967), that is, the basal Ludian (*i.e.*, Priabonian). We have presented field data above for the Esparron syncline supporting the suggestion that the shore deposits of the "Nummulitic" sea pinch out to the west so close to the torrential breccia of our sequence that they

cannot be considered to be coeval. Hence, the basal breccia of sequence 1 cannot be a lateral equivalent of the Eocene breccias of St-Geniez. They belong to another depositional sequence that cannot be Eocene (Priabonian) in age.

GIGOT *et al.* (1974) further reported the discovery of a tooth of *Ronzotherium velaunum*, a rhinoceros species of "Sannoisian" (*i.e.*, lower Rupelian) age (see chart of SPEIJER *et al.*, 2020) within the polygenic conglomerate at the base of our MR2 sequence on the eastern flank of the Esparron syncline (Sardinières area, Fig. 1.B). However, the MR1 and MR2 sequences were not recognized at that time. Therefore, this discovery does not constrain the age of the MR1, as it is stratigraphically inconsistent (Figs. 7, 9).



According to TISSIER *et al.* (2021) the genus *Ronzotherium* appeared in Europe just after the "Grande Coupure" which corresponds to a major faunal change linked to climatic cooling around the Eocene-Oligocene transition, a change identified both in isotope records worldwide (ZACHOS *et al.*, 2001; WESTERHOLD *et al.*, 2020) and regional vegetation changes (SUC *et al.*, 2025). *R. velaunum* would cover the mammal zone MP 21 (lower Rupelian). This may explain why the Molasse Rouge *s.l.* has remained so long (SZTRAKOS & FORNEL, 2003), since the regional stratigraphic synthesis of CAVELIER (1984) in the upper Rupelian-Chattian bracket.

The detailed investigation of the Paleogene succession in the Barrême syncline, about 20 km to the SE from the area studied here, showed that the residual western part of the "Nummulitic" marine basin underwent a stepped forced regression, traced through correlation of serial log sections to the SE, up to the Taulanne syncline (GROSJEAN *et al.*, 2012). The regressive upper Rupelian succession contains well-rounded conglomerate bearing radiolarites (GROSJEAN *et al.*, 2012) and metamorphic Alpine "green rocks" (serpentinites, gabbros) (GRACIANSKY *et al.*, 1971), which implies that the flysch basin of the Annot Sandstones was subaerially exposed and carved by rivers transporting this inner Alpine material. The study by GRACIANSKY *et al.* (1971; see also GROSJEAN *et al.*, 2016, 2017) indicates that an hiatus of significant duration must have occurred before deposition of the overlying Molasse Rouge formation in the Chattian.

4.2.1. Age of sequence 1

The new field data from the Esparron syncline presented in this study preclude the possibility that sequence 1 includes a shore facies of the marine "Nummulitic" succession such as that that crops out a little farther to the east. Because the internal organization of sequence 1 is that of a full depositional sequence, its basal breccia cannot be regarded as a simple breccia facies at the base of the MR1. Since the top of the Annot Sandstones is dated to the lower Rupelian (SZTRAKOS & FORNEL, 2003) and the MR1 is now dated to the upper Chattian (see below), the time bracket for deposition of sequence 1 corresponds to the late Rupelian, possibly extending into the early Chattian.

4.2.2. Age of sequence 2 (MR1-MG)

The recent discovery in the lower part of the MR1 deposits of a partial skeleton of *Mesacera-therium gaimersheimense* associated with a few teeth of the rodent *Issiodoromys limognensis* in the Rousset ravine (Esclangon) is additional compelling evidence that the base of the MR1 is placed in the late Chattian (mammal zone MP 28), the lower Chattian zones MP26 and 27 not being recognized (ANTOINE *et al.*, 2020). The superimposition of the Molasse Grise (MG) on the MR1 in the Esclangon area (Fig. 12) correlates with a similar succession recognized in the nearby Barrême syncline (CHAUVEAU & LEMOINE, 1961). Once

ascribed to the Aquitanian, the MG of the Barrême syncline was later ascribed a late Oligocene age on the basis of pollen, ostracods, charophytes and mammals (CARBONNEL *et al.*, 1972).

