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Basement-involved thrusting, salt migration and intramontane conglomerates: a case from the Southern Pyrenees

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Abstract – The northern margin of the Organyà basin (Southern Pyrenees) has a complex structure in which syn-rift Lower Cretaceous carbonates flank a wide Keuper evaporite province, featuring the leading edges of the basement-involved thrust sheets of the Pyrenean antiformal stack. Recent studies show that Keuper diapirs and salt walls grew during the Cretaceous extensional episode, conditioning the development of differentiated depocenters and minibasins. The role of salt tectonics during the Pyrenean orogeny has not been addressed in previous structural studies, but present-day cross-sections indicate a Keuper evaporite-bearing vertical thickness of up to 3000 m in the Senterada-Gerri de la Sal area. We infer that salt migration was a determinant mechanism in triggering a gentle northward tilting of the Organyà basin during the Eocene-Oligocene, recorded in the La Pobla de Segur and Gurp syn-tectonic conglomerates in a large north-directed onlap, opposite to the main sedimentary influx direction. Contemporaneously, we interpret that salt migration, promoted by conglomerate differential loading, enabled the sinking and rotation of the unrooted Nogueres thrust units (*têtes plongeantes*). We use new and published structural data for the Lower Cretaceous margin of the Organyà basin, combined with structural and clast provenance data from the Cenozoic alluvial fan conglomerates of La Pobla and Gurp, to understand the Lutetian to late Oligocene evolution of the northern margin of the Central South-Pyrenean Unit. The tectono-sedimentary evolution of this area and the salt evacuation patterns are closely related to the exhumation history of the stacked Paleozoic thrust sheets of the Pyrenean hinterland to the north. In this study, we correlate the movements over a mobile substratum and the paleogeographic changes of conglomeratic basins at the toe of an exhuming orogenic interior.

Keywords: Salt tectonics / Antiformal stack / Basement thrusting / Alluvial fans / Differential loading / Routing systems / Pyrenees

Résumé – Chevauchements de socle, migration du sel et conglomérats intramontagneux : un cas des Pyrénées méridionales. La marge nord du bassin d'Organyà (Pyrénées méridionales) présente une structure complexe dans laquelle les carbonates du Crétacé inférieur, syn-rift, flanquent un vaste domaine d'évaporites du Keuper, en interaction avec la partie frontale des nappes chevauchantes de l'empilement axial pyrénéen (têtes plongeantes des Nogueres). Des observations récentes montrent que des diapirs de Keuper se sont développés pendant l'épisode d'extension crétacée, conditionnant le développement de dépocentres et de minibassins différenciés. Le rôle de la tectonique salifère pendant l'orogenèse pyrénéenne n'a pas été abordé dans ce secteur dans les études structurales précédentes, mais les coupes transversales actuelles indiquent une épaisseur verticale de Keuper à évaporites allant jusqu'à 3000 m dans la région de Senterada-Gerri de la Sal. Nous en déduisons que la migration du sel a été un mécanisme déterminant dans le déclenchement d'un léger basculement vers le nord du bassin d'Organyà pendant l'Éocène-Oligocène, enregistré dans les conglomérats syn-tectoniques de La Pobla de Segur et de Gurp par un onlap régional dirigé vers le nord, à l'opposé de la direction principale du flux sédimentaire. Simultanément, la migration du sel, favorisée par la charge différentielle des conglomérats, a permis l'enfoncement et la rotation des têtes plongeantes des Nogueres, séparées de leur racine par l'érosion. Nous utilisons des données structurales nouvelles et publiées sur la marge du Crétacé inférieur du bassin d'Organyà, combinées aux données structurales et de provenance des clastes des conglomérats alluviaux du Cénozoïque de La Pobla et de Gurp, pour comprendre l'évolution du Lutétien à l'Oligocène tardif de la marge nord de l'Unité Sud-Pyrénéenne

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Centrale. L'évolution tectono-sédimentaire de cette zone et les modèles d'évacuation du sel sont liés à l'histoire de l'exhumation des nappes chevauchantes de matériel paléozoïque empilées au nord dans la Zone Axiale pyrénéenne. Dans cette étude, nous corrélons les mouvements sur un substrat mobile avec les changements paléogéographiques des bassins conglomératiques au pied d'un intérieur orogénique en exhumation.

Mots clés : Tectonique salifère / Chevauchements de socle / Éventail alluvial / Charge différentielle / Systèmes de routage sédimentaire / Conglomérats / Pyrénées

1 Introduction

In basins that evolve on top of thick evaporite detachment levels, differential loading of prograding sedimentary systems triggers salt mobilization towards areas with a smaller overburden load and an associated depocentre migration (Ge *et al.*, 1997). In salt-bearing foreland basins, load-induced halokinetic movements in addition to the compressional forces from the orogeny can play an important role in shaping the architecture of alluvial fans. Nevertheless, due to the imprint of compressional structures such as thrusts and fault-related folds, the contribution of halokinesis in syn-orogenic sedimentation on fold-and-thrust belts has been often disregarded.

The intramontane alluvial fans of the Central South-Pyrenean Unit (CSPU) are late Lutetian to late Oligocene in age and crop out in three main areas known from East to West as the La Pobla de Segur, Gurp, and Sis conglomeratic basins (Rosell and Riba, 1966; Mey, 1968; Séguret, 1969; Garrido-Mejías and Ríos, 1972; Mellere, 1993; Vincent, 2001) (Fig. 1). Additionally, to the north of the La Pobla and Gurp basins, the Senterada conglomeratic basin is an E-W depression that comprises three smaller isolated outcrop areas, on top of the Paleozoic and Triassic of the Nogueres thrust sheet. From south to north, the alluvial fans progressively retrograde, displacing the apical areas to the north, shifting sedimentation from the Organyà basin northern margin towards the unrooted leading edge of the Axial Zone antiformal stack (the Nogueres *têtes plongéantes*; Séguret, 1972) and a Keuper evaporite province in between, which we call the Senterada salt province (Fig. 2). The evolution of the catchment areas and geometry of these alluvial systems (Figs. 2 and 3) has been strongly influenced by the joint effects of the Axial Zone uplift, horizontal shortening and salt evacuation. With the intervention of such diverse factors, the geological history registered within the Middle Eocene to Oligocene intramontane conglomerates in the South-Pyrenean thrust belt puts forward an interesting case study.

The starting point of this study involved revisiting the work by Rosell and Riba (1966) and Garrido-Mejías and Ríos (1972), who noted an unusual dip and apparent downlap to the north in the lower alluvial systems of the La Pobla basin (Fig. 4A). This observation contrasted with the major northward provenance of the fans, and the authors attributed the downlap to the synsedimentary tilting of the conglomeratic basin towards the north, progressively shifting the basin depocentre in that direction. In this study, we return to this idea in the light of the more recently developed salt tectonics concepts, invoking load-induced salt migration as the main factor inducing the north-directed tilting and associated depocentre migration.

Salt tectonics may quickly modify the connection between catchment areas, sedimentary routing systems and depocentres. In the framework of a growing orogen, sudden local changes in provenance often indicate smaller-scale tectonic activity related to salt expulsion, but can often be overprinted by basement thrusting and related growth structures. Originally interbedded with Triassic Keuper evaporites, the uninterrupted presence of ophite clasts within the intramontane conglomerate of the Southern Pyrenees indicates the continuous erosion of Keuper exposures. This provides an excellent marker to track salt-related movements from the mid Lutetian to the Oligocene, where exposed diapirs and salt walls can be interpreted as part of the source area. Focusing on the geometry and provenance indicators of the Gurp, La Pobla and Senterada basins, we present new palaeogeographic maps and cross-sections, illustrating the evolution of the conglomeratic basins in relation to the uplifting antiformal stack and the migration of the Keuper evaporites.

2 Geological setting and previous studies

The Alpine thrust structure of the Axial Zone of the Pyrenees has been extensively studied (Séguret, 1972; Williams and Fischer, 1984; Roure *et al.*, 1989; Muñoz, 1992; Vergés, 1993; Beaumont *et al.*, 2000; Mouthereau *et al.*, 2014; Muñoz *et al.*, 2018; Teixell *et al.*, 2018; García-Senz *et al.*, 2019; Calvet *et al.*, 2020), defined as an antiformal stack of Paleozoic basement-involved, south-directed thrust sheets. The frontal part of the antiformal stack, detached by erosion from its root to the north, consists of foreland-dipping thrusts and related downward-facing folds referred to as the Nogueres *têtes plongeantes* (Séguret, 1972). Recent numerical modelling studies have explored the role of the Triassic evaporites in crustal-scale orogenic inversion, which are key in enabling gliding, stacking and rotation of the duplex thrusts (Grool *et al.*, 2019; Jourdon *et al.*, 2020). In the South-Central Pyrenees, the Nogueres thrust sheet consists internally of a set of minor imbricates of Silurian and Devonian metasedimentary rocks with Permo-Triassic deposits unconformably on top (Mey, 1968; Séguret, 1972; Zwart, 1979; Muñoz, 1992; Saura and Teixell, 2006). These subunits are interleaved with Triassic shales and evaporites of the Keuper facies (Fig. 2). The Variscan structure of the Nogueres units, preceding the Pyrenean Orogeny, and the Permo-Triassic basin configuration has been documented in several works (Mey, 1968; Zwart, 1979; Muñoz, 1992; Saura, 2004; Saura and Teixell, 2006; Lloret *et al.*, 2018). Under the Nogueres thrust sheet, the Orri thrust sheet, bearing the igneous and metamorphic complexes of the Axial Zone (Muñoz, 1992), crops out to the north (Fig. 1).

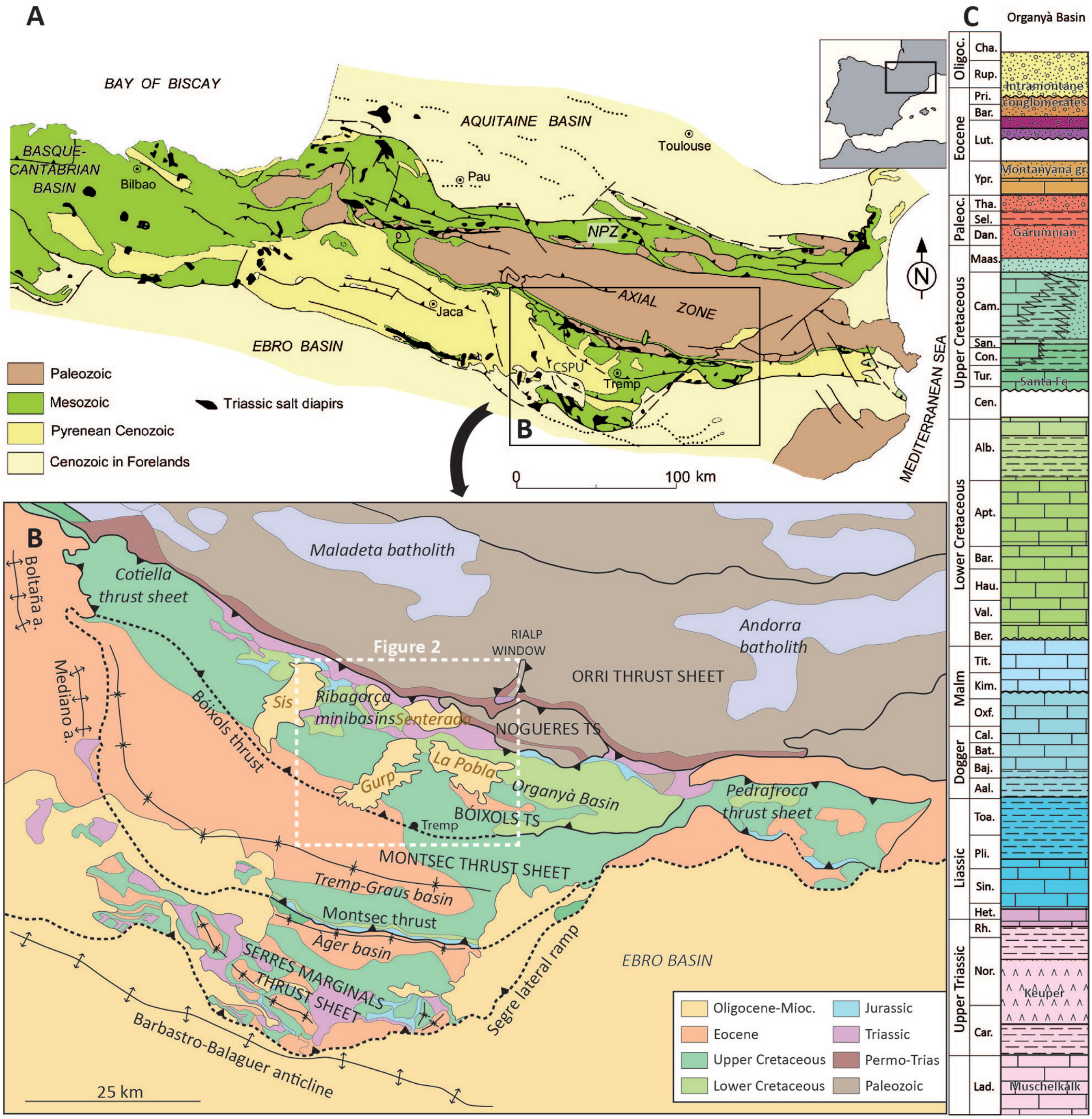

Fig. 1. A. Geologic sketch map of the Pyrenean orogen. B. Geological map of the South-Central Pyrenean unit indicating the location of the study area (Fig. 2). C. Stratigraphic column of the Organyà and Tremp-Graus basins.

