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Abrupt increase in seasonal extreme precipitation at the Paleocene-Eocene boundary

This Data Repository (DR) item provides supplementary information to the paper above, mainly in graphic formats, DR Figures 1 to 8, that are briefly discussed below.

DR Fig. 1A is a paleogeographic reconstruction of the study area during Paleocene time. This reconstruction is based on: (a) facies and facies associations of the outcropped "Garumnian" (= Tremp Group) deposits; (b) paleocurrents, mainly obtained from clast imbrications and cross-strata; (c) clast composition of conglomerates and sandstones, which demonstrate a derivation from lower and upper Cretaceous carbonate rocks, and (d) a paleotectonic restoration of the area for P-E boundary time, modified from Teixel and Muñoz (2000), which shows that these Cretaceous source rocks were uplifted 10 to 15 km to the north of the present day Garumnian outcrops (**DR Fig. 1B**).

As shown in the reconstruction, the bulk of the Paleocene rocks outcropped in the studied sections were deposited in a coastal alluvial plain adjacent to a wide shallow-water carbonate platform, recorded in boreholes in the SW part of the study area and extensively exposed to the west of the Tremp-Graus basin (Baceta et al., 2004).

Two different Paleocene facies associations can be recognized: in outcrops of the central and eastern parts of the study area (e.g., Berganuy, Esplugafreda, Gurp, Tendrui and Claret sections), the succession is mainly composed of red silty mudstones, calcarenites and calcareous conglomerates. The mudstones contain numerous carbonate-rich paleosols, with well-developed Bca horizons. The calcarenites and conglomerates generally occur as multi-storey channelized bodies ranging 2-9 m in thickness and 10-200 m in lateral extent and exhibit cross-bedding and clast imbrication. This entirely continental facies association is customarily interpreted as having been deposited by fluvial channels derived from alluvial fans (e.g., Cuevas, 1992; Rosell et al., 2001). This interpretation can be confirmed in one small outlier of Garumnian deposits preserved about 30 km east of Tremp, in the Coll de Nargó area (Robador, 2005). As shown in **DR Fig. 1C** the Paleocene is represented there by conglomerates that clearly correspond to proximal parts of alluvial fans, or alluvial fan cores. These, in turn, evolve down-current to a more fine-grained facies association, similar to that of the study area, which obviously represent more distal alluvial deposits, or fan-fringe facies. Incidentally, it is worth noting that the width of the conglomeratic cores of the Coll de Nargó Paleocene alluvial fans are less than 1 km in dip section, an order of magnitude smaller than the confirmed width of the Claret Conglomerate.

Paleocene sequences of the western outcrops (e.g., Serraduy, Rin, Merli, S Martín, La Cinglera and Campo) are made up of alternations of mudstone-dominated alluvial deposits and very shallow marine carbonates. Such mixed marine-continental alternation is clear proof of repeated transgressions and regressions in the strip of the coastal plain bordering the Paleocene sea.

This paleogeography, which lasted with little changes for ca. 10 Myr, was abruptly altered at the onset of the PETM interval by the development of a vast megafan of far greater magnitude than the former Paleocene fans. This megafan is represented by the Claret Conglomerate and its laterally correlative sandstones and pebbly sandstones.

DR Figures 2 and 3 illustrate P-E boundary sections and isotope profiles representative of the outcrops in the central and eastern part of the studied transect. The Claret Conglomerate is underlain by red mudstones with soil nodules giving $\delta^{13}C$ values ranging between -8 to –6 ‰ (i.e., pre-CIE), and overlain by yellowish mudstones with soil nodules giving $\delta^{13}C$ values of around -13 ‰ (i.e., typical full CIE values). In addition, nodules from the upper part of the Claret Conglomerate in the Berganuy and Esplugafreda-B sections give “intermediate” isotopic values, a key evidence that the Claret Conglomerate was deposited at the onset of the PETM.

DR Fig. 4 depicts P-E boundary sections and isotope profiles of the western outcrops. The isotopic results are very similar to those of the sections in DR Figs. 2 and 3: pre-CIE $\delta^{13}C$ values were recorded at Rin and Campo just below the Claret Conglomerate; intermediate $\delta^{13}C$ values were obtained at Campo in the upper part of the Claret Conglomerate, and peak CIE $\delta^{13}C$ values were obtained in the yellowish soils overlying the Claret Conglomerate at Rin and La Cinglera.

DR Fig. 5 demonstrates a key feature of the Claret Conglomerate, namely its striking lateral continuity along almost the entire 50 km east-west transect studied.

DR Fig. 6 offers details of the internal architecture of the Claret Conglomerate. The three photos respectively contain examples of: (A) lateral accretion; (B) cross-cutting channeling; and, (C) two sets of large-scale inclined strata, probably recording a compound braid bar. All these features make obvious the polyphased character of the unit. For a recent discussion on lateral accretion, see Lunt et al. 2004.

DR Fig 7 shows the clast-supported nature of the Claret Conglomerate, its polyphased character and its coarse-grained nature.