4.2.3. Age of sequence 3 (MR2)

On the basis of its lithological assemblage, the polygenic conglomerate (fluvial braid facies) at the base of the MR2 at Esparron and Esclangon is the lateral equivalent of the Montmaur conglomerate to the north and to the Grès Verts (Green Sandstones) in the Barrême syncline (JOURDAN *et al.*, 2013; GROSJEAN *et al.*, 2016, 2017). The Grès Verts of Barrême are interpreted as being deposited by a fluvial system. They are likely to be the southern distal facies of the braided Montmaur and Esparron conglomerates. The sandstone contains inner-Alpine serpentinite grains which are responsible for the greenish colour. The Grès Verts are considered to be Aquitanian in age (JOURDAN *et al.*, 2013; GROSJEAN *et al.*, 2016, 2017).

However, the tooth of *Ronzotherium velaunum* (GIGOT *et al.*, 1974) found at the base of the MR2 deposits in the Esparron syncline does not support such an age. According to TISSIER *et al.* (2021), the genus *Ronzotherium* does not extend into the Aquitanian. Therefore, the MR2 deposits of the Esparron syncline would have a latest Chattian age rather than Aquitanian.

This is also supported by upper Oligocene charophytes found in the upper Grès Verts of the Barrême syncline (CARBONNEL *et al.*, 1972).

4.2.4. Revision of the stratigraphic scheme

On the basis of the above results and discussion, we propose a reappraisal of the stratigraphic scheme for the Molasse Rouge *s.l.* (Fig. 19).

The marine "Nummulitic" succession, comprising in ascending order the Calcaire Nummulitique (Nummulitic Limestone), the Marnes Bleues (Blue Marls) and the Grès d'Annot (Annot Sandstones), of Priabonian to early Rupelian age (SZTRAKOS & FORNEL, 2003), is represented only by the shore facies of the Calcaire Nummulitique, *i.e.*, the bored boulders discovered in the Sardinières area (Figs. 7, 8.A-B). Overturned Tithonian limestone in the nearby tectonic slices of the Digne thrust (Fig. 7, cross-section in box) also show borings filled with *Nummulites*, supporting the occurrence of a rocky shore during the Nummulitic transgression (HACCARD *et al.*, 1984).

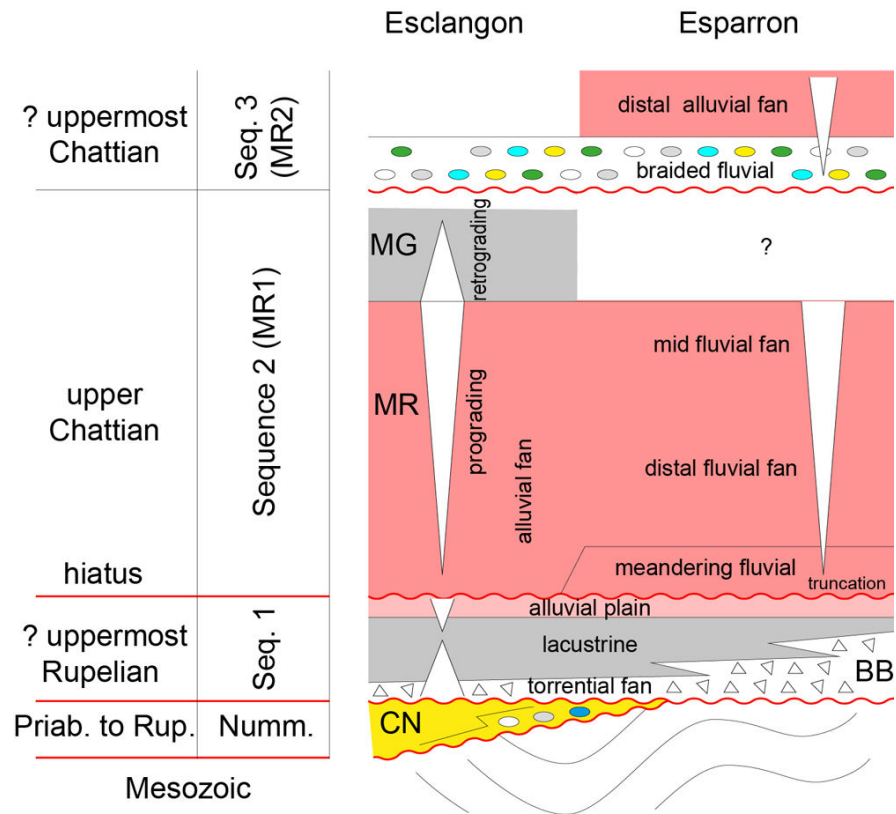
Based on the available evidence, the age of sequence 1 ranges between late Rupelian and early Chattian. Its continental facies cannot be correlated with Nummulitic marine deposits which are transgressive (Blue Marls). Sequence 1 is likely a full depositional sequence predating the deposition of the MR1.