According to thermochronological data (apatite and zircon fission tracks: AFT, ZFT) by Fitzgerald *et al.* (1999) and Metcalf *et al.* (2009), a first stage of heating around 70–50 My in the Orri thrust sheet can be attributed to burial by the upper thrust sheets as the Nogueres (Fig. 3). Oldest cooling ages of the Lacourt massif of the North Pyrenean zone (the root zone to the Nogueres zone according to Teixell *et al.*, 2018) at 70 (ZFT) and 55 My (AFT) (Yelland, 1991; Fitzgerald *et al.*, 1999) could be consistent with this. From 50 to 30 My, the uplift of the Orri thrust sheet accelerates the amplitude growth of the Axial Zone antiformal stack, rapidly exhuming and cooling the granite massifs contained in the sheet (Ribérot, Maladeta, Marimanya, etc.). Rapid cooling continued in the massifs of the North Pyrenean Zone (Sinclair *et al.*, 2005; Vacherat *et al.*, 2016). Finally, the emplacement of the lowermost Rialp thrust sheet, at around 30 My, marks a stage of slower cooling and exhumation

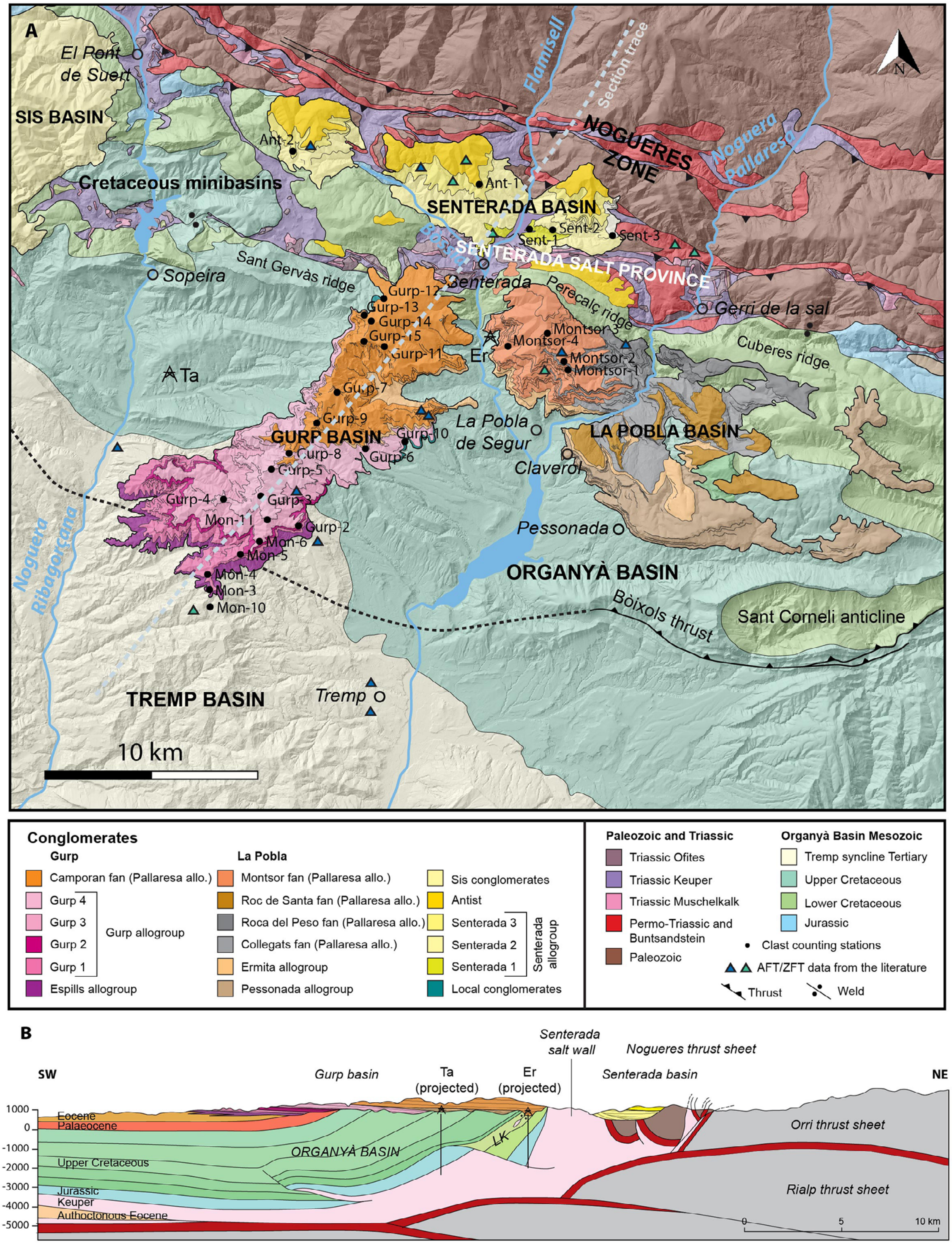

Fig. 2. A. Detailed geological map of the study area showing the location of the clast counting stations. Ta: Tamúrcia well; Er: Erinyà well. The limits of the conglomerate fans are modified from the ICGC 1:25000 maps of Tremp and Espills for the Gurp basin, and from Saura (2004) and Barsó (2007) for the La Pobla and Senterada Basins. The Organyà Basin and the Nogueres Zone have been drawn from the ICGC 1:50000 map of the Pallars Jussà. The AFT/ZFT sample locations refer to the papers by Beamud *et al.*, 2011, Whitchurch *et al.*, 2011, Fillon *et al.*, 2013, and Michael (2013). B. Schematic cross-section along the Gurp basin transect. LK, lower Cretaceous. The Organyà basin structure is modified from the sections in Mencos *et al.* (2015) and Muñoz *et al.* (2018), the Nogueres shallow structure is from Saura and Teixell (2006), and the deep structure of the antiformal stack is modified from Muñoz *et al.* (2018).

up to the present day (Gibson, 2004; Sinclair et al., 2005; Metcalf et al., 2009; Whitchurch et al., 2011; Calvet et al., 2020).

The Axial Zone antiformal stack is flanked to the south by the thin-skinned South-Pyrenean fold-and-thrust belt, constituted by Mesozoic and Paleogene rocks detached from the basement by the Triassic Keuper, which is also a source layer for diapirism (see a review in Cámara and Flinch, 2017). The eastern part of the thrust belt in the central Pyrenees was referred to as the Central South-Pyrenean Unit (CSPU; Séguret, 1972) (Fig. 1), a name we retain for convenience in the description. The Keuper outcrops extensively between the Nogueres thrust slices and the CSPU, forming what we call the Senterada salt province. Over the mid-Triassic Muschelkalk carbonates, the Keuper facies of the Senterada salt province is composed of four different formations (Salvany and Bastida, 2004): (a) the Adons mudstones and carbonates; (b) the Boix gypsum formation, consisting of red and versicolor gypsum; (c) the Senterada gypsum formation, cropping out in the Pont de Suert and Senterada areas; and finally (d) the Avellanes mudstones and carbonates formation. Due to the weathering conditions, halite is not found in the outcrops. However, most wells that cut across the Keuper in the SCPU, including Erinyà and Tamúrcia wells in the study area (Fig. 2), indicate thick halite successions (Lanaja et al., 1987). Moreover, the salty water springs in Gerri de la Sal confirm that halite is an important component of the Keuper facies under the surface.

The evaporite depositional thickness within the Keuper facies in the Senterada province is hard to estimate, due to intense deformation. The Erinyà and Tamúrcia wells (Fig. 2) stopped after drilling 46 m and 29 m into the Keuper halite and mudstone, so the basal depth of the evaporite unit is unknown. The presence of abundant Muschelkalk carbonate lenses within the deformed Keuper facies suggest that Middle Muschelkalk evaporites, not clearly identified at the surface but reported in wells in the Iberian and Ebro basins (Bartrina and Hernández, 1990; Jurado, 1990; Ortí et al., 2017), could have acted as the basal level of the source layer for fault detachment and diapirism.

Halokinetic deformation has been reported along the northern margin of the CSPU in the Cotiella thrust sheet (McClay et al., 2004; Lopez-Mir et al., 2014) and the Ribagorça basin (Saura et al., 2016; García-Senz and Muñoz, 2019a) (Fig. 1) during the Pyrenean Mesozoic rifting stage. To the southeast of these halokinetic depocenters, the lower Cretaceous Organyà basin was a synformal basin filled with a thick carbonate succession (Berástegui et al., 1990; Caus et al., 1990; García-Senz, 2002). The Jurassic and lower Cretaceous succession of the northern limb of the Organyà syncline is shown in these works with constant thickness by the isopach data. It terminates sharply against a south-dipping discontinuity interpreted as an Eocene backthrust (the Morreres backthrust) that uplifts the basin above the Senterada Keuper province (Berástegui et al., 1990; Muñoz, 1992; García-Senz, 2002). In this study, we revise this concept.

The Organyà basin is limited to the south by the Bóixols thrust, the oldest of the South-Pyrenean piggy-back succession, emplaced during the late Santonian as a reactivation of an extensional fault system (Berástegui et al., 1990; Vergés and Muñoz, 1990). Peybernès (1976), Berástegui et al. (1990) and García-Senz (2002) report a progressive onlap of the Lower Cretaceous carbonates against the Jurassic pre-rift strata in the Bóixols hanging-wall and interpret it as a roll-over anticline against a listric fault, inspired by the geometries observed in physical models by Ellis and McClay (1988). To the south of the Bóixols thrust, the central part of the CSPU is the broad, flat-bottomed syncline known as the Tremp-Graus basin, filled by the synorogenic sediments from the upper Santonian to the Eocene, and limited to the south by the Montsec thrust (Fig. 1).

Mid Eocene and Oligocene alluvial conglomerate inliers of the South-Pyrenean thrust belt were sedimented unconformably above deformed Mesozoic and Tertiary rocks of the SCPU (Fig. 1) (Rosell and Riba, 1966). The major basal unconformity at the base of these intramontane conglomerates, and an apparent downlap to the north of the conglomerate beds against it (Fig. 4A), has been reported since the early Pyrenean studies. During the first half of the 20th century, the fossil-bearing levels of Sossís in the lower part of the succession were dated as Bartonian (Bataller, 1943; Crusafont et al., 1956). Rosell and Riba (1966) published the first complete stratigraphic description, and mapped the La Pobla basin. Their study also included clast compositional identification, differentiating alluvial fan units with predominant Paleozoic or Mesozoic provenance, and the downlap against the basal unconformity is interpreted as produced by the tilting of the basin, pointing towards a progressive development of the basal unconformity, rather than a post-depositional tilting. Robles and Ardévol (1984) studied the relationships between the alluvial fans and the Sossís and Claverol lacustrine intercalation, differentiating climatic cycles within the stratigraphic succession that were correlated with the progradation and retrogradation of the fans, and produced a series of palaeogeographic maps. The carbonate and marly members of the lacustrine units, often interbedded with coal beds, are very rich in vertebrate and invertebrate fossil content indicating a Bartonian age (*i.e.* compilation of paleontological data in López-Martínez et al., 1998 and Beamud et al., 2003).

Studies by Mellere and Marzo (1992) and Mellere (1993) proposed a new stratigraphic framework for the La Pobla de Segur conglomerates, which was based on mappable unconformity surfaces and clast compositional changes. Five allogroups were defined: Pessonada, Ermita, Pallaresa, Senterada, and Antist. The apparent downlap of the conglomerate beds against the basal unconformity was attributed to the reactivation of the Bóixols thrust or deeper structures. Magnetostratigraphic dating of the La Pobla conglomerates (Beamud et al., 2003, 2011) was anchored in the lacustrine fossil localities, and covered an age span of around 18 My. These data, combined with AFT data in granitic clasts (Beamud et al., 2011), in detrital samples of the CSPU (Whitchurch et al., 2011; Fillon and van der Beek, 2012; Fillon et al., 2013) and thermal modelling (Beamud et al., 2011; Whitchurch et al., 2011) led to a refined chronostratigraphic framework for the La Pobla and Sis conglomerates, which range from the late Lutetian to the late Oligocene. Provenance studies in the La Pobla conglomerates by Barsó (2007) and Barsó and Ramos (2007), focused on clast counting and heavy minerals identification. The observed provenance changes were correlated with exhumation data in the Axial zone antiformal stack (Gibson, 2004; Beamud et al., 2011). These studies explain the disconnection of the La Pobla and Senterada basins as a result of the Morreres backthrust emergence.

Contrary to what happens in the La Pobla basin, there are no extensive stratigraphic studies nor a solid chronostratigraphic framework for the Gurp conglomerates. The southern part of the Serra de Gurp is mapped in the ICGC 1:25000 maps of Tremp and Espills (Muñoz *et al.*, 2009; Samsó *et al.*, 2010), outlining the sedimentological and compositional characteristics of the main conglomerate units. The Gurp basin succession starts with the Espills allogroup, which is followed by the Gurp allogroup and the Ermita and Pallaresa allogrups, the latter two equivalents to the La Pobla basin. Michael (2013) correlated the Gurp conglomerates with the Escanilla fluvial system of the Ainsa basin based on clast counting, and also provided sparse detrital AFT data. In this study, we will use the unit divisions proposed by Mellere and Marzo (1992) for the La Pobla and Senterada basins and the ICGC maps for the Gurp basin.