DR Fig 8 is intended to give a wider view of the geological setting of the study area. It shows the present day outcrops and structure of the Pyrenees, an E-W oriented collision mountain belt situated along the boundary of mainland Spain and France, with a Mesozoic-Cenozoic history controlled by the interaction of the European and Iberian plates. A string of rapidly subsiding interplate sedimentary basins were created during a distension period that extended from the early Triassic to the early Santonian time. The coming together of the two plates during late Santonian-early Miocene interval created N-S directed compressional conditions that caused the inversion and deformation of the former Mesozoic basins and eventually their emergence. Post-orogenic uplift, distension and erosion sculptured the present day outcrops (DR Fig. 1A). A shortening of 150-165 km has been calculated in the central Pyrenees for the whole compressional phase (Muñoz, 1992; Teixel, 2004). This was accomplished, at depth, by a partial subduction of the plates and at shallower structural levels by the stacking of northwards and southwards directed thrust sheets that created foreland basins (DR Fig. 1B).

The process was pulsating, with alternating phases of active thrusting and tectonic quiescence (Puigdefábregas et al., 1992; Pujalte et al., 2002).

Thus, two main episodes of active trusting have been recognized, which respectively occurred during the late Santonian-late Maastrichtian, and the middle Ilerdian-middle Lutetian intervals (Puigdefábregas et al., 1992), both characterized by enhanced differential subsidence and high sedimentation rates, and also by an initial phase of rapid facies deepening followed by a long phase of gradual facies shallowing. By contrast, the latest Maastrichtian early Ilerdian interval was a time of subdued tectonism, not only of the Tremp-Graus basin but in the whole Pyrenean realm, reflected in slow and homogeneous subsidence rates in the study area and elsewhere, as recorded by successions of comparatively modest thickness (Muñoz, 2002; Pujalte et al., 2002; Baceta et al., 2004). In this context, it is worth exploring the possible influence of tectonic, climatic and other factors in the development of the Claret Conglomerate.

As pointed out by Heller and Paola (1992), progradation of alluvial conglomerates can be due to:

1, an increase in sediment flux following tectonic uplift and erosion of source areas
2, a decrease in basin subsidence rates
3, a relative sea-level fall
4, an increase in rainfall enhancing the discharge of streams and their capacity to transport gravel.

Tectonic uplift was certainly the main forcing mechanism for the progradation of the thick Lutetian conglomerates of the study area, which were deposited during the main phase of thrusting in the Pyrenees and show evidence of their syntectonic character, including growth strata and internal unconformities (Barnolas et al., 2004).

On the other hand, the encroachment of “Garumnian” continental conditions in the study area can best be explained by the coeval marked decrease in subsidence rates during the late Maastrichtian to early Ilerdian. It is worth noting, however, that because of such low subsidence rate, any further reduction in subsidence rate during this interval could only have been of small magnitude. Therefore, it would be unrealistic to think that the important progradation recorded by the Claret Conglomerate was linked to a decrease in subsidence.

A relative lowering of sea level coeval with the Claret Conglomerate can be ruled out on the base of field evidence (Pujalte and Schmitz, 2005).

In conclusion, as argued in the paper, the most plausible cause to explain the rapid progradation of gravel recorded by the Claret Conglomerate is a dramatic increase in seasonal rainfall at the onset of the PETM warming.