Sequence 2 is likely entirely late Chattian, leaving at its base a stratigraphic hiatus longer than previously reported.

The age of sequence 3 (MR2) is likely latest Chattian, not Aquitanian, from the few biostratigraphic data available.



Figure 19: Revision of the stratigraphic scheme for the Molasse Rouge.



5. Conclusions

The comprehensive Molasse Rouge deposits of the Esparron-Esclangon area within the Digne nappe consist of three depositional sequences bounded by unconformities, which span the late Rupelian to late Chattian time interval. The Molasse Rouge successions mostly rest on folded Mesozoic deposits; whereas, the Nummulitic marine deposits of the Paleogene foreland basin are found mostly farther eastward. The westward shift of depocenters with time is evidence that the sequences were each deposited after a phase of tectonic deformation and erosion. The paleoflow direction for deposits of sequence 1 is toward the Alps, as reported in the literature. Its basal channelized breccia is a multi-sourced torrential system originating in a western high-relief region which is likely the border of a transported basin corresponding to the Digne nappe. The paleoflow direction of sequences 2 (MR1) and 3 (MR2) is reversed and reflects the erosion of upper Paleogene relief in the Alps. Sequences 2 and 3 have a similar vertical organization. They begin with deposits of low-gradient rivers (meandering in the MR1, large braided in the MR2), and finish with prograding alluvial fans. Such a pattern can be interpreted in terms of progressive foreland subsidence, beginning with a flattening of the landscape, and followed by uplift (relaxation of tectonic constraints), accounting for changes in the fluvial regime. This study therefore shows that upper Paleogene landscapes underwent drastic reorganizations associated with Alpine tectonics. The drainage of the MR1 and MR2 to the west, beyond the transported basin, remains elusive.

Acknowledgements

We thank the three reviewers for their comments (one French, two Americans). The sound suggestion to use the difference between alluvial and fluvial fans is taken into account in the revised version. However, we do not agree with the suggestion to follow the now common practice of using facies associations (FAs) for a number of reasons which are beyond the scope of this paper. Special thanks to W. LITTLE (Colorado) and S. CAREY (Australia) for their careful checking of the manuscript.





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Plates

Plate 1: Facies of the Esparron road section (section 1, Fig. 1.B. A, aerial view of the NW termination of the Esparron syncline showing the sharp thickening of sequence 1 on the axis of the syncline; B, Detail of the onlap of basal breccia beds on the northern flank; C, ravinement surface at the base of sequence 1; **D**, coarse-grained gullied breccias alternating with the larger channelized breccias (Fig. 1.B) within the lower part of sequence 1; **E**, large channel filled with matrix-supported breccia; **F**, transition to the lacustrine-to-palustrine facies in the middle part of sequence 1 (palustrine beds show closely spaced vertical root casts); **G**, lacustrine-to-palustrine facies devoid of breccia beds in the middle part of sequence 1; **H**, fluvial facies marking the upper part of sequence 1 (JACOB staff, circled, for scale).





Plate 2: Facies of the Patègue (section 2, Fig. 1.B). **A**, view of the basal breccia of sequence 1 overlain by a lacustrine-to-palustrine facies (bbr, basal breccia; Cr, Cretaceous deposits); **B**, Aerial view of the Patègue summit with deposits of sequences 1 and 2 indicated; **C**, view of the succession of the Patègue summit; **D- E**, close view of the breccia beds (matrix- or grain-supported) composing the basal breccia of sequence 1; **F**, closer view of the upper part of sequence 1 showing the transition from the grey-to-whitish lacustrine-palustrine facies to the reddish claystone-to-siltstone deposits of the uppermost alluvial-plain facies of sequence 1 (note the repeated occurrence of whitish beds (? palustrine) in the red deposits); **G**, close view of palustrine beds in the middle part of the succession, showing vertical root casts, especially in palustrine sequence p1.