3 Methods

Field campaigns were carried out to obtain additional structural data of the northern Organyà Basin flanking with the Senterada salt province. Structural data has also been gathered within the conglomeratic basins to constrain their geometry, with special focus in the less studied Gurp basin. The deep structure of the Organyà basin adopted in this work for cross-section construction is modified from the sections in Mencos *et al.* (2015) and Muñoz *et al.* (2018), the Nogueres Zone shallow structure is from Saura (2004) and the deep structure of the basement thrust system stack is modified from Muñoz *et al.* (2018).

Quantification of the main clast lithologies in the conglomerate units was performed in the outcrop locations indicated in Figure 2. We have analyzed a total of 18 clast-counting stations, 11 of which are located in the Gurp basin, 4 in the La Pobla basin, and 3 in the Senterada basin. In the La Pobla and Senterada basins fewer stations were required given that clast counting had been previously performed by Barsó (2007). The method used was that by Howard (1993), which consists in counting subsets of 100 clasts each to obtain lithology percentages. The repetition of four clast-countings, which are closely spaced in each station, was not possible in some localities due to the limited outcrop space and conditions. In cases where in-situ identification of clasts was difficult, their lithology was determined by thin-section observations under microscope.

To simplify the clast counting results, we have grouped the 42 identified lithologies (Appendix 1) into 8 provenance groups:

- Tertiary limestones and sandstones: Alveolina limestones, and deltaic and fluvial Eocene sandstones from the Tremp basin;
- Mesozoic carbonates: Dogger black dolomites and breccias, orbitolina-bearing limestones, rudist bearing limestones, sparitic limestones, black shales, and bioclastic limestones from the Cretaceous of the CSPU;
- Micritic limestone: Grey coloured limestone clasts with no visible fossil content. Likely to belong to the Triassic Muschelkalk, the Jurassic, or the lower Cretaceous.
- Triassic dolerites (ophites), originally interbedded with the Keuper evaporites and mudstones;
- Permo-Triassic clasts: Permian red sandstones and breccias, Buntsandstein quartz conglomerates and quartz pebbles, Buntsandstein white sandstones, caliche nodules, and pumite fragments. They were likely sourced from the Nogueres area (the thrust sheet and its relative autochthon);
- Carboniferous: Microconglomerate and sandstone typical of the Culm facies, sourced from the Nogueres thrust sheet;
- Silurian and Devonian: Silurian black slates, ochre Devonian limestones and calcareous slates, and crinoid or goniatites bearing Devonian limestones (Griotte facies), sourced from the upper subunits of the Nogueres thrust sheet;
- Paleozoic granites;
- Paleozoic metamorphic rocks: marbles (occasionally with pyrite and andalusite crystals), slates, gneiss, deformed quartz and quartzites.

4 Tectonostratigraphy of the La Pobla, Gurp and Senterada conglomeratic basins

4.1 The substratum of the northern margin of the Organyà basin

This study addresses the role that salt tectonics played in the Eocene and Oligocene evolution of the northern half of the Organyà basin. However, to fully understand the role of pre-compressional salt behavior, we made new field observations of the Mesozoic strata, the detailed architecture of which goes beyond the scope of this paper. The Lower Cretaceous stratigraphy and structure of the Noguera Pallaresa and Flamisell transects is extensively documented by García-Senz, (2002). The northern margin of the Organyà basin was represented as a salt wall in the chronostratigraphic chart in García-Senz and Muñoz (2019b, Fig. 5.8).

We observed that the Aptian and Albian carbonate and marl strata in the Flamisell river valley (Fig. 2) describe a progressive unconformity from dips of 60–80 degrees overturned adjacent to the Senterada Keuper province to right way-up dips of 40–50 degrees further south (Fig. 4C), consistent with synsedimentary diapiric rise at Senterada. In the Noguera Pallaresa river valley, the Peracalç overturned syncline (Fig. 2) has a complex faulted structure (García-Senz, 2002), which has challenged the identification of growth patterns in this area. The Albian Lluçà marls (Fig. 1C) in the Flamisell valley contain interbedded lenses of Keuper evaporites (Fig. 2B). These bodies were reported as high-angle extensional fault welds (García-Senz and Muñoz, 2019b), although regarding their interbedded position within the succession and the proximity with the Senterada salt province they could also be the remnants of a salt sheet extruded from the Senterada diapir during the rifting stage. Towards the east, in the Cuberes ridge (Fig. 2A) the diapiric contact between the Keuper province and the Mesozoic overburden cuts across older carbonates of the Upper Jurassic, Neocomian and Barremian (García-Senz, 2002). Dips change from 65°N overturned in the Noguera Pallaresa valley to 50°S in the eastern part of the study area (Fig. 2A), where Keuper evaporites have been completely squeezed out and the Jurassic strata are directly in contact with the Paleozoic of the Nogueres thrust sheet (Fig. 2A). In the

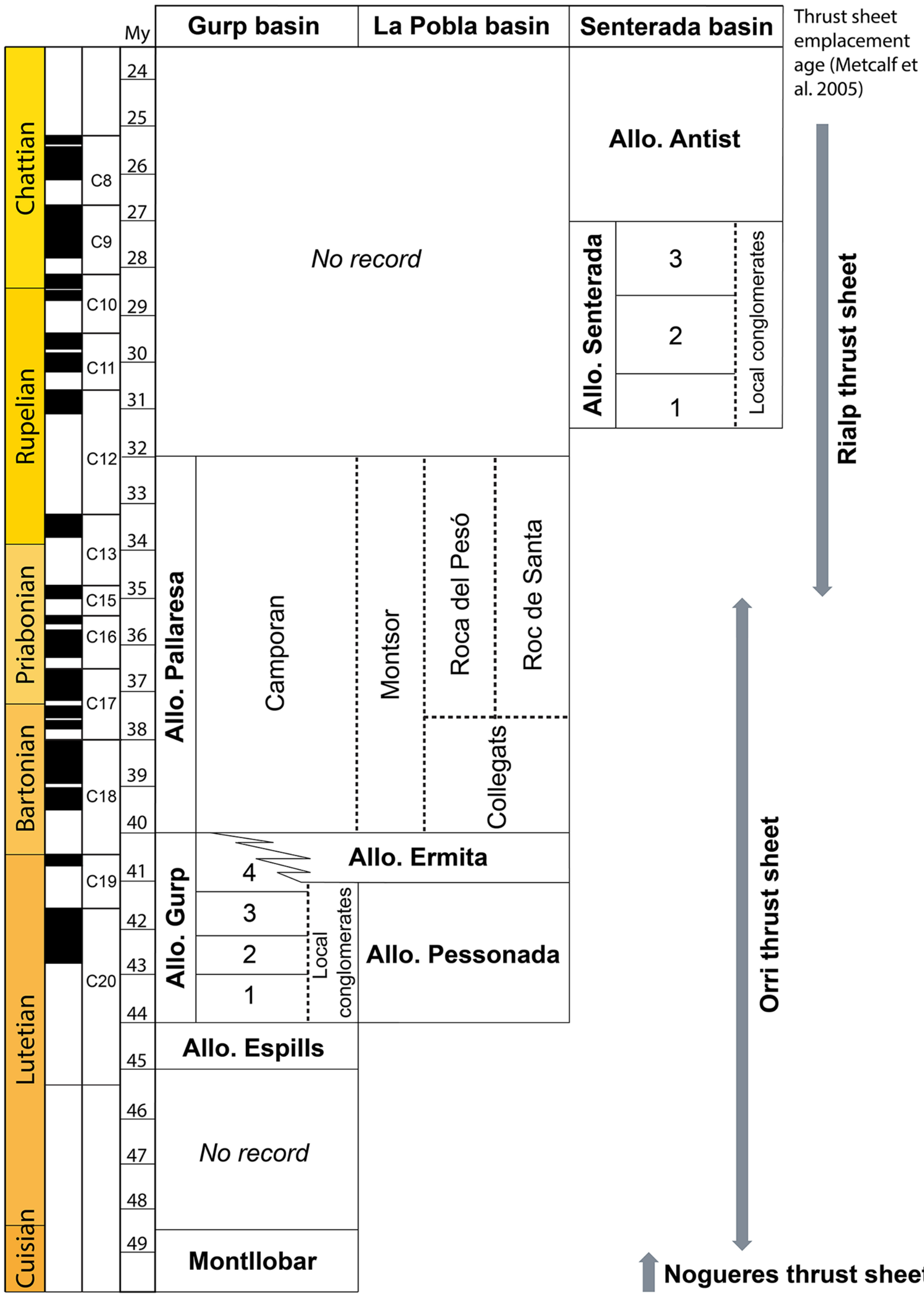

Fig. 3. Tectonostratigraphic framework for the syn-orogenic conglomerate units used in this study. Modifications from previous works are explained in the text. The ages of the allogroups are constrained by magnetostratigraphy (Beamud *et al.*, 2003) but the ages of the different fans within the allogroups are estimated from their stratigraphic relationships. The age of emplacement of the basement thrust sheets is taken from Metcalf *et al.* (2009).

light of these observations and the work by previous authors indicating syn-rift diapir rise in the northern margin of the Organyà basin (Saura *et al.*, 2016; García-Senz and Muñoz, 2019b), we interpret the contact between the Mesozoic carbonates at the basin edge and the Keuper province primarily as a diapiric contact (Fig. 2B). Although some fault reactivation during the Pyrenean contraction may not be discarded, we do not find evidence supporting its interpretation as a major backthrust (*i.e.* the Morreres backthrust; Muñoz, 1992, Mellere, 1993). Further research will be required to understand the numerous faults identified the northern margin of the Organyà basin in contact with the Keuper (García-Senz, 2002). In Section 6, we put forward a case for salt tectonic activity during the Cretaceous rifting and the Cenozoic orogeny in the area.

In the following sections, we focus on observations for the syn-orogenic evolution of the Paleogene intramontane conglomeratic basins. In view of the variability of the alluvial systems through space and time, we describe them unit by unit using the allogroup classification proposed by Mellere and Marzo (1992) for the La Pobla basin, but incorporating some modifications in the stratigraphy (Fig. 3).

4.2 The Espills allogroup (Middle Lutetian)

The Espills allogroup (Muñoz *et al.*, 2009) is the first unit above the basal unconformity in the Gurp basin. In the southern area, the Espills conglomerates are deposited in a low angle unconformity with the Cuisian Montanyana group of the Tremp-Graus basin (Fig. 1C). The Espills strata dip about 10 degrees N and the underlying Cuisian layers are close to horizontal.

The maximum vertical thickness of the allogroup is 110 m (Samsó *et al.*, 2010). To the north, the Espills conglomerates onlap and pinch out against the Alveolina limestone ridge of the Tremp-Graus basin (Fig. 2A). Paleocurrent directions in the Espills allogroup are SSW directed and the clast composition is mainly Paleozoic, with a significant number of metamorphic clasts and granites (Fig. 5B), indicating a northern provenance. Within the Espills allogroup there are also clasts with provenance from the Mesozoic and Tertiary cover, as well as Triassic dolerites (ophites). Although no studies have conclusively dated the Espills allogroup yet, based on the correlation with the units above, this allogroup has been assigned to the Middle Lutetian (Beamud *et al.*, 2003; Samsó *et al.*, 2010), older than the Pessonada Allogroup of the La Pobla basin.

4.3 The Gurp allogroup (Upper Lutetian)

The Gurp allogroup (Samsó *et al.*, 2010) was deposited unconformably above the Espills allogroup. The ICGC cartography divided this allogroup in four units: Gurp-1, 2, 3 and 4, based on mappable photohorizons, with a total thickness of about 500 m.

The Gurp conglomerates also register the tilting to the north, with dips of 10 to 20 degrees towards the N and NE. The northern extent of the allogroup is limited by the Upper Cretaceous limestone and sandstone ridges of the Tremp-Graus basin, where the Gurp allogroup units onlap and pinch out. The paleocurrents in the Gurp units are SSW directed (Samsó *et al.*, 2010), recording a northern provenance mainly constituted by Devonian limestones and calcareous slate clasts (calcshists), metamorphic rocks and scarce granites. There is also an important fraction of Triassic ophitic dolerites and Lower and Upper Cretaceous clasts (Fig. 5C and D).

4.4 The Pessonada allogroup (Upper Lutetian)

The Pessonada allogroup (Robles and Ardévol, 1984; Mellere and Marzo, 1992), named after the conglomerate ridge east of La Pobla de Segur, is the first and southernmost in the La Pobla basin. It has a thickness of about 1000 m (Mellere, 1993) and lays directly on the basal unconformity, flat or tilted to the north in this part of the La Pobla basin (Fig. 3A). There are smaller-scale angular intraformational unconformities related to minor thrusts (Mellere and Marzo, 1992). The Pessonada conglomerates dip 30 to 40 degrees N, in apparent downlap against the basal unconformity.

The Pessonada allogrup is the proximal and middle part of a locally sourced alluvial fan. Paleocurrent directions are mostly SSW directed (Mellere, 1993). However, cobble imbrications suggest that some small fans were sourced from the E and S. The conglomerates are clast-supported and their composition is almost exclusively Mesozoic micritic grey limestones, probably Cretaceous in age, as well as minor Upper Cretaceous sandstone (Mellere, 1993; Rosell *et al.*, 1994a, 1994b). Magnetostratigraphic data places the base of the Pessonada allogroup in the upper Lutetian at 44 My (Beamud *et al.*, 2003, 2011) (Fig. 3).