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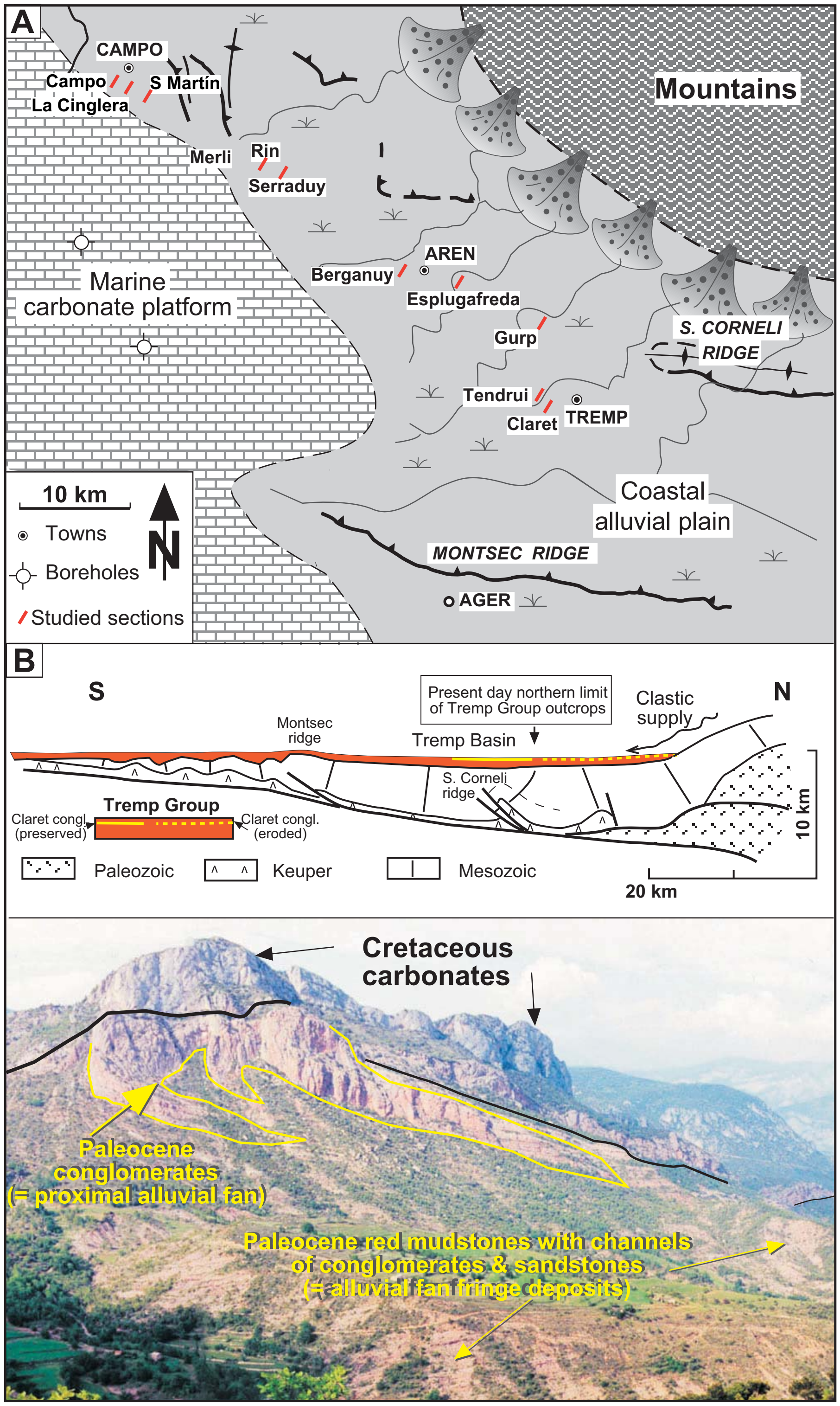