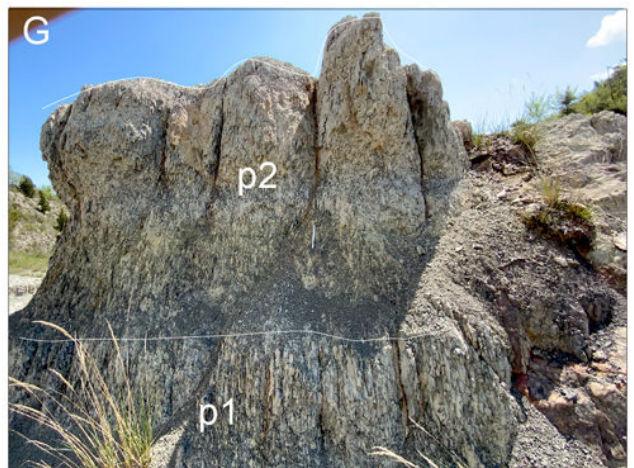
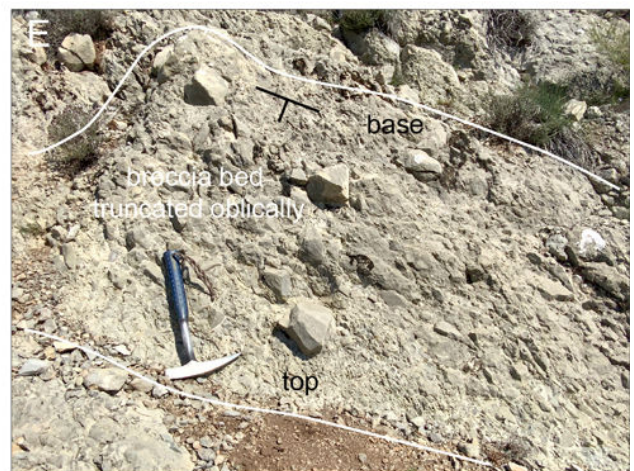
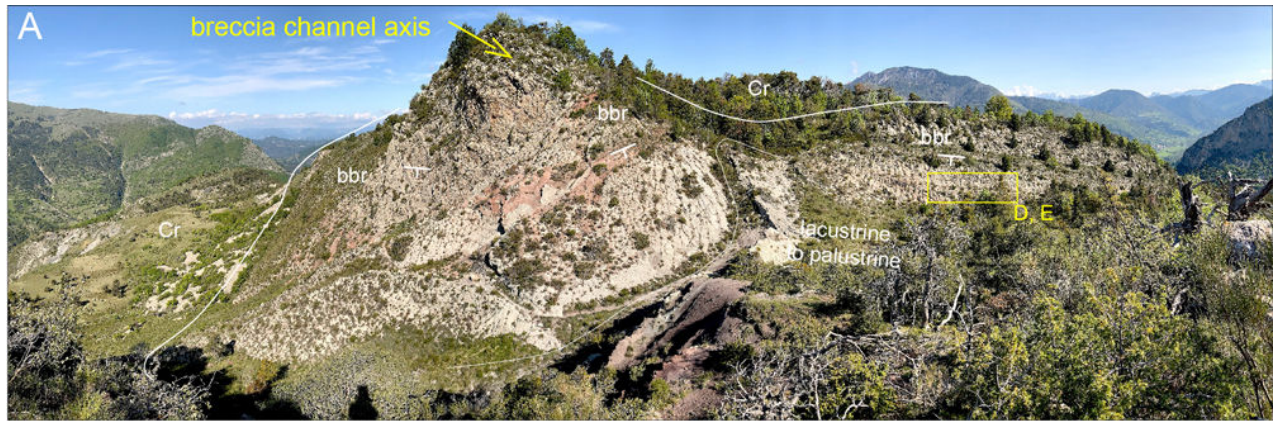




Plate 3: Lateral continuity of sequences 1 and 2 along the SW flank of the Esparron syncline.