4.5 The Ermita allogroup (Uppermost Lutetian to Bartonian)

The Ermita allogroup (Robles and Ardévol, 1984; Mellere and Marzo, 1992) is a fan-delta system which progrades into lacustrine environments to the south, and reaches a total thickness of 200–250 m (Mellere, 1993). The Ermita conglomerates overlie the Pesonada allogrup in the south of the La Pobla basin, while to the north they sit on top of the flat basal unconformity (Fig. 4A).

As is the case in the Pessonada allogroup, the clast composition of the Ermita conglomerates is local Mesozoic limestone and paleocurrents are also SSW directed. The Ermita allogroup also crops out in the eastern sector of the Gurp basin, overlying the Gurp allogroup, with a vertical thickness no greater than 100 m.

Based on mammal fossil chronostratigraphy and magnetostratigraphy, the Ermita allogroup sedimentation happened near the Lutetian-Bartonian boundary, at ~41–40 My (Beamud *et al.*, 2011) (Fig. 3).

4.6 The Pallaresa allogroup (Bartonian to Rupelian)

The Pallaresa allogroup (Mellere and Marzo, 1992) comprises five interfingering alluvial fan systems, with different composition and provenance: Collegats, Roc de Santa, Roca del Pesó and Montsor in the La Pobla Basin, and Camporan fan in the Gurp basin.

The lower ones lie unconformably over the Gurp and Ermita allogroups (Fig. 4A and B). Towards the north of the Gurp and La Pobla basins, the Pallaresa allogroup conglomerates lie directly above the basal unconformity over the Mesozoic. In this area, the basal unconformity transitions from being flat-lying in its lowest point in the Noguera Pallaresa valley, to become irregular and climbing up the uplifted carbonate ridges of the northern margin of the Organyà basin (Fig. 4B and C). The conglomerates of the La Pobla basin cut across the ridges of Peracalç and Cuberes, the most likely entering points of the alluvial systems into the basin. Dips in the La Pobla basin for the Pallaresa allogroup are around 10 to 30 degrees towards the N and NW. In contrast, the conglomerate beds of the allogroup in the Gurp basin are tilted to the E (dips of 15 to 25 degrees NE). This eastward component is likely depositional, since the conglomerates truncate the Sant Gervàs cretaceous ridge and progressively onlap to the north (Figs. 2 and 4C). The erosional incision at

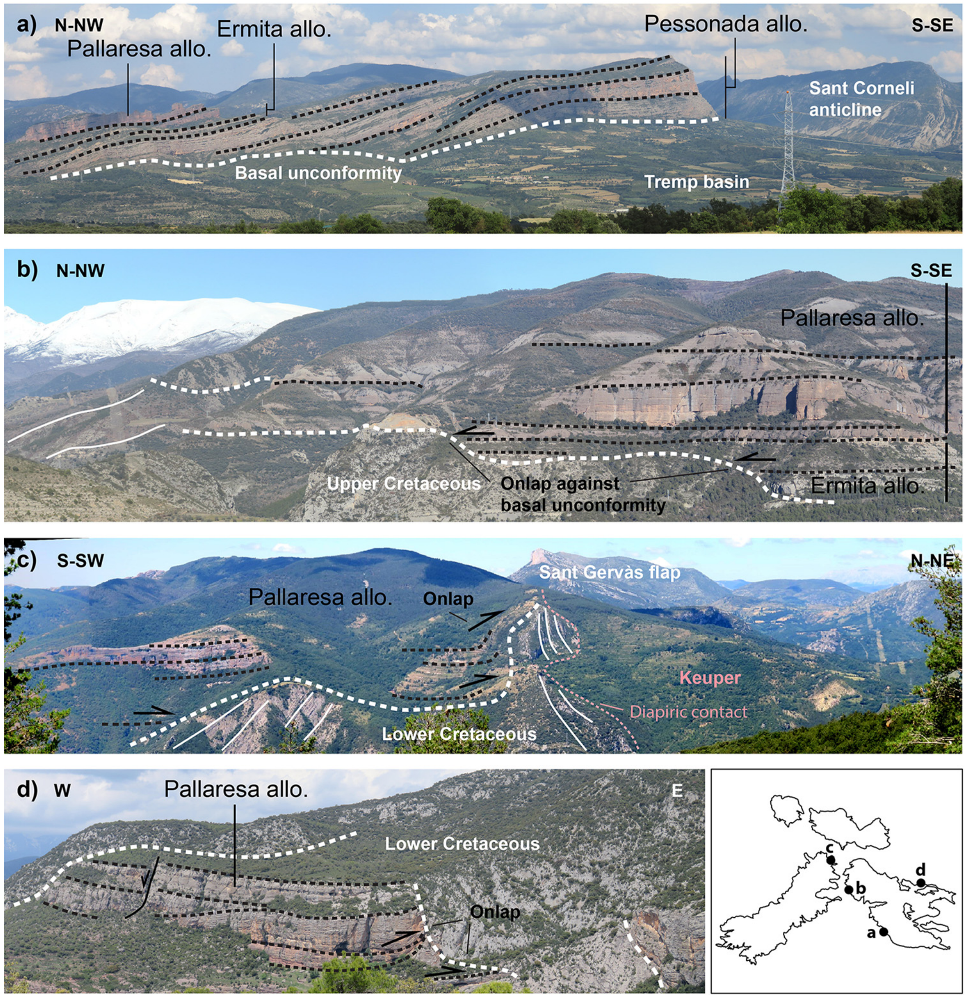

Fig. 4. A. Flat basal unconformity and north-directed downlap of the conglomerates in the Serra de Pessonada. Field of view is 5 km B. Ermita and Pallaresa allogroups onlapping against the irregular basal unconformity in the Flamisell valley (Serra de Montsor). The horizontal dip of the beds is apparent due to the orientation of the photo. Tilting of the beds ranges from 20°N at the bottom of the Pallaresa allogroup to nearly horizontal at the top. Field of view is 6 km. C. Onlap of the Pallaresa allogroup conglomerates (Camporan system) against the Lower Cretaceous ridge in the northern Gurp basin. Field of view is 4 km. D. Pallaresa allogroup conglomerates (Roca del Pesó system) infilling Lower Cretaceous palaeoreliefs in the NE margin of the Organyà basin. Field of view is 2 km.

Sant Gervàs indicates a possible entry point of the conglomerate sediments into the basin.

The Pallaresa allogroup in the La Pobla basin transitions gradually from the Ermita allogroup. The Collegats system maintains a very local source area and small size (2 km^2 extension and 200 m thick). In the Congost de Collegats in the Noguera Pallaresa river valley, conglomerates onlap over a folded paleorelief in the Mesozoic carbonates (Reille, 1971). During the orogeny the onlap geometries were deformed by flexural slip, producing fault-propagation growth folds in the conglomerate beds (García-Senz, 2002, Fig. 3.27). Between the Noguera Pallaresa and Flamisell valleys, the Collegats system interfingers with the Montsor fan system (Rosell and Riba, 1966; Robles and Ardévol, 1984), around 800 m thick (Beamud *et al.*, 2003) and active during the entire sedimentation of the Pallaresa allogroup. Montsor fans covered larger areas (more than 50 km^2) (Mellere, 1993). In the south, the Montsor layers sit on top of the basal Collegats system, dipping between 8 and 27 degrees to the N. In the Flamisell river valley, the Montsor conglomerates directly onlap the basal unconformity over the Lower Cretaceous palaeoreliefs (Fig. 4B). On top of the Collegats system in the SE of the La Pobla Basin, the Roc de Santa system dip around 20 degrees to the NE and show W-directed palaeocurrents. The Roca del Pesó system infill the Lower Cretaceous palaeorreliefs in the northern La Pobla Basin (Fig. 4D). The irregularities in the basal unconformity cause a variety of dips, but the regional dip to the north is still predominant.

Barsó (2007) loosely assigned the Pallaresa allogroup of the Gurp basin to the Montsor alluvial fan system. However, our new clast counting results (Fig. 6) show very different clast composition between the stations in the Montsor fan in the La Pobla basin, and the fan in the Gurp basin. The most remarkable difference is the presence of Carboniferous Culm clasts in Montsor fan (Figs. 5D and 6) and their total absence in the Gurp basin (Camporan area), which indicate two time-equivalent fans but with different catchment areas. Hence the Gurp and La Pobla upper Pallaresa allogroup conglomerates belong to different fans, even if time-equivalent. We have named the newly identified fan at Gurp the Camporan fan, after the name of the highest peak in the Serra de Gurp (Figs. 2 and 3).

The Pallaresa allogroup fans were active from the Lutetian-Bartonian boundary to the late Priabonian, about 34 My ago (Beamud *et al.*, 2011). Previous studies (Mellere and Marzo, 1992; Mellere, 1993; Beamud *et al.*, 2003; Barsó, 2007) considered the upper part of the Serra de Montsor succession as belonging to the Oligocene Senterada and Antist allogroups (Fig. 3). In the following sections, we discuss the reasons to keep the conglomerates of the upper part of the Serra de Montsor within the Pallaresa allogroup.

4.7 The Senterada allogroup (Rupelian to Chattian)

The Senterada allogroup (Mellere and Marzo, 1992) has been reported as cropping out in the upper part of the Serra de Montsor in the La Pobla basin, as well as in the Senterada basin to the north, which is a narrow E-W sedimentary depression disconnected form the Pobla basin to the south (Fig. 2A).

The Senterada basin section is around 400 m thick (Beamud *et al.*, 2011), and in the present day it is considerably lower in the topography than the upper levels of the La Pobla and Gurp basins. Progressive unconformities within the Senterada allogroup (Saura, 2004) open to the north and onlap against the margin of the Faiada Lower Cretaceous minibasin of the Ribagorçana valley (Saura *et al.*, 2016). The lower units have variable dip directions as the beds are infilling an irregular topography, usually sitting directly above the Keuper evaporites and ophites (Fig. 2). The clasts in this basal unit are heterometric and angular, indicating limited transport, and Permo-Triassic and Devonian lithologies reflect the composition of the nearby Nogueres thrust sheet. Saura (2004), named these deposits Sarroca group, after the locality to the NW of Senterada.

The Senterada allogroup conglomerates are here divided into three different units. The lower one is characterized by dominant Permo-Triassic clasts (Fig. 5G), the second is predominantly made up of Devonian and Carboniferous clasts, and the third without a clear lithologic predominance. The third unit of Senterada is usually matrix-supported and heavily weathered, so the poor outcrop conditions challenge a systematic clast composition analysis. The matrix in the Senterada conglomerates is composed of fine-grained material with reddish coloration, characteristic of the Buntsandstein sandstones and lutites. It is worth noting that, within the Senterada basin conglomerates, the Mesozoic carbonate clasts are almost non-existent.

The age of the Senterada allogroup, determined by palaeomagnetism in the Senterada basin profile, was determined as Rupelian to early Chattian, 33 to 27 My (Beamud *et al.*, 2011). The magnetostratigraphic profiles by Beamud *et al.* (2011) in the Pallaresa allogroup were sampled across a continuous section from the base of the allogroup to halfway up the Montsor mountain. The sampling was resumed in the base of the Senterada basin in the Flamisell valley, assumed to be time-equivalent to the upper part of Serra de Montsor, attributed to Senterada and Antist allogroups. As a consequence of the sampling interruption, the data show a hiatus of 3 My (34–31 My) between the last sample in the Montsor mountain and the first sample in the Senterada basin. However, the stratigraphic succession at Serra de Montsor ridge appears fairly continuous, with no major unconformities or identifiable paraconformities. We have not observed any significant change in the clast composition between the lower Montsor fan and the conglomerates in the upper part of the ridge. For this reason, we assign the upper part of the Montsor mountain to the Pallaresa allogroup (Figs. 2 and 3), and not to the Senterada and Antist allogroups as defined in the separate Senterada basin, which, in contrast, do present a different composition from Montsor fan (Fig. 6).

Another important reason to consider the upper part of the Serra de Montsor ridge as not equivalent to the Senterada basin conglomerates is the present-day difference in topographic elevation between the two. While the base of the unsampled upper section of the Montsor mountain is around 1330 m high, the base of the conglomerates in the Senterada basin succession is around 800 m high in the Flamisell and Bòssia river valleys (Fig. 2). To sediment on top of the Montsor ridge, the north-derived Senterada alluvial systems would have had to climb up a topographic difference of more than 500 m. This appears to be an unlikely scenario, taking into account the height of the Lower Cretaceous ridges and the fact that the source area of the Senterada conglomerates is very local. We consider that a potential sinking of the Senterada basin, or an uplift of La Pobla basin due to a late-Oligocene to Miocene backthrust reactivation after the deposition of the Senterada and Antist conglomerates would not account for the compositional differences between the upper Montsor ridge and the Senterada basin.

Instead, we interpret that the small scale of the alluvial fans (with very local provenance and matrix support) and the significant height of the Lower Cretaceous ridges prevented the Senterada conglomerates to overspill into the upper parts of the La Pobla basin. We favour the idea that Senterada conglomerates had a very local catchment area within the nearby Nogueres thrust sheet (hence the mainly Permo-Triassic and Devonian composition, Figs. 5G and 6).