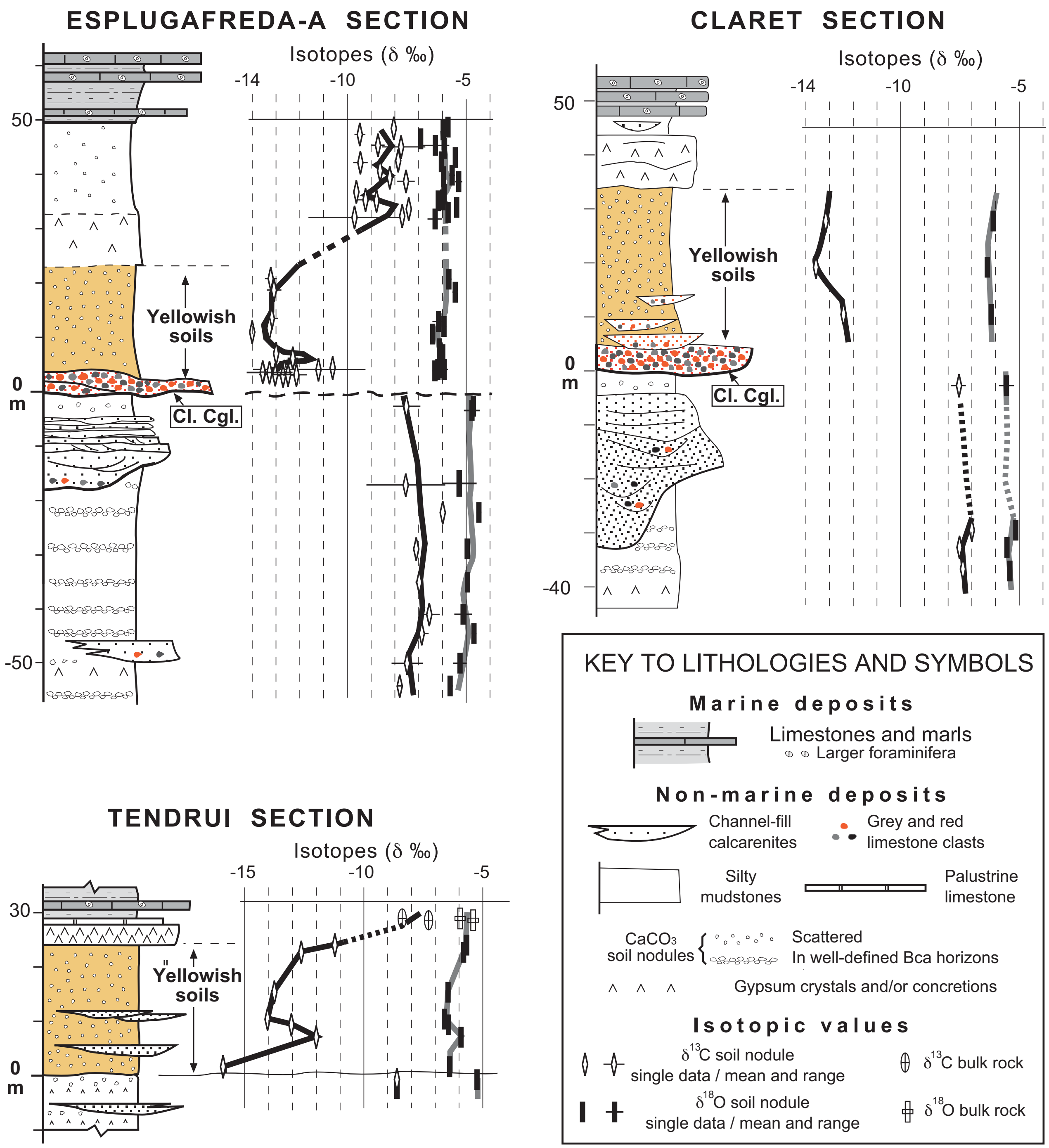
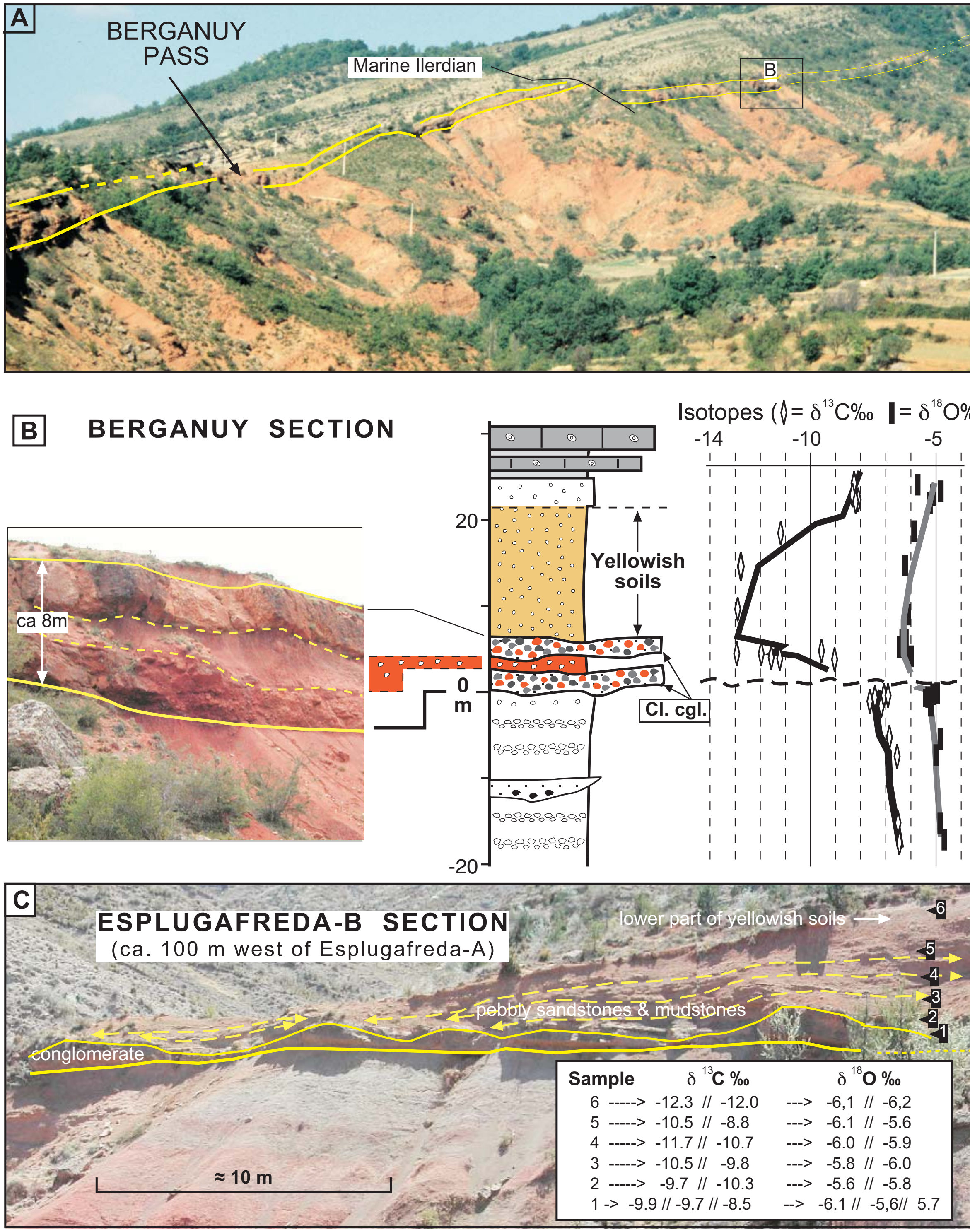