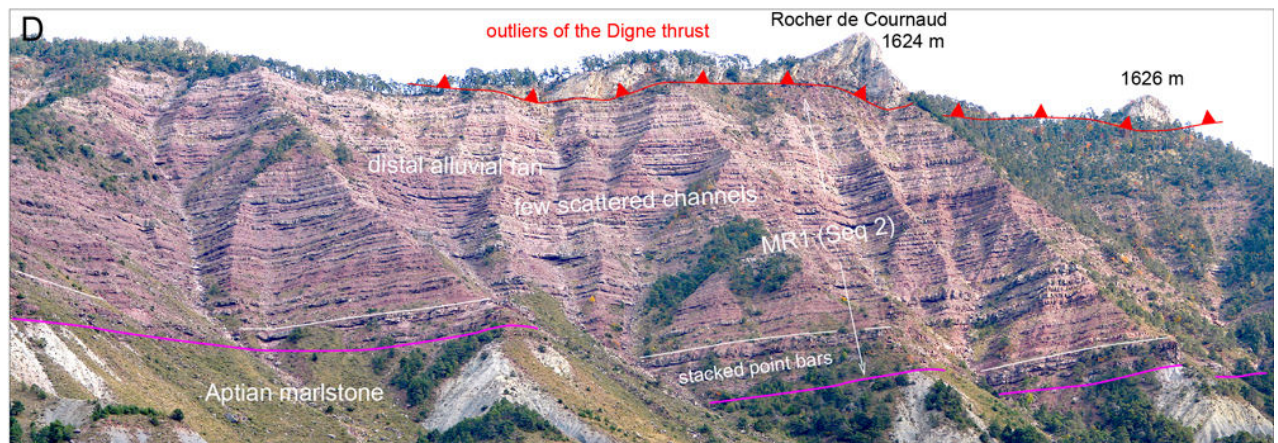
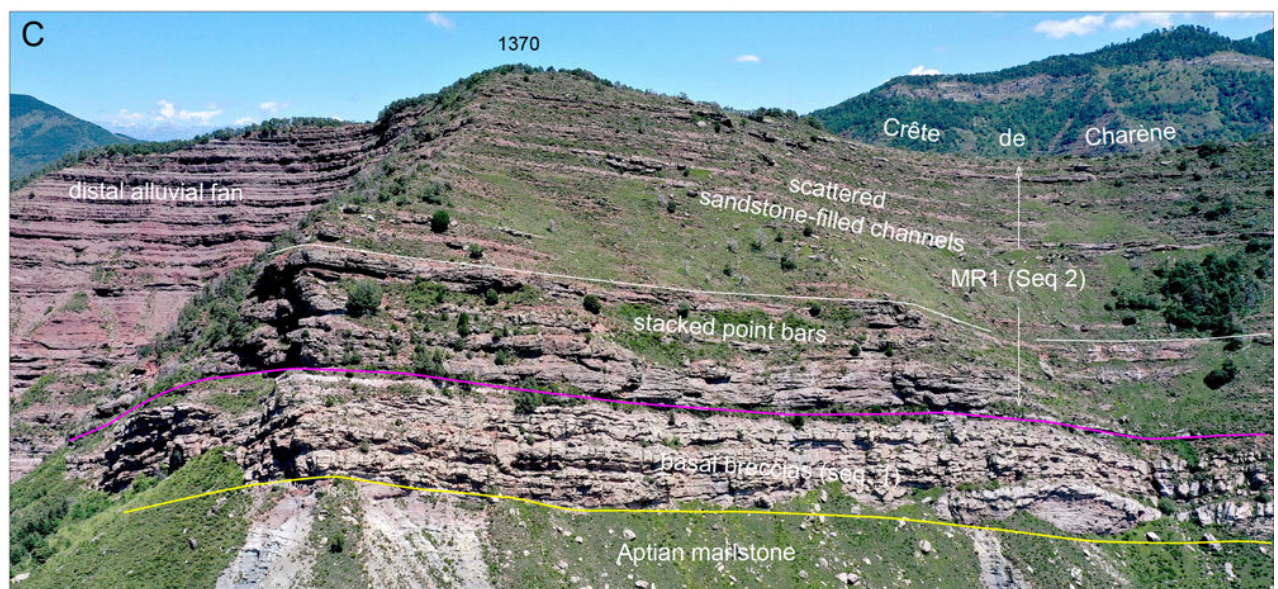