4.8 The Antist allogroup (Chattian)

The Antist allogroup, 300 m thick (Mellere and Marzo, 1992), has been reported to crop out in the Senterada basin and in the upper part of the Serra de Montsor in the La Pobla basin. As the upper Senterada unit, the Antist conglomerates are very coarse, matrix-supported and poorly cemented, so the outcrop conditions are an impediment to a systematic composition analysis. The Antist alluvial fan is very proximal and contains a clast composition characteristic of the Nogueres thrust sheet, predominantly Devonian limestones and Permo-Triassic red clasts. Triassic ophites, green quartzites, and marbles are common clasts as well. To the west there are local areas with abundant granite clasts (Fig. 5h). The presence of Carboniferous Culm sandstones has also been reported for the eastern area. The Antist allogroup is not deformed or tilted, so it has

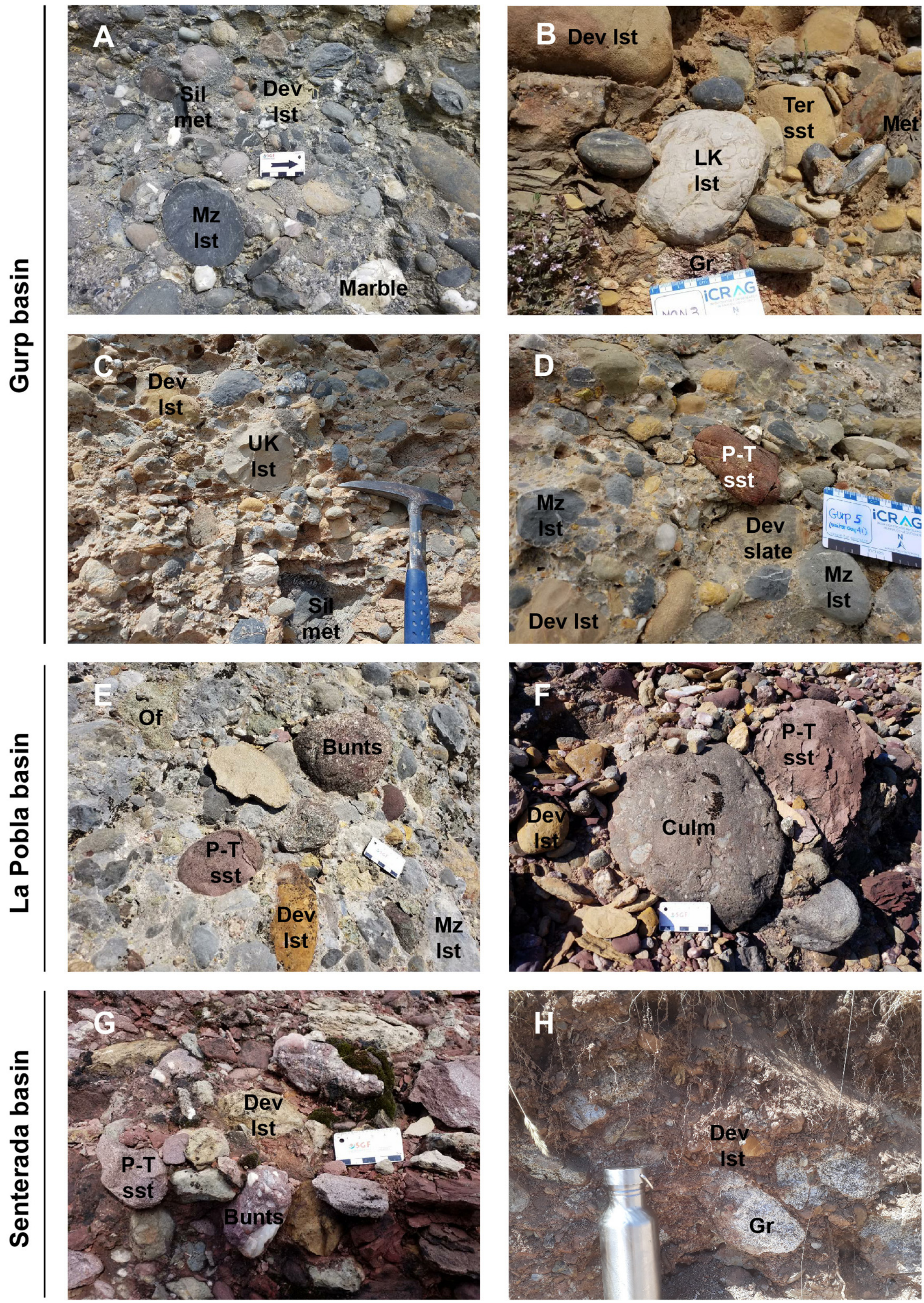

Fig. 5. Images of clast-counting stations, illustrating different clast lithologies (locations in Fig. 2A). A. Mon-10, Montllobar conglomerates. B. Mon-3, Espills allogroup. C. Mon-5. Gurp allogroup, unit 1. D. Gurp-5. Gurp allogroup, unit 4. E. Montsor-1, Pallaresa allogroup, Montsor fan. F. Montsor-3, Pallaresa allogroup, Montsor fan. G. Sent-1, Senterada allogroup, unit 1. H. Ant-2, Antist allogroup. Dev lst: Devonian limestone; Mz lst: Mesozoic limestone, Gr: Granit; P-T sst: Permo-Triassic sandstone; Bunts: Buntsandstein conglomerate; Culm: Culm conglomerate and sandstone; Of: Ophite; Sil met: Silurian metamorphic schist; Dev sch: Devonian schist; UK lst: Upper cretaceous limestone; LK: Lower cretaceous limestone; Met: Metamorphic rock fragment; Ter sst: Tertiary sandstone.

been stated that the Antist conglomerates register the end of the Pyrenean deformation in this area (Mellere and Marzo, 1992; Beamud *et al.*, 2003).

The age of the Antist system has been determined as Chattian, 27–24 My (Fig. 3), and it is time-equivalent to the Sis Collegats alluvial system in the Sis valley (not to be mistaken with the Pallaresa allogroup Collegats system) and the Graus fluvial sediments of the Tremp-Graus basin (Beamud *et al.*, 2011).

5 Clast-counting lithology results

A profile through the Gurp basin records significant changes in provenance from base to top. The Montllobar conglomerates (Fig. 5A), from the underlying Montanyana group, which forms the upper part of the filling of the Tremp-Graus syncline (Nijman and Nio, 1975), are mostly sourced from Mesozoic and Tertiary carbonates from the surrounding palaeoreliefs (69%). However, the proportion of Paleozoic clasts is around 31%, indicating a clear northern provenance already in the late Ypresian (Fig. 6).

In the Lutetian Espills unit (Mon-3 station) (Fig. 5B) over 50% of the clasts derive from Paleozoic rocks: Silurian black slates (10.9%) and Devonian brown limestones (14.6%) and calcareous slates (29.3%) with occasional granite (1.2%) and gneiss (1.2%) pebbles. Post-Paleozoic lithologies are in a lesser proportion: Tertiary calcarenites (12.2%), Alveolina limestone (4.9%), Micritic grey limestone (19.5%), Orbitolina limestone (5.3%) and rudist limestone (1.2%). It is also worth noting that 4.9% of the clasts are Triassic ophites, despite this being a weak lithology that quickly weathers during transport. This proportion is similar to that of the lower sections of the overlying Gurp allogroup (Fig. 5C).

Several counting stations were analysed in the Gurp allogroup (Figs. 2, 5c, 5d and 6): the allogroup is mainly constituted by clasts of grey micritic limestones (42.7% Gurp-1; 21.4% Gurp-2; 30.3% and 27.2% Gurp-3; and 15.3% and 28.9% Gurp-4), Devonian limestones (18.6% Gurp-1; 8.3% Gurp-2, 11.2% and 18.5% Gurp-3; 24.7% and 11.1% Gurp-4) and Devonian calcareous slates (13.3% Gurp-1, 36.9% Gurp-2, 29.2% and 19.8% Gurp-3, 12.9% and 7.8% Gurp-4). Triassic ophites (2.7% Gurp-1; 9.5% Gurp-2, 9% and 13.6% Gurp-3; 14.1% and 6.7% Gurp-4) are also well represented. Minor proportions of Axial Zone metamorphic pebbles (8% Gurp-1, 1.2% Gurp-2, 1.1% and 12.3% Gurp-3, 5.9% and 7.7% Gurp-4) and granites (around 1% in Gurp-2, Gurp-3 and Gurp-4) have also been found.

It should be noted that the Permo-Triassic clasts are absent in the Espills, Gurp-1, Gurp-2, Gurp-3 units and in the lower and middle part Gurp-4 unit (Fig. 5D). These begin to appear at the top of Gurp-4 unit (3.3%%) and are common throughout the Camporan unit (Pallaresa allogroup) at the top of the Gurp basin (17.5–34.2%). These Permo-Triassic clasts mainly derive of detrital red beds. White to green colored ignimbrite clasts are also occasionally found.

The Ermita allogroup in the Serra de Gurp section (Gurp-6 station) is predominantly composed of 82.1% Mesozoic cover (42.4% grey micritic limestones, 38.8% Mesozoic carbonates, and 1.1% ophites). Tertiary sandstone and limestone clasts (15.6%) are also present. Additionally, there is an occasional appearance of Devonian limestones (2.2%) (Fig. 6), very similar to the proportions reported by Mellere and Marzo, (1992) and Barsó (2007) for the La Pobla basin. However, the finding of epidote detrital grains in the Ermita allogrup of the La Pobla basin may indicate that the catchment area went through of Triassic ophites.

The transit from the Gurp to the Pallaresa allogroup, where the Ermita group is absent (Gurp-8 station), is marked by an increasing proportion of Permo-Triassic clasts (17.5%). Silurian black slates (1%), Devonian calcareous slates (4.1%) and Devonian ochre limestones (19.6%) clasts are still present in a significant proportion (24.6%). The Mesozoic lithologies (grey micritic limestones 43.3%, Orbitolina bearing limestones (5.2%), undifferentiated Mesozoic carbonates (6.3%), ophites (3.1%) represent more than half of the clasts throughout the Pallaresa allogroup in the Gurp basin. To the top of the Pallaresa Allogrup (Gurp-9 station) in the Gurp basin (Camporan fan), the presence of Mesozoic lithologies decreases (47.1%) and Permo-Triassic (34.2%) clasts increase with a minor contribution of Devonian limestone (11.8%) and Axial Zone clasts (1.2%).

Clast-counting data in the Montsor system of the Pallaresa allogroup of the La Pobla basin (Figs. 2, 5E, F and 6), in contrast, provides significantly different results. The Mesozoic clasts content is much lower than in the Gurp basin, ranging from 20% to just 6% in the upper part. The proportion between Permo-Triassic clasts on the one hand, and Silurian and Devonian on the other, varies throughout the unit. At the base (Montsor-4 station), the proportion of Permo-Triassic pebbles is 55.9% while for Silurian and Devonian clasts it is 18.3% and for grey Mesozoic limestones it is 7.5%. An important observation is the presence of Carboniferous Culm sandstones and microconglomerates (Fig. 5F) in a proportion of 16.1%, even though this lithology is completely absent in the Gurp basin succession. The Montsor-1 clast-counting station (Fig. 5E) is located in a bed with unique clast proportions, to such an extent that the layer has a distinct colour in the outcrop and it can be distinguished in aerial images, so much that the bed was specifically mapped in the 1:50000 geological map Tremp chart (Rosell *et al.*, 1994a, 1994b). This is due to a comparatively high proportion of Mesozoic carbonates (45%), some of them light-coloured, and green ophites (25%) together with a significant presence of granites and leucogranites (10.9%). This is the highest proportion of ophites reported in the entire conglomerate succession. Permo-Triassic (7.9%), Devonian limestones (5.9%) and Culm clasts (2%) are also represented.

In the following stations in Serra de Montsor succession (Montsor-2 and Montsor-3 stations) (Fig. 5F) the Permo-Triassic clasts increase significantly towards the top (21.8% Montsor-2; 55.9% Montsor-3) together with Silurian and Devonian clasts (35.4% Montsor-2; 24.4% Montsor-3). The proportion of Culm clasts increases and then decreases to the top (19.8% Montsor-2; 6.1% Montsor-3). Mesozoic carbonates (19.8% Montsor-2; 6.1% Montsor-3) decrease from base to top. There are no clasts of green ophites and the weathered granites, frequent in the white layer appear in very minor proportions in the upper part of the succession (2.1% Montsor-2, 1% Montsor-3).