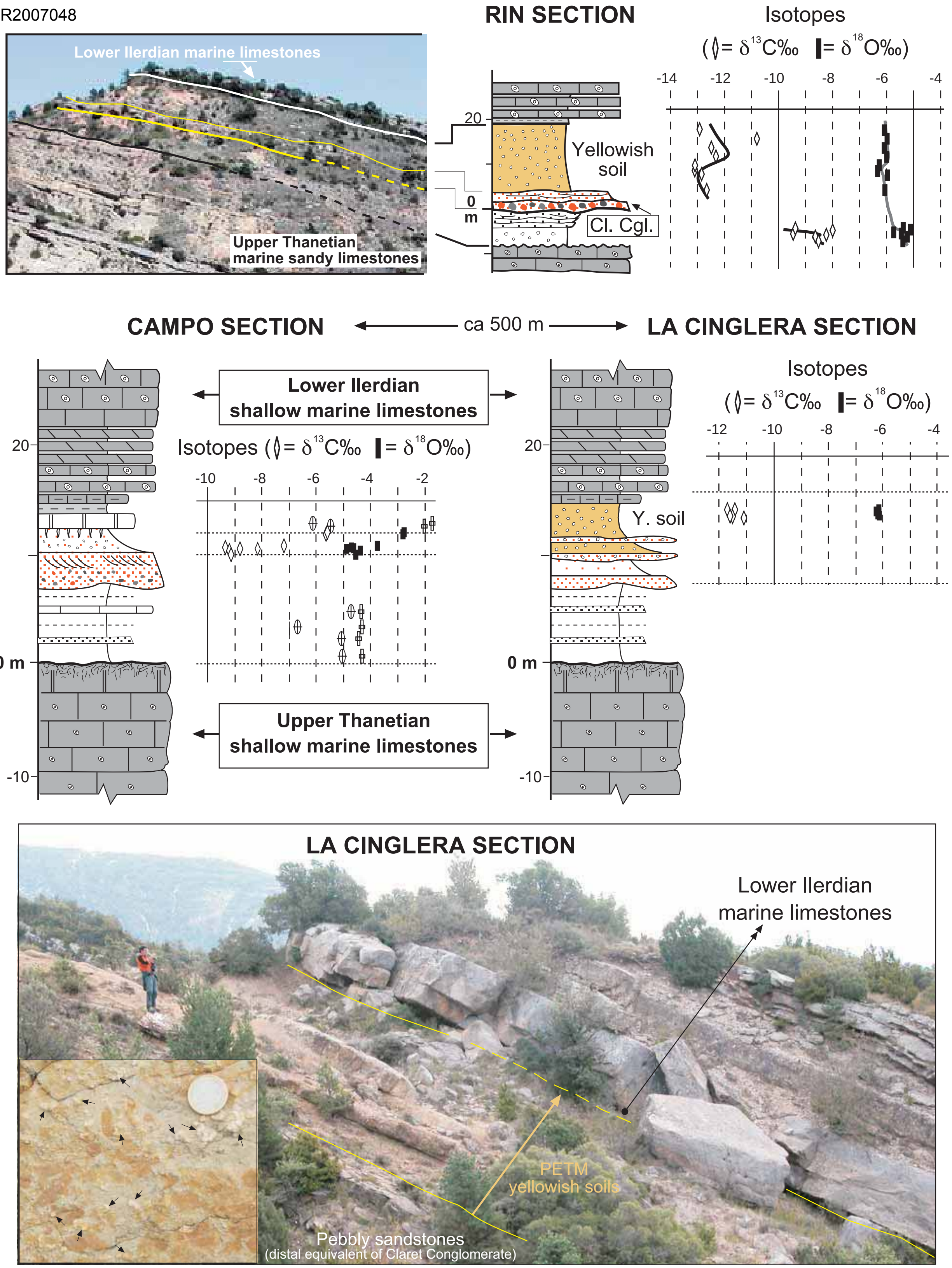
DR Fig. 1: (A) Reconstructed paleogeography of the study area for mid-Paleocene time. (B) S-N structural restoration of the study area for early Ilerdian time through the Aren meridian (based on Teixel and Muñoz, 2000) .
(C) Outcrop of Garumnian deposits in the Coll de Nargó area, looking north (photo courtesy A. Robador). This outcrop, placed 30 km to the east of Tremp, shows Paleocene conglomerates pinching out within a succession of red mudstones, conglomerates and sandstones. The former represents proximal parts of small-sized alluvial fan, the latter their lateral equivalents, or fan fringe. Field view width is just above 1 km.