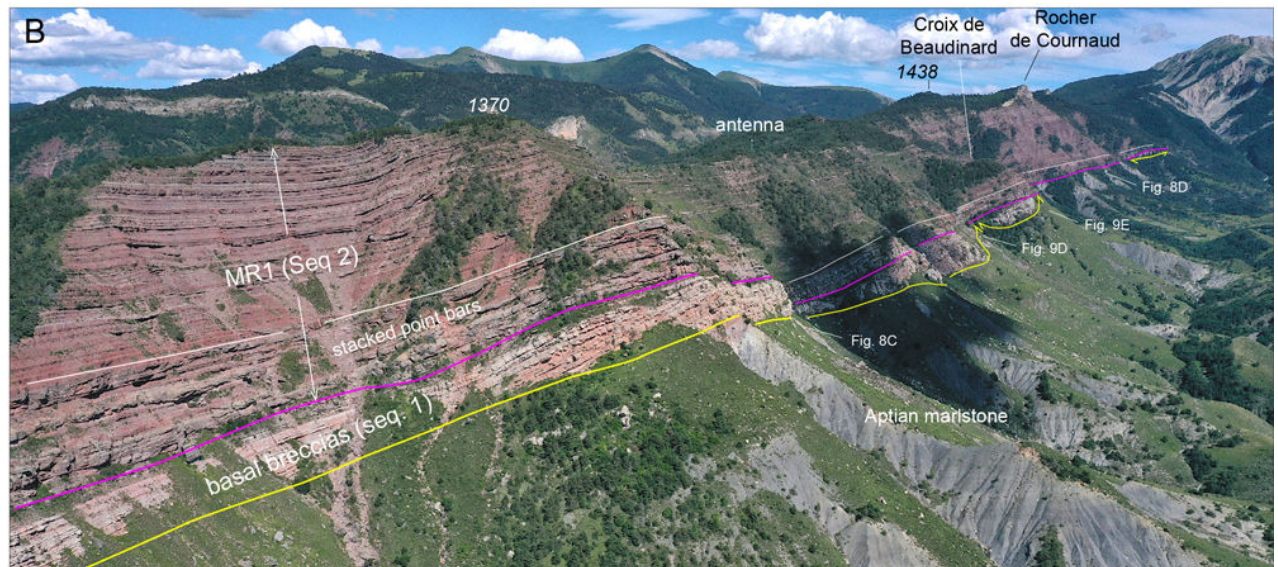