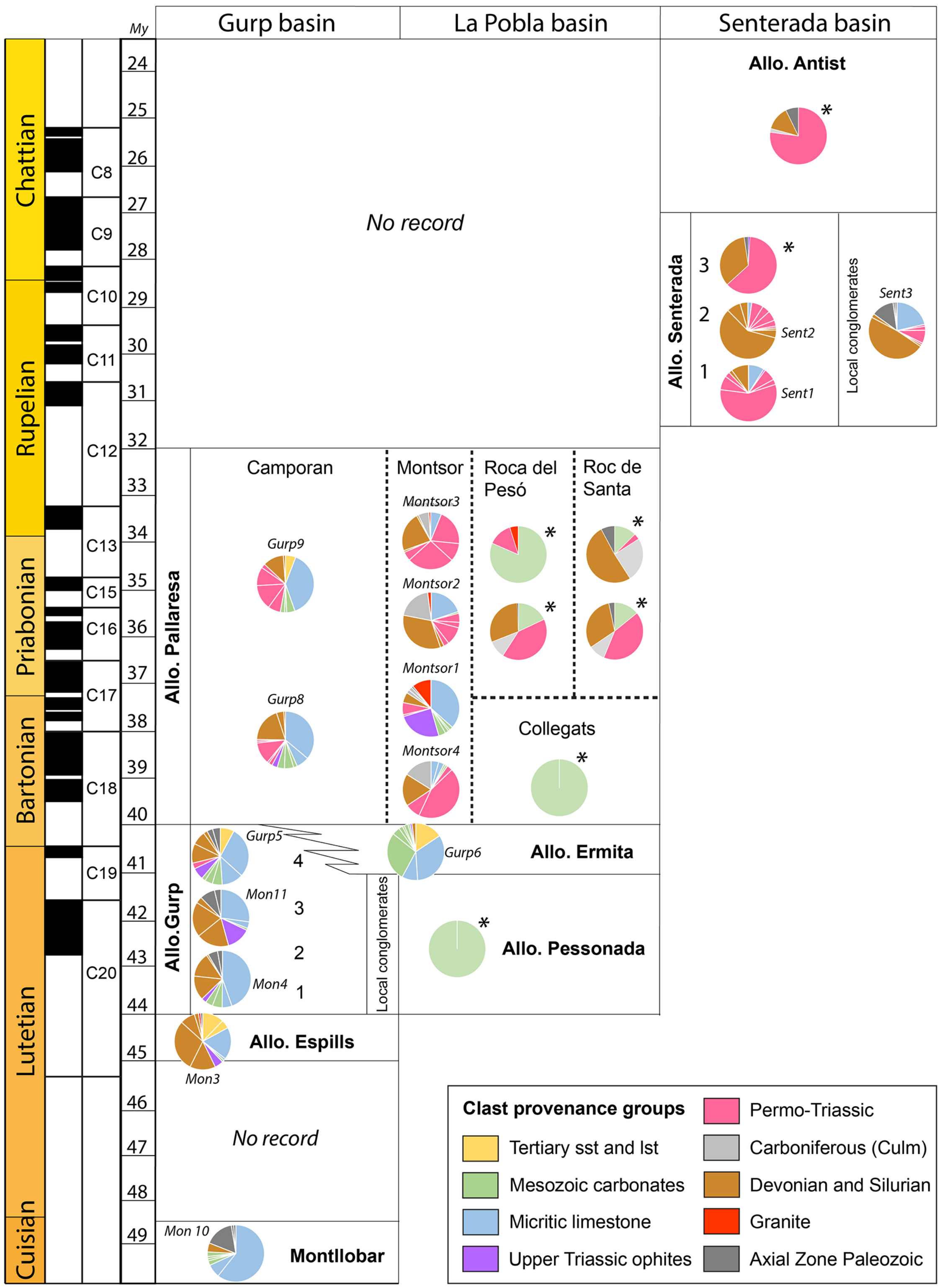

Fig. 6. Pie charts documenting the clast lithology percentages in the counting stations. Location of samples in Figure 2. The charts marked with * are from Barsó (2007).

The results of the Senterada basin reveal a very different clast composition between the Senterada 1 unit (Sent-1 station; Figs. 5G and 6), with predominantly cobbles of Permo-Triassic lithologies (78%) in a fine-grained matrix of red sand, and the Senterada 2 unit (Sent-2 station; Fig. 6), mostly composed of Devonian clasts (76.4%, with brown crinoidal limestone and pink Goniatites-bearing limestone of Griotte facies). In this latter unit, the Permo-Triassic conglomerates and sandstones are in 21.3%, whereas Mesozoic limestones are represented in a very minor proportion (2.2%). The upper Senterada 3 unit has very poor outcrop conditions, due to the high proportion of matrix content, so we were unable to set a clast counting station in any of the areas surveyed. It has been reported as having a clast proportion of approximately half Devonian limestones and half Permo-Triassic clasts (Barsó, 2007). The poor outcrop conditions have also prevented systematic clast-counting in the Antist allogroup. Field observations have shown that clast composition within the Antist allogroup varies in different outcrops. In certain there is a predominance of granite clasts (Fig. 5h), while in other areas the predominance is pebbles of Buntsandstein conglomerates and sandstones and Devonian limestone clasts (Barsó, 2007). Axial Zone well-rounded metamorphic clasts as green quartzites with folded quartz veins, marbles, dark-metasandstones, slates and quartz pebbles are lithologies widely represented.

6 Evolution of alluvial fan catchment areas

The middle Lutetian Espills allogroup at the base of the Serra de Gurp succession has no time-equivalent in the La Pobla basin. It is composed of 50% of Paleozoic clasts, mostly originated in Devonian and Silurian lithologies of the Nogueres thrust sheet but with the occasional appearance of granite and gneiss pebbles. The upper Lutetian Pessonada allogroup fans in the La Pobla basin are entirely composed of Cretaceous carbonate clasts, while the equivalent Gurp allogroup fans in the Gurp basin have around 40–60% of clast composition from the Nogueres Devonian and Silurian, metamorphic clasts and Triassic ophites (Fig. 6).

Based on the counting results and the geometrical observations in Section 3, we interpret the Pessonada allogroup as a small system of local alluvial fans sourced from Cretaceous carbonates to the north over the Senterada salt province (now eroded), equivalent to the northern Ribagorça diapir and minibasin province (*i.e.* Saura *et al.*, 2016), and from the northern margin of the Organyà basin (Fig. 7A). To the southern part of the Organyà basin, the Pessonada alluvial fans likely onlapped the relief of the Sant Corneli anticline, which could have also provided carbonate clasts in smaller-scale flows. In contrast, the catchments of the Gurp fans (Espills and Gurp allogroups) were much larger, extending throughout a larger area in the hinterland (Fig. 7A). Although an important contribution was from the Cretaceous reliefs immediately to the north, the catchment area extended up to the exposed salt province, supplying the Triassic ophitic dolerites, as well as further north into the Nogueres thrust sheets supplying Devonian and Silurian clasts. The absence of Permo-Triassic clasts in the Espills and lower Gurp allogroups suggests that the Paleozoic clasts where sourced from an area where Cretaceous carbonates were directly overlying the Silurian and Devonian (Fig. 7A). The omission of the Permo-Triassic succession is most probably caused by a northern termination of the Permo-Triassic basins in the Nogueres thrust sheet (as inferred in the Nogueres reconstruction by Teixell *et al.*, 2018, and similarly to what happens in parts of Axial Zone today). However, the precise position of the northern limit of the Permo-Triassic basins and the extent of the Mesozoic cover during the Late Lutetian are unknown.

The granite and gneiss pebbles were sourced by more distant areas. The most likely source are the Lower Paleozoic gneiss massifs and Variscan plutons like those of Castillon, Trois Seigneurs and Lacourt, located in the North Pyrenean zone (the root of the Nogueres thrust sheet following the tectonic reconstruction by Teixell *et al.*, 2018). These massifs have AFT and ZFT cooling ages from the Late Cretaceous to the early Oligocene (Sinclair *et al.*, 2005; Whitchurch *et al.*, 2011), therefore it is possible that they were exposed at the surface by the late Lutetian, the age of sedimentation of the first alluvial fan of the Gurp basin. This is further supported by AFT ages of 75–55 Ma in clasts of the upper Gurp and Pallaresa allogroups in the Gurp basin (Michael, 2013) and geomorphological criteria that place the mid Eocene watershed past the North-Pyrenean Zone (Ortuño and Viaplana-Muzas, 2018). It is worth noting that the crystalline massifs of the present-day Axial Zone yielded younger fission-track cooling ages (centered on 45–30 My in the above referred works), with which they are unlikely sources for the Lutetian conglomerates.

Regarding clast composition, the Bartonian-Priabonian Pallaresa allogroup systems can be separated into two groups: on one hand local fans (Collegats system) predominantly sourced from adjacent reliefs formed by Mesozoic carbonates, and on the other, more extensive fans with larger catchment areas predominantly sourced from the Nogueres thrust sheet Siluro-Devonian, Carboniferous and Permo-Triassic rocks (Camporan, Montsor, Roca del Pesó and Roc de Santa systems) (Figs. 6 and 7B). The abundance of Buntsandstein and Permian clasts in all the Nogueres-sourced fans indicates that the leading edge of the thrust sheet, containing the Permo-Triassic lithologies, was cropping out during the Bartonian.

The almost complete absence of gneiss and other Lower Paleozoic lithologies within the Pallaresa allogroup fans we interpret it reflects the progressive southward displacement of the Pyrenean water divide: during the Lutetian the North-Pyrenean massifs were part of the drainage area (Roigé *et al.*, 2017; Ortuño and Viaplana-Muzas, 2018), while in the Bartonian and Priabonian a local southward migration of the divide localized the drainage area in the southern Nogueres thrust sheet domain (Fig. 7A and B). The few granite pebbles found within the Pallaresa allogroup could have been sourced from minor intrusions within the Nogueres thrust sheet, now eroded (Beamud *et al.*, 2011).

The southern extent of the eastern fans in the La Pobla basin was probably still limited by the Sant Corneli anticline, while the Camporan and Montsor fans infilled the Lower Cretaceous reliefs to the north and then expanded freely to the south, stacking flat above the Pessonada, Ermita, and Gurp allogroups (Figs. 4A and B and 7B). The proximity between the present-day outcrops of the Camporan and Montsor systems, together with the reported dip measurements, suggests that the two could have interfingered in the area of the present-day Flamisell river valley (Fig. 2A).

As explained in Section 3, we consider the Oligocene conglomerates of the Senterada and Antist groups as restricted to the Senterada basin. These conglomerate systems were trapped and confined in an E-W oriented synformal minibasin, sitting directly above the Keuper, and finally overlapping onto the Paleozoic to the north and the Sant Gervàs and Peracalç ridges to the south (Fig. 7C). The clast composition within the Senterada units, with predominant Buntsandstein and

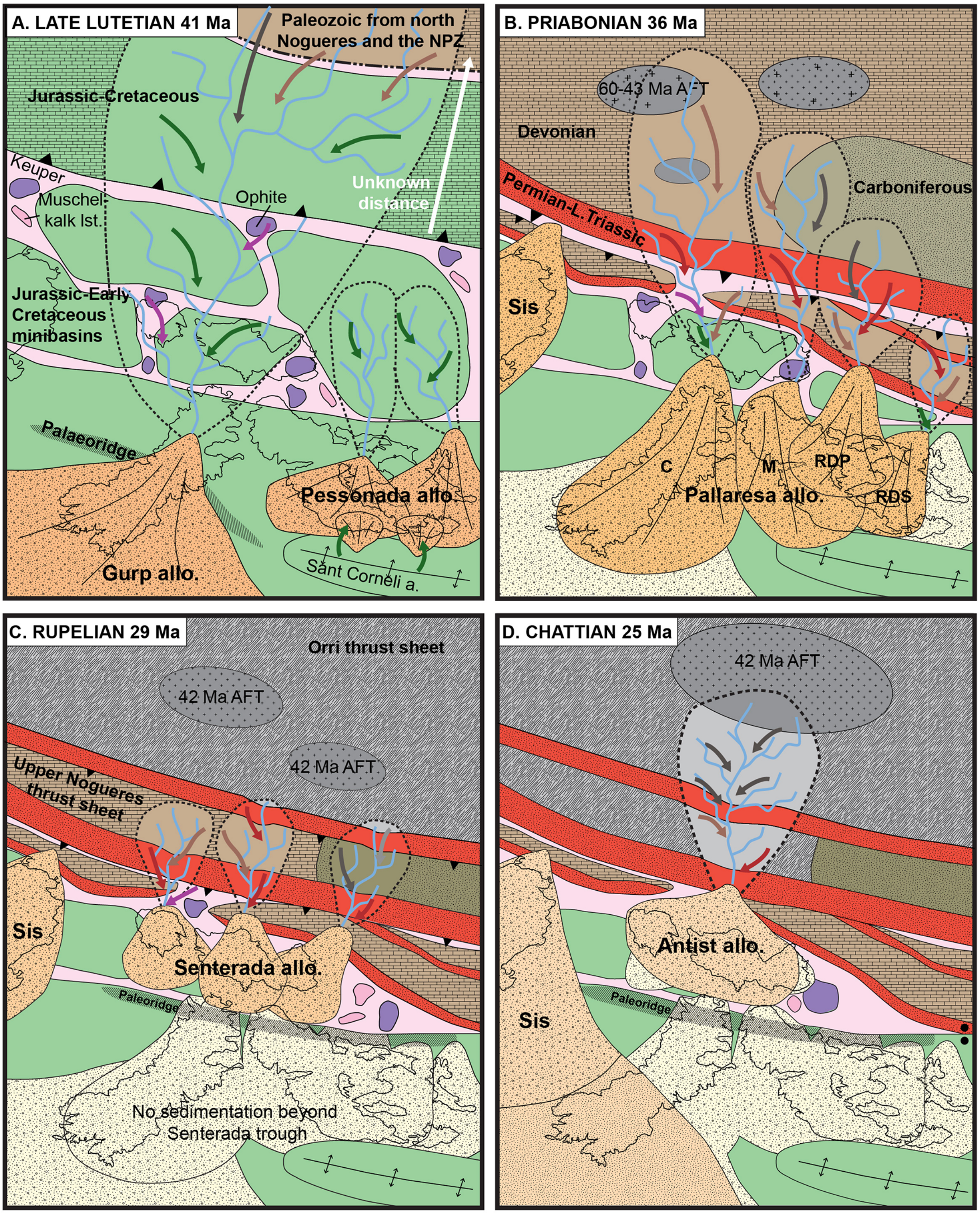

Fig. 7. Palaeogeographical reconstruction showing the evolution of the intramontane alluvial fans and their catchment areas from Late Lutetian to Late Oligocene. AFT data from Beamud *et al.*, 2011. C: Camporan fan; M: Montsor fan; RDS: Roc de Santa fan; RDP: Roca del Pesó fan.