DR Fig. 2: Isotopic profiles across the P-E boundary in three representative sections of the central and eastern outcrops (locations in Fig. 1 and DR Fig. 1; Esplugafreda-A and Tendrui sections modified from Schmitz and Pujalte, 2003). Tendrui is a rare example of a section in the study area where the Claret Conglomerate is missing below the yellowish soils.



DR Fig. 3: (A) General view of the Garumnian continental red beds and the overlying Ilerdian marine carbonates in the Berganuy pass area. The laterally extensive Claret Conglomerate (yellow lines) rests here on a mudstone-dominated Paleocene succession. (B) Isotopic profiles across the P-E boundary at the Berganuy section (location in Fig. 1 and DR Fig. 1; for legend, see box in DR Fig.2), and close-up showing the red soil intercalated in the Claret Conglomerate. (C) Field photo of the Esplugafreda-B section, where the lower part of the Claret Conglomerate is made up of conglomerates, while the upper part consists of an alternation of pebbly-sandstone and mudstones with carbonate soil nodules and rhizoconcretions. The mounded upper topography of the lower conglomerate is thought to represent the top of gravely bars, which were onlapped by the pebbly sandstones after the flow decreased. Isotopic values from soil concretions in mudstone interbedded with the sandstones (samples 1 to 5) and from the overlying yellowish soils (sample 6) are shown in the box.



DR Fig. 4: Isotopic profiles and field photos across the P-E boundary in three representative sections of the western outcrops (location in Fig. 1 and DR Fig. 1; Campo section modified from Schmitz and Pujalte, 2003; for legend of logs see box in DR Fig. 2). The photo of La Cinglera section only shows the upper part of the outcrop (compare with log). The small photo in the lower left conner is a close-up of the yellowish soils, showing mottling and small carbonate nodules (some of them arrowed).

The location of the CC/yellowish couplet between Thanetian and Ilerdian marine carbonates in these sections is irrefutable proof that the couplet represent the PETM and not a younger or older thermal event.