Plate 4: Facies of the breccia at base of sequence 1 along the southern flank of the Esparron syncline. **A**, General view showing the superimposition of two subunits (a, complex geometry due to nested channelized breccia beds; b, more regularly stratified breccia beds); **B**, closer view of subunit a; **C**, internal structure of a breccia bed in subunit b; **D**, laterally continuous breccia bed made of angular, unsorted material within subunit b; **E**, General view, close to Beaudinard hamlet, showing the relationships between subunits a and b (note the isolated channel (subunit a) with nested breccia bodies to the right); **F**, closer view of the lateral onlap of subunit 2 showing the transition to finer-grained deposits; **G**, view of the front of a debris flow on a modern torrential fan for comparison with breccia beds of sequence 1.

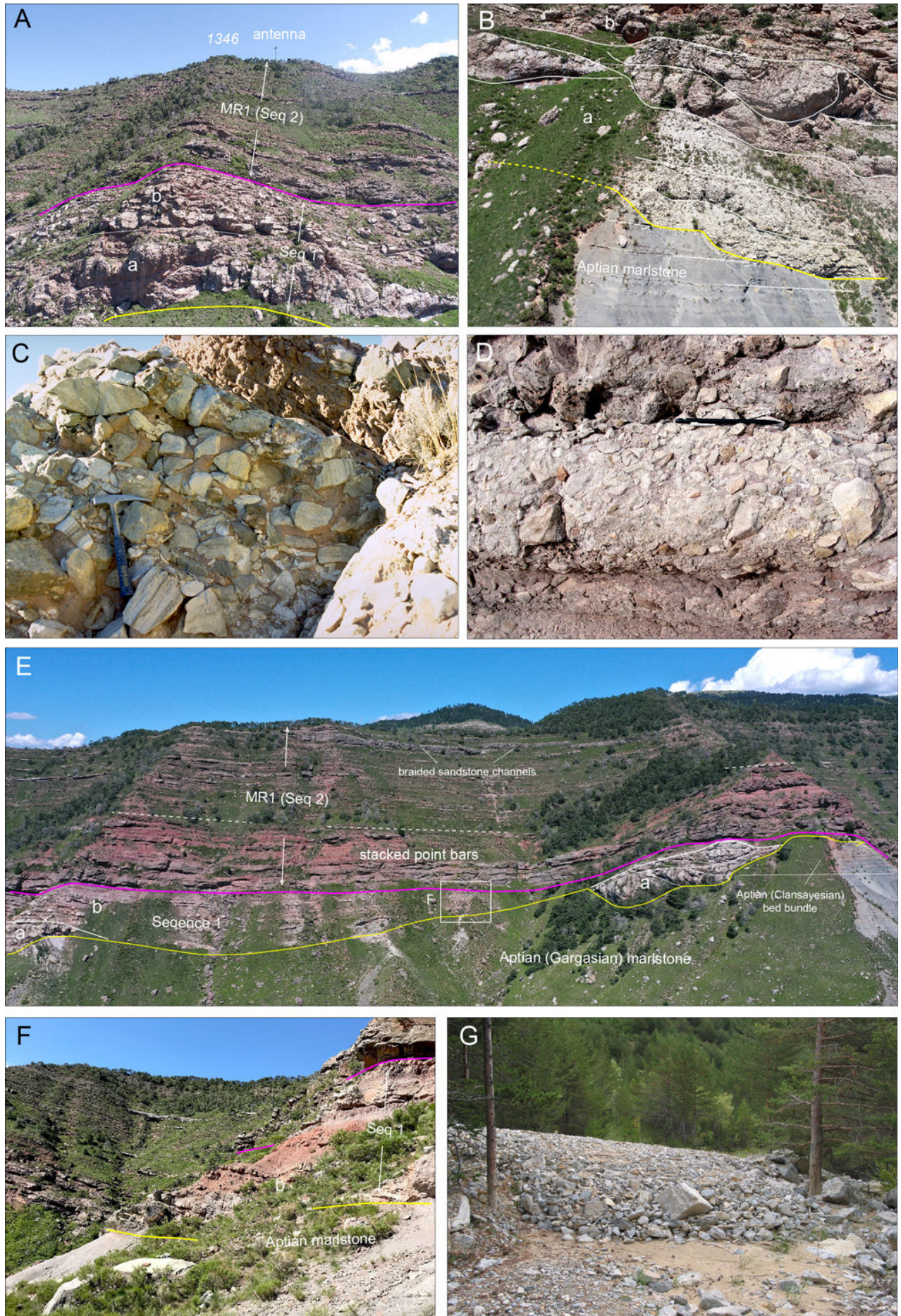




Plate 5: Facies of sequences 1 to 3 in the Esclangon area. **A**, Channelized breccia at base of sequence 1; **B**, closer view of the ungraded breccia within a torrential debris flow lobe; **C**, Channelized sandstone beds within the MR1; **D**, red siltstone beds representing overbank lobes within the MR1; **E**, section across an overturned sandstone-filled channel showing low-angle cross lamination and small-dune cross lamination; **F**, paleosols (underlined) within the lower part of the MR1 (path to the Vieil Esclangon) showing calcified root casts; the upper dark-grey claystone is likely a lateral equivalent of the level that yielded several teeth of the rodent *Issiodoromys limognensis* (ANTOINE *et al.*, 2020) in the nearby Rousset ravine, see text; **G**, view of a block of polygenic conglomerate forming the base of the MR2, carried by the Rousset stream from the front of the Digne thrust; **H**, closer view of the conglomerate showing a diverse lithological assemblage, including red chert (not radiolarites).