Siluro-Devonian limestones and slates (Fig. 6) reflects the composition of the nearby Nogueres thrust subunits. There is very little contribution of granites or high-grade metamorphics from areas further north, indicating that the fans had small catchment areas (Fig. 7C). In the Antist allogroup, however, the presence of Lower Paleozoic metamorphics and granite pebbles indicates that the late Oligocene the catchment areas expanded, draining also from the plutons of the Orri thrust sheet at the core of the antiformal stack (Fig. 7D) that was progressively unroofed during the late Eocene and Oligocene, as indicated by thermochronology (Metcalf *et al.*, 2009).

7 Role of salt tectonics and basement thrusting in the evolution of the synorogenic conglomeratic basins

For most of the Early Cretaceous rifting stage the Senterada Keuper province was already a complex salt wall system, probably exposed or close to the surface (García-Senz *et al.*, 2019). The differential load of syn-rift sediments in the Organyà basin likely mobilized salt withdrawal from under the basin towards the salt walls, contributing to the rising and tilting of the northern basin margin and forming the progressive unconformity observed in Cretaceous sediments. The northern boundary of the Organyà basin observed today is primarily the diapiric contact with the Senterada salt province.

Salt wall rise was reactivated by the early Pyrenean shortening, by squeezing between the Organyà basin and the Nogueres thrust sheet emplaced onto the Keuper. The uninterrupted contribution of Triassic ophite clasts in the Gurp and La Pobla conglomerates (Fig. 6) indicates that diapirs of the Senterada salt province were exposed at the surface throughout the entire evolution of the conglomeratic basins. This is between the mid Lutetian and the late Rupelian-Chattian (and possibly since the Early Eocene as witnessed by the Triassic clasts in the upper Montanyana group Montllobar conglomerates, Fig. 6). The content of ophite clasts in the conglomerates begins much earlier than the appearance of Triassic Bundtsandstein clasts from the Nogueres zone at around 40 My, and for this reason we discard the Keuper interleaved between the Nogueres thrust slices as the primary ophite contributor to the conglomerate basins. The continuous exposure of the salt walls during conglomeratic sedimentation had a major effect in enabling uninterrupted load-induced salt withdrawal and associated basin tilting, that would not have happened if the salt province was covered and salt had nowhere to extrude.

On the basis of the structural and provenance data presented above, we propose new palaeogeographic and cross-section reconstructions (Figs. 7 and 8) of four stages in the evolution of the intramontane conglomeratic basins of Gurp, La Pobla, and Senterada between the mid Eocene to the Oligocene.

As explained in the previous section, the Gurp and La Pobla basins were separate depocentres in the interior of a low-relief, South-Pyrenean thrust belt during the mid and late Lutetian (Fig. 7A). Differential loading caused by the conglomerate weight triggered low-amplitude salt evacuation of the evaporites under the Organyà basin towards the Senterada salt walls (Fig. 8A). However, the Mesozoic carbonate succession of the Organyà basin edge is much thicker compared to the synorogenic conglomerates (Fig. 2B). For this reason, load-induced movements produce only a moderate tilting of the basin margin, reflected in the apparent north-directed downlap of the La Pobla and Gurp conglomerates against the basal unconformity and the long-lived progressive unconformity within the conglomerate beds (Fig. 4A). The resulting geometry is very similar to the classic illustrations by Trusheim (1960) (Fig. 7) on the development of a salt stock.

In the latest Lutetian, stacking under the Nogueres thrust sheet begun: the Orri thrust sheet was in the early stages of emplacement (Muñoz, 1992; Sinclair *et al.*, 2005; Metcalf *et al.*, 2009). The Nogueres thrust sheet was under further exhumation but not yet eroded enough to disconnect the downward facing leading edge from the root zone to the north. The Orri thrust sheet granites (*e.g.* Maladeta, Fig. 2A) have late Lutetian and younger AFT cooling ages, indicating that they were still covered by a great thickness of rock (Fig. 8A).

From the Bartonian onwards, the Orri thrust sheet uplift caused complete erosion the Nogueres thrust sheet Mesozoic cover to the east of the Flamisell river (Fig. 8B). This exposed the Permo-Triassic rocks of the Nogueres leading edge, which became the main source area for the Pallaresa allogroup fans in the Gurp and La Pobla basins (Fig. 7B). The fact that the La Pobla fans are enriched in Carboniferous clasts, while this lithology is absent in the Gurp basin, suggests that the Gurp and La Pobla systems were different fans with distinct catchment areas, but likely interfingered in a shared alluvial plain (Fig. 7B). The differential loading of the conglomerates and the retrogradation of the systems kept pumping salt towards the Senterada salt province, continuing the northward tilting of the conglomeratic basins (Fig. 8B).

Detrital AFT data from the upper Gurp and Pallaresa allogroups of the Gurp basin yield cooling ages between 75 and 55 My (Michael, 2013), reflecting the timing of the Nogueres sheet emplacement. The absence of younger detrital AFT ages from the Orri sheet is consistent with the evidence gathered from clast composition, indicating that the Nogueres thrust sheet was the main contributor to the upper fans in the Gurp basin (Beamud *et al.*, 2011).

By the start of the Oligocene, with the emplacement of the lower basement thrust sheets (Rialp and others, Muñoz *et al.*, 2018), the leading edge of the Nogueres thrust sheet was erosionally detached from its root (Fig. 8C). Sinking into the Keuper salt may partly account for the strong rotation and complete overturning of the Triassic layers of the Nogueres "*têtes plongéantes*". The immersion of the overturned thrust leading edge into the Senterada salt province, together with regional shortening, further mobilized of the underlying Keuper evaporites towards the salt diapirs. In a positive feedback loop, the loading of the conglomerates on top of the Triassic and the detached Paleozoic sheets accelerated their gravitational sinking in the salt (Fig. 8C). This caused the development of an E-W orientated sedimentary depression along the Senterada evaporite province (a "minibasin"). The locally sourced conglomerates were confined to this depression (Senterada basin), too low to be able to climb up the Cretaceous ridges to the south and overspill onto the La Pobla basin (Fig. 7C). Due to salt evacuation to the south, the Senterada basin depocentre progressively displaced to the north, and sediments onlapped the Paleozoic and Triassic outcrops (Fig. 8C).

The flat-lying, late Oligocene Antist allogroup had a wider catchment area, including Axial Zone granites and metamorphic clasts from the then exhumed Orri thrust sheet. Sedimentation of the lower members of the Antist allogroup was still confined to the Senterada trough (Fig. 7D), as attested by the position of the present day outcrops. It cannot be discarded that sedimentation of the Antist group could overspill the Senterada basin and cover the older conglomerates of the Gurp and La Pobla basin towards the south. This was suggested by Fillon *et al.* (2013) on the basis of

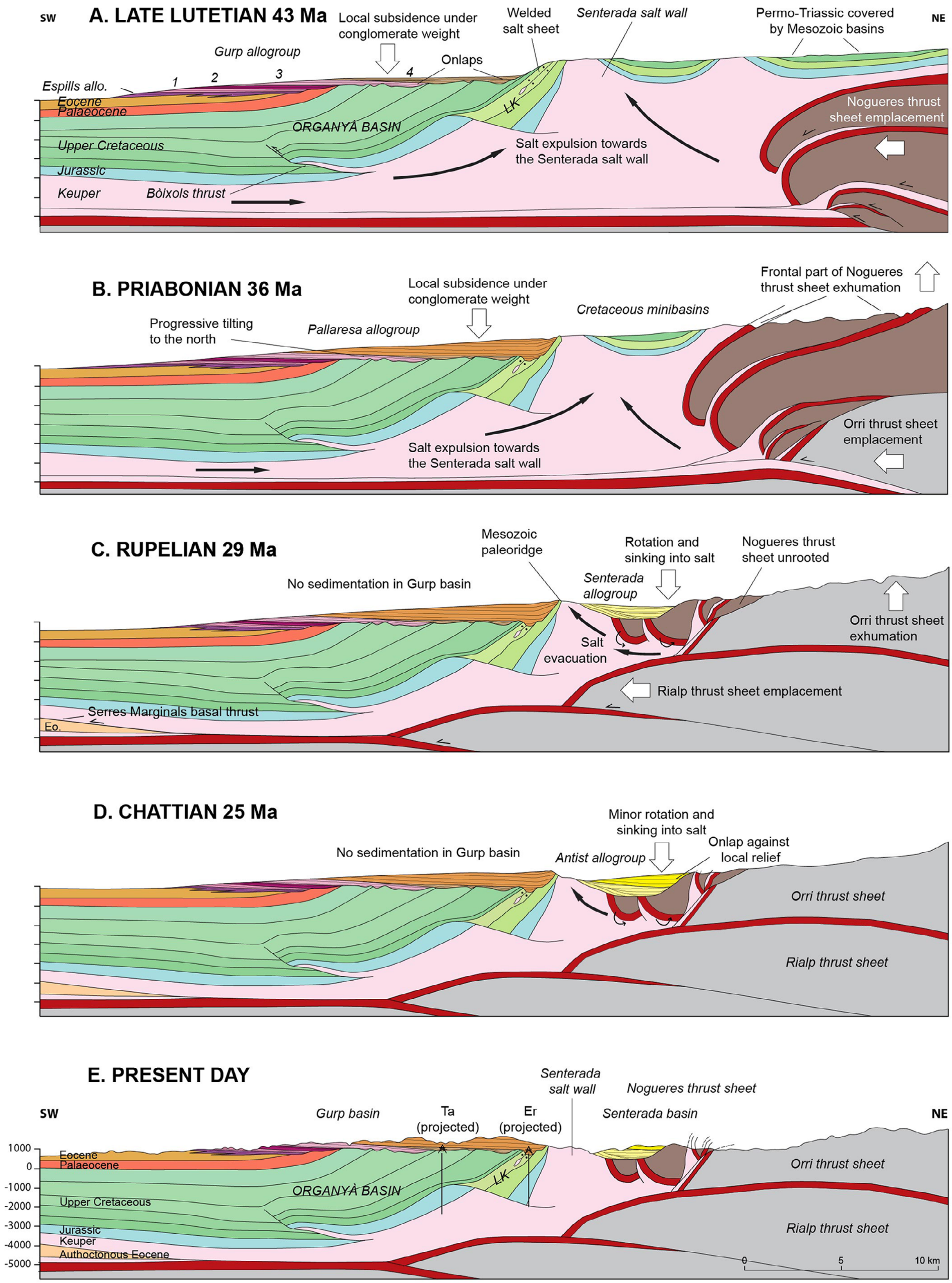

Fig. 8. Restored cross-sections of the sequential evolution (Late Lutetian to present day) of the northern margin of the Organyà basin and the adjacent salt province as a response of the growth of the Axial Zone antiformal stack and the differential loading by synorogenic alluvial sediments. Er: Erinyà well; Ta: Tamúrcia well.

thermochronology-derived burial data, although such upper conglomerate succession, if present, has been removed by erosion.

The sedimentation of the Antist conglomerates during the Chattian is contemporary to the Rialp thrust sheet emplacement. As interpreted by Teixell and Muñoz (2000) and Muñoz *et al.* (2018), the leading edge of the Rialp thrust sheet has significant displacement below the Senterada basin and even the northern edge of the Organyà basin (Fig. 8D). However, the basement thrusting did not translate in deformation of the Mesozoic cover or the Eocene-Oligocene conglomerates, which crop out flat and undeformed. A possible explanation for this is that the thick Keuper accumulations within the Senterada salt province promoted the complete decoupling between the basement and the cover above. In this case, shortening was accommodated by the expulsion of great volumes of salt through the exposed Senterada salt walls and the pumping of salt towards the foreland. A second interpretation is that the conglomerates and the Mesozoic cover do not register thrust uplift during the Rupelian because the Rialp thrust sheet did not reach that far south as interpreted. With this solution, the thick volumes of Keuper would not have extruded, and present day Senterada salt province would still have preserved several kms of vertical evaporite thickness underneath. In the restorations in Figure 8 we have followed the first approach, relying on the displacement attributed to Rialp thrust sheet by the authors cited above. We would like to emphasize again the large initial volumes of Keuper involved in either of the two interpretations.

8 Conclusions

In this study we present a reinterpretation of the evolution of the intramontane conglomeratic basins in the northern part of the Southern Pyrenees based on new field observations, clast counting and revisiting previous structural interpretations taking into account the recent advances in salt tectonics. The results are illustrated in new palaeogeographic maps and a representative cross-section sequentially restored at four stages from the late Lutetian to the late Oligocene of the La Pobla, Gurp and Senterada conglomeratic basins and their drainage areas. The maps and the restored cross-section highlight the role of the interplay between hinterland basement thrusting and Keuper salt migration in conditioning the dimensions and shape of the intramontane alluvial fan systems.

Diapirism is identified in the northern margin of the Organyà Mesozoic basin since the Early Cretaceous rifting times: thinning stratigraphy towards the Senterada salt province, progressive unconformities and interbedded Keuper lenses within the Lower Cretaceous carbonates and shales are strong evidence for salt movements in this epoch, as has been recently documented in this and other areas of the Southern Pyrenees by different authors. Consequently, we reinterpret the Morreres backthrust structure as a diapiric contact between the northern margin of the Organyà basin and the Senterada salt wall province.