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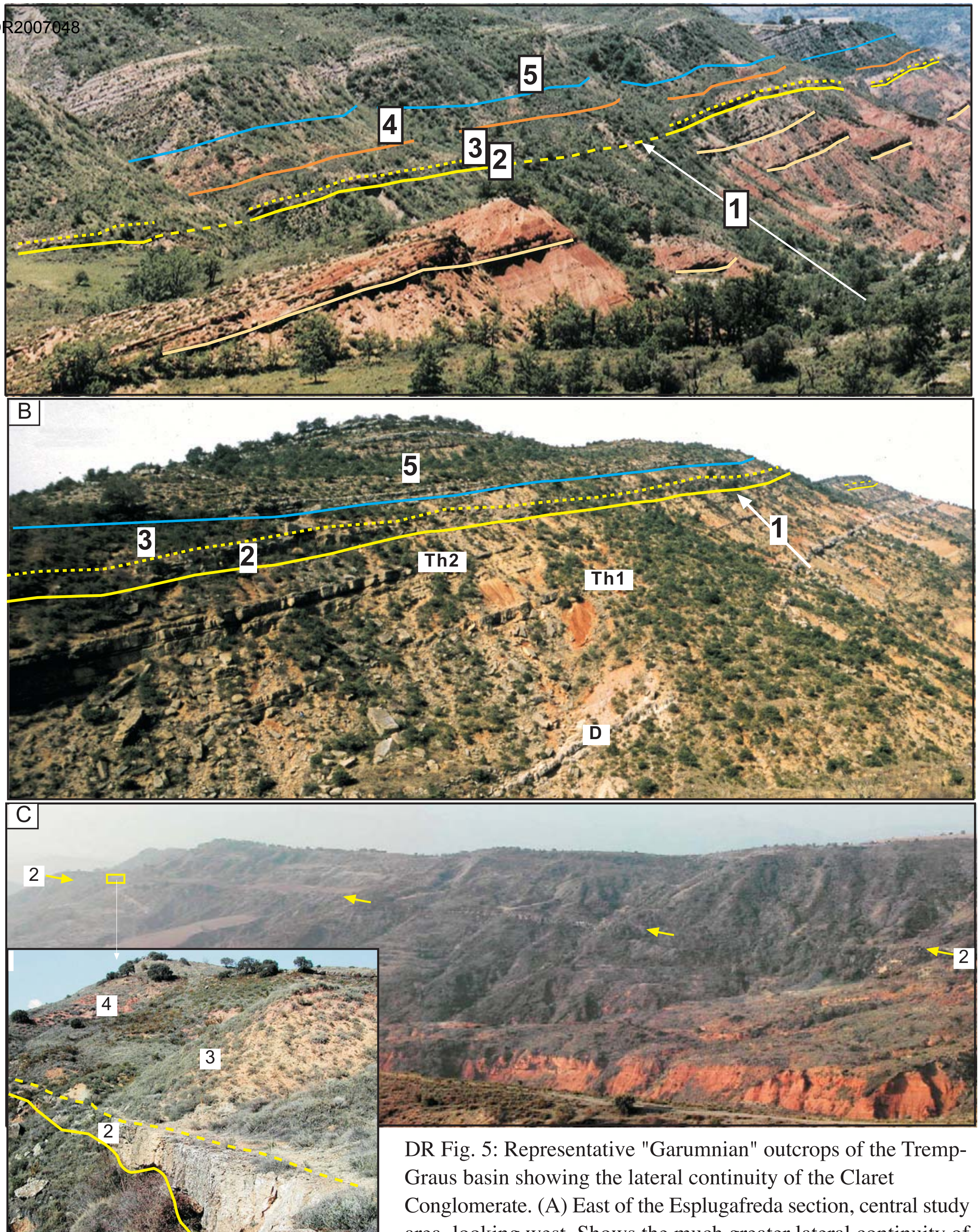
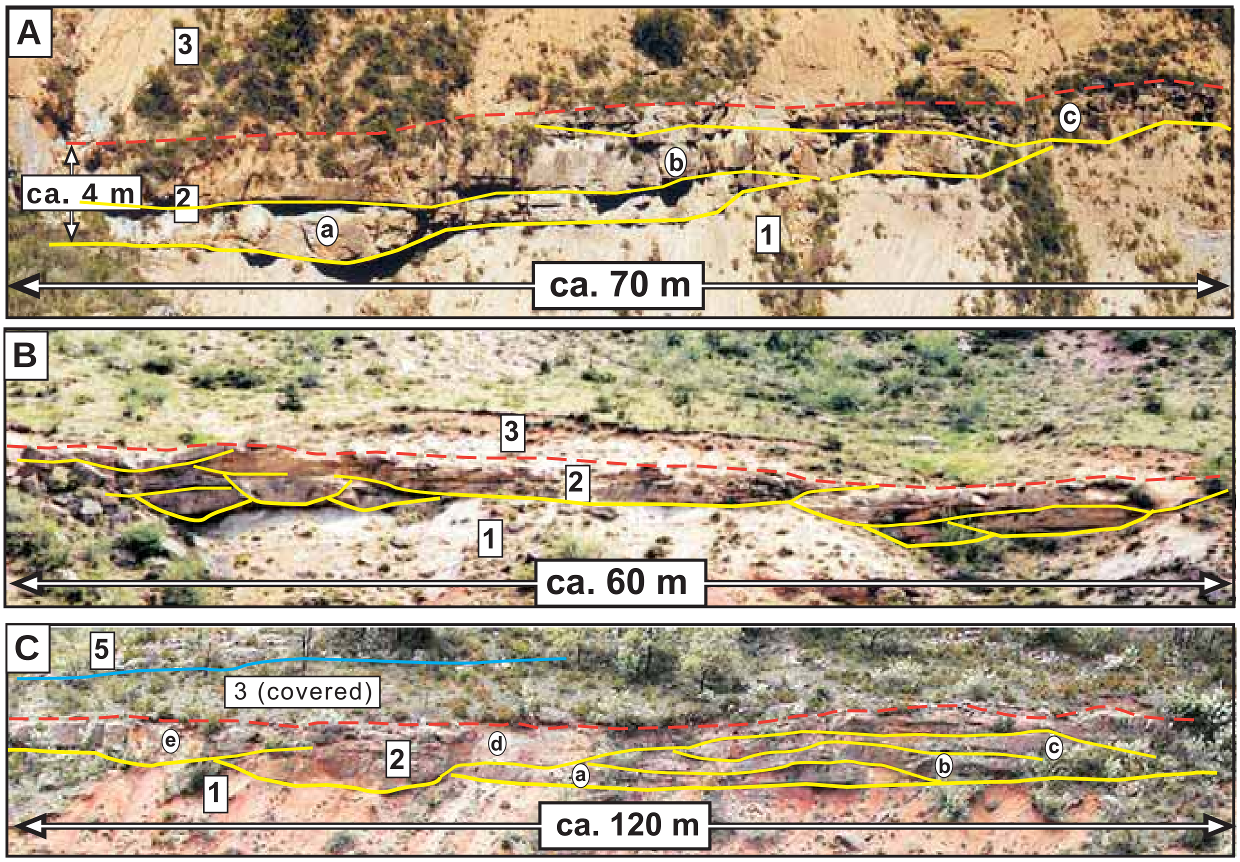
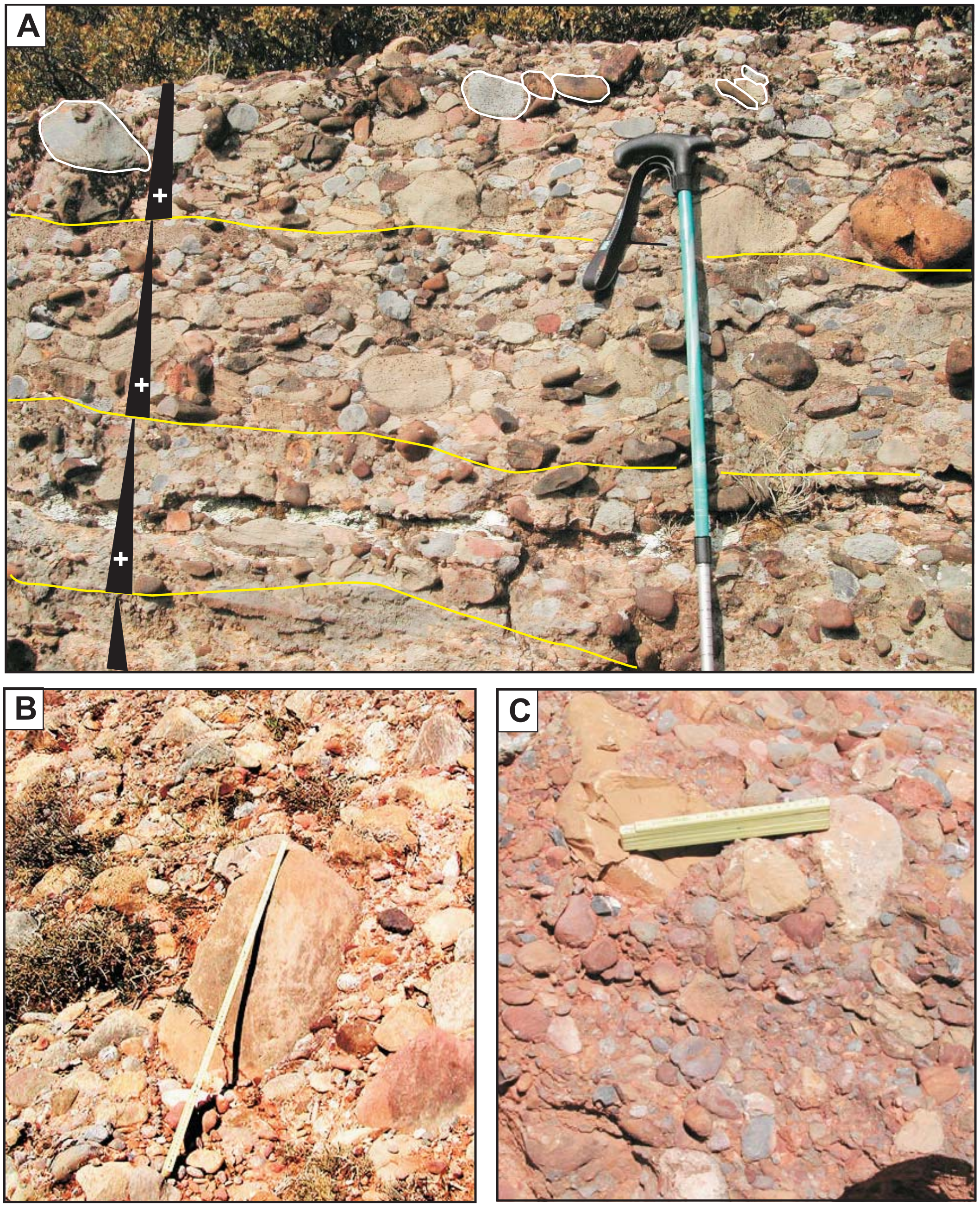


DR Fig. 5: Representative "Garumnian" outcrops of the Tremp-Graus basin showing the lateral continuity of the Claret Conglomerate. (A) East of the Esplugafreda section, central study area, looking west. Shows the much greater lateral continuity of the Claret Conglomerate (yellow lines) relative to the underlying Paleocene channel-fill deposits (light brown lines). Field view width is ca. 2 km. (B) Serraduy area, looking west. Shows the great lateral persistence of the Claret Conglomerate also in the western outcrops (D = Danian palustrine limestones; Th 1 & Th 2 = lower and upper Thanetian shallow-marine sandy limestones). Field of view is ca. 1.5 km. (C) Gurp area, eastern outcrops, looking south: while this area is less well outcropped than the two above, the Claret Conglomerate can still be traced in the landscape (yellow arrows) due to its greater resistance to erosion than the mudstones above and below it. Field of view is ca. 2 km. Inset: Close up view of the outcrop, showing the Claret Conglomerate and the overlying yellowish soil.

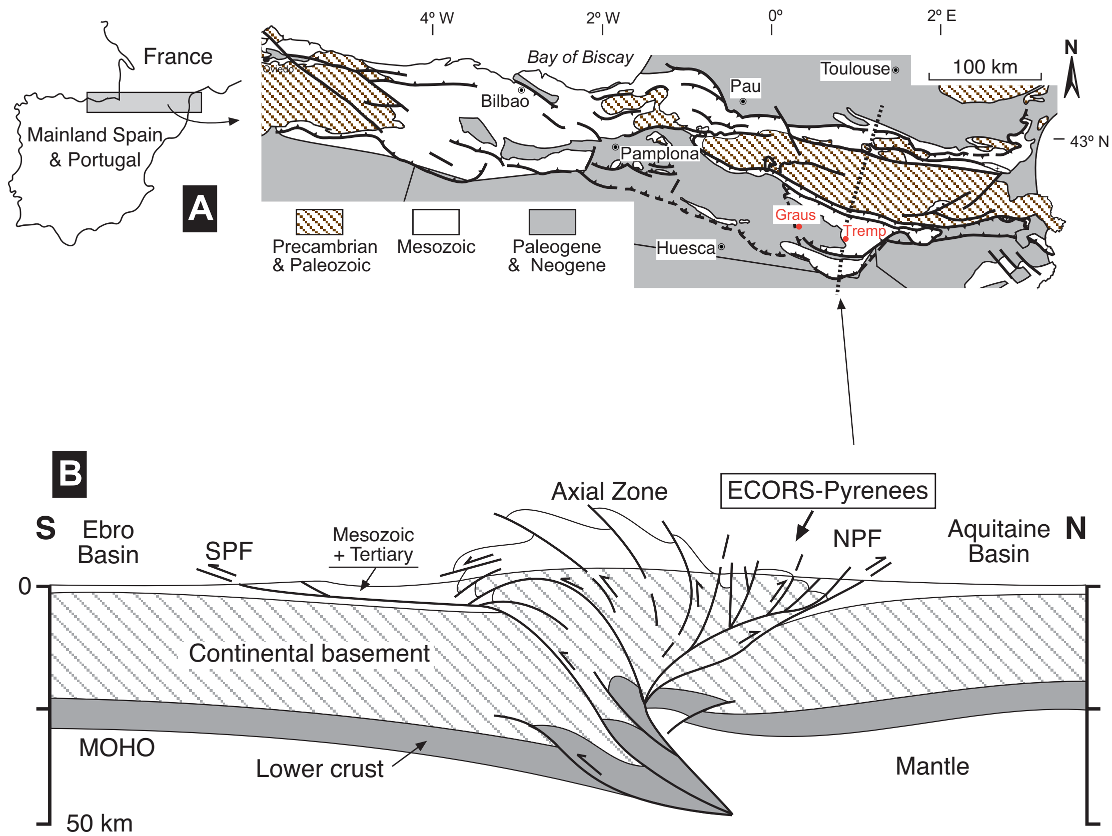
Key: 1 = Paleocene red beds; 2= Claret conglomerate, base of PETM interval; 3= yellowish cumulate soils; 4= post-PETM red soils (absent at Serraduy); 5= base of marine Ilerdian (lower Ypresian) deposits.



DR Fig. 6: Internal architecture of Claret Conglomerate:
A, Large-scale low-angle inclined strata (a, b, c) recording lateral accretion (about 1 km east of the Esplugafreda section).
B, Cross-cutting channelling, a typical feature of braided streams (about 300 m east of the Esplugafreda section).
C, Two sets of large-scale low-angle inclined strata (a,b,c/d,e), probably recording a compound braid bar (Serraduy section).
Key: 1 = Paleocene red beds; 2= Claret Conglomerate; 3= yellowish cumulate soils (covered at Serraduy).
5= Ilerdian marine limestones



DR Fig. 7: Close-up photos of the Claret Conglomerate showing its clast-supported nature. (A) Claret locality, view in vertical section. Stacked fining-up depositional units (delineated by yellow lines) and clast-imbrication (some of them delineated in white) (for scale, the bluish part of the stick is 43 cm). (B) Berganuy section, plan-view. Shows the coarse-grained nature of the Claret Conglomerate clasts, the one in the foreground being 65 cm (measuring rule = 1 m). (C) Berganuy section. Abundant red limestone and sandy limestone clasts is a common feature of the Claret Conglomerate (measuring rule = 20 cm).
For location of sections see Fig. 1 and DR Fig. 1.



DR Fig. 8: (A) Simplified outcrop map of the Pyrenees and situation of the Tremp-Graus basin (B) Interpreted crustal structure of the mountain chain along the ECORS profile, (after Muñoz, 1992).