During the Pyrenean contraction, the Senterada salt walls were exposed in the surface at least from the upper Ypresian to the Oligocene, as evidenced by the widespread presence of Triassic ophite clasts in all the conglomerate units. Alluvial fans sourced in the reliefs of the growing antiformal stack of the Axial Zone rapidly deposited the gravel load over a mobile salt-bearing substratum at its toe. From Lutetian times onwards, the differential load of the alluvial systems of the La Pobla and Gurp basins contributed to generate accommodation space and caused a moderate and progressive northward tilting of the northern Organyà basin margin, enabled by the expulsion of salt through the exposed Senterada salt province. This is reflected in the north-directed onlap of the Pessonada and Gurp conglomerates against the basal unconformity, opposite to the main sediment influx direction.

During the late Lutetian, the La Pobla basin was receiving only local sediment influx from the Mesozoic carbonates of the extensional minibasins (like those preserved today in the northern Ribagorçana valley) and northern Organyà basin margin. At the same time, the alluvial fans of Espills and Gurp allogroups drained from a much more extensive area; we propose that the North Pyrenean zone metamorphic and granite massifs sourced the gneiss, marble and granite pebbles, while the Siluro-Devonian limestones and slates were supplied by the Nogueres thrust sheet, not yet unrooted by erosion. By the Priabonian, the emplacement of the Orri thrust sheet had already uplifted the Nogueres thrust sheet and the topographic uplift of the antiformal stack initiated the migration of the watershed divide to the south. This is reflected in the increasing proportion of proximal lithologies derived from the Nogueres Zone in the Pallaresa allogroup fans, such as Permo-Triassic lithologies of the frontal part of the Nogueres sheet and Carboniferous Culm sandstone pebbles. The alluvial fans progressively retrograded to the north, infilling the palaeoreliefs of the northern Organyà basin. In any case, the total subsidence and Eocene-Oligocene strata rotation was moderate due to the thick Mesozoic succession existing between the fan conglomerates and the Keuper salt. The erosional unrooting of the Nogueres thrust sheet during the Oligocene enabled the sinking and rotation of the detached leading edge into the evaporites of the Senterada salt province, partly explaining their strong overturning. Subsidence was enhanced by the sedimentation of the Senterada and Antist conglomerates on top, which due to load-induced salt withdrawal kept trapped into the Senterada sedimentary depression, defined by the width of the salt province.

The study of the northern margin of the South-Pyrenean Central Unit revisits important observations regarding intramontane conglomerate geometries. With the addition of new structural and compositional data, and making use of salt tectonics concepts developed in the last decades we propose a new interpretation of the structural evolution of this complex area of the Southern Pyrenees. This study presents a good example of how halokinesis, induced by differential sedimentary loading, can interact with compressional structures and their erosion, having a strong effect in basin geometry and shaping of alluvial routing systems.

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References

Barsó D. 2007. Análisis de la procedencia de los conglomerados sinorogénicos de La Pobla de Segur (Lérida) y su relación con la evolución tectónica de los Pirineos centro-meridionales durante el Eoceno medio-Oligoceno. Tesis de la Universitat de Barcelona.

Barsó D, Ramos E. 2007. Procedencia de los conglomerados sinorogénicos de La Pobla de. *Geogaceta* 41: 19–22.

Bartrina T, Hernández E. 1990. Las unidades evaporíticas del Triásico del subsuelo del Maestrazgo. In: Formaciones Evaporíticas de La Cuenca Del Ebro y Cadenas Periféricas y de La Zona de Levante. Nuevas Aportaciones y Guía de Superfície. Universitat de Barcelona, pp. 34–38.

Bataller JR. 1943. El Anoplotherium commune CUV. del Eocénico de Sossís. *Las Ciencias* 8.

Beamud E, Garcés M, Cabrera L, Muñoz JA, Almar Y. 2003. A new middle to late Eocene continental chronostratigraphy from NE Spain. *Earth and Planetary Science Letters* 216: 501–514. https://doi.org/10.1016/S0012-821X(03)00539-9.

Beamud E, Muñoz JA, Fitzgerald PG, Baldwin SL, Garcés M, Cabrera L, *et al.* 2011. Magnetostratigraphy and detrital apatite fission track thermochronology in syntectonic conglomerates: constraints on the exhumation of the South-Central Pyrenees. *Basin Research* 23: 309–331. https://doi.org/10.1111/j.1365-2117.2010.00492.x.

Beaumont C, Muñoz JA, Hamilton J, Fullsack P. 2000. Factors controlling the Alpine evolution of the central Pyrenees inferred from a comparison of observations and geodynamical models. *Journal of Geophysical Research* 105: 8121–8145. https://doi.org/10.1029/1999JB900390.

Berástegui X, García-Senz J, Losantos M. 1990. Tecto-sedimentary evolution of the Organyà extensional basin (central south Pyrenean unit, Spain) during the Lower Cretaceous. *Bulletin de la Societé Géologique de la France* 8: 251–264.

Calvet M, Gunnell Y, Laumonier B. 2020. Denudation history and palaeogeography of the Pyrenees and their peripheral basins: an 84-million-year geomorphological perspective. *Earth-Science Reviews*, in press. https://doi.org/10.1016/j.earscirev.2020.103436.

Cámara P, Flinch JF. 2017. The Southern Pyrenees: A Salt-Based Fold-and-Thrust Belt. *Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins*: 395–415. https://doi.org/10.1016/B978-0-12-809417-4.00019-7.

Caus E, Rod D, Sire A. 1990. Stratigraphy of the Lower Cretaceous (Berriasian-Barremian) sediments in the Organyà Basin, Pyrenees, Spain. *Cretaceous Research* 11: 313–320.

Crusafont M, Vilalta J, Truyols J. 1956. Caracerización del Eoceno continental en la cuenca de Tremp y edad de la orogénesis pirenaica. *IIe Congr. Int. Etud. Pyr. Toulouse* 2: 29–53.

Ellis PG, McClay KR. 1988. Listric extensional fault systems – results of analogue model experiments. *Basin Research* 1: 55–70. https://doi.org/10.1111/j.1365-2117.1988.tb00005.x.

Fillon C, Gautheron C, van der Beek P. 2013. Oligocene–Miocene burial and exhumation of the Southern Pyrenean foreland quantified by low-temperature thermochronology. *Journal of the Geological Society* 170: 67–77. https://doi.org/10.1144/jgs2012-051.

Fillon C, van der Beek P. 2012. Post-orogenic evolution of the southern Pyrenees: Constraints from inverse thermo-kinematic modelling of low-temperature thermochronology data. *Basin Research* 24: 418–436. https://doi.org/10.1111/j.1365-2117.2011.00533.x.

Fitzgerald PG, Muñoz JA, Coney PJ, Baldwin SL. 1999. Asymmetric exhumation across the Pyrenean orogen: Implications for the tectonic evolution of a collisional orogen. *Earth and Planetary Science Letters* 173: 157–170. https://doi.org/10.1016/S0012-821X(99)00225-3.

García-Senz J. 2002. Cuencas extensivas del Cretácico Inferior en los Pirineos centrales, formación y subsecuente inversión. Phd thesis, Universitat de Barcelona.

García-Senz J, Muñoz JA. 2019a. The Late Albian to Middle Cenomanian Aulet and Las Aras Basins, in: Martín-Chivelet J, *et al*. Late Cretaceous Post-Rift to Convergence in Iberia. In: Quesada C, Oliveira J, eds. The Geology of Iberia: A Geodynamic Approach. Regional Geology Reviews. Springer International Publishing, pp. 320–324.

García-Senz J, Muñoz JA. 2019b. South Central Pyrenees: The Organyà Rift Basin, in: Martín-Chivelet J, *et al*. The Late Jurassic–Early Cretaceous Rifting. In: Quesada C, Oliveira J, eds. The Geology of Iberia: A Geodynamic Approach. Regional Geology Reviews. Springer International Publishing, pp. 169–249. https://doi.org/10.1007/978-3-030-11295-0_5.

García-Senz J, Pedrera A, Ayala C, Ruiz-Constán A, Robador A, Luis, *et al.* 2019. Inversion of the north Iberian hyperextended margin: the role of exhumed mantle indentation during continental collision. In: Hammerstein JA, Di Cuia R, Cottam MA, Zamora G, Butler RWH, eds. Fold and Thrust Belts: Structural Style, Evolution and Exploration. *Geological Society of London, Special Publications* 490. https://doi.org/10.1144/SP490-2019-112.

Garrido-Mejías A, Ríos LM. 1972. Síntesis geológica del Secundario y Terciario entre los ríos Cinca y Segre (Pirineo Central de la vertiente sur pirenaica, províncias de Huesca y Lérida. *Boletín Geológico y Minero* 83: 1–47.

Ge H, Jackson MPA, Vendeville BC. 1997. Kinematics and Dynamics of Salt Tectonics Driven by Progradation. *AAPG Bulletin* 81: 398–423. https://doi.org/10.1306/522B4361-1727-11D7-8645000102C1865D.

Gibson M. 2004. The localisation of erosional denudation during the growth and decay of the Pyrenean Orogen. PhD thesis. University of Edinburgh.

Grool AR, Huismans RS, Ford M. 2019. Salt décollement and rift inheritance controls on crustal deformation in orogens. *Terra Nova* 31: 562–568. https://doi.org/10.1111/ter.12428.

Howard L. 1993. The statistics of counting clasts in rudites: a review, with examples from the upper Palaeogene of southern California, USA. *Sedimentology* 40: 157–174. https://doi.org/10.1111/j.1365-3091.1993.tb01759.x.

Jourdon A, Mouthereau F, Le Pourhiet L, Callot J. 2020. Topographic and Tectonic Evolution of Mountain Belts Controlled by Salt Thickness and Rift Architecture. *Tectonics* 39. https://doi.org/10.1029/2019TC005903.

Jurado M. 1990. El Triásico y el Liásico basal evaporíticos del subsuelo de la cuenca del Ebro, in: Formaciones Evaporíticas de La Cuenca Del Ebro y Cadenas Periféricas, y de La Zona de Levante. ENRESA-GPPG, Universidad de Barcelona, pp. 21–28.

Lanaja J, Querol M, Navarro A. 1987. Contribución de la exploración petrolífera al conocimiento de la geología de España.

Lloret J, Ronchi A, López-Gómez J, Gretter N, De la Horra R, Barrenechea JF, *et al.* 2018. Syn-tectonic sedimentary evolution of the continental late Palaeozoic-early Mesozoic Erill Castell-Estac Basin and its significance in the development of the central Pyrenees Basin. *Sedimentary Geology* 374: 134–157. https://doi.org/10.1016/j.sedgeo.2018.07.014.

López-Martínez N, Civis J, Casanovas ML, Daams R. 1998. Geología y Paleontología del Eoceno de la Pobla de Segur (Lleida). Edicions i Publicacions de la Universitat de Lleida.

Lopez-Mir B, Muñoz JA, García Senz J. 2014. Restoration of basins driven by extension and salt tectonics: Example from the Cotiella Basin in the central Pyrenees. *Journal of Structural Geology* 69: 147–162. https://doi.org/10.1016/j.jsg.2014.09.022.

McClay K, Muñoz JA, García-Senz J. 2004. Extensional salt tectonics in a contractional orogen: A newly identified tectonic event in the Spanish Pyrenees. *Geology* 32: 737–740. https://doi.org/10.1130/G20565.1.

Mellere D. 1993. Thrust-Generated, Back-Fill Stacking of Alluvial Fan Sequences, South-Central Pyrenees, Spain (La Pobla De Segur Conglomerates). *Special publications International Association of Sedimentology* 20: 259–276. https://doi.org/10.1002/9781444304053.ch14.

Mellere D, Marzo M. 1992. Los depósitos aluviales sintectónicos de la Pobla de Segur: alogrupos y su significado tectonoestratigráfico. *Acta Geol Hispánica Volum homenatge a Oriol Riba* 27: 145–159.

Mencos J, Carrera N, Muñoz JA. 2015. Influence of rift basin geometry on the subsequent postrift sedimentation and basin inversion: The Organyà Basin and the Bóixols thrust sheet (south central Pyrenees). pp. 1452–1474. https://doi.org/10.1002/2014TC003692.Received.

Metcalf JR, Fitzgerald PG, Baldwin SL, Muñoz JA. 2009. Thermochronology of a convergent orogen: Constraints on the timing of thrust faulting and subsequent exhumation of the Maladeta Pluton in the Central Pyrenean Axial Zone. *Earth and Planetary Science Letters* 287: 488–503. https://doi.org/10.1016/j.epsl.2009.08.036.

Mey PHW. 1968. Geology of the Upper Ribagorzana valleys, Central Pyrenees, Spain. Leidse Geol. Mededelingen 41: 229–292.

Michael NA. 2013. The Functioning of Sediment Routing Systems Using a Mass Balance Approach: Example from the Eocene of the. https://doi.org/10.1086/673176.

Mouthereau F, Filleaudeau PY, Vacherat A, Pik R, Lacombe O, Fellin MG, *et al.* 2014. Placing limits to shortening evolution in the Pyrenees: Role of margin architecture and implications for the Iberia/Europe convergence. *Tectonics* 33: 2283–2314. https://doi.org/10.1002/2014TC003663.

Muñoz JA. 1992. Evolution of a continental collision belt: ECORS-Pyrenees crustal balanced cross-section. In: Thrust Tectonics. Dordrecht: Springer, pp. 235–246. https://doi.org/10.1007/978-94-011-3066-0_21.

Muñoz JA, Carrera N, Mencos J, Beamud E, Perea H, Arbués P, *et al.* 2009. 252-1-1 sheet, Tremp, 1:25000 geological map.

Muñoz JA, Mencos J, Roca E, Carrera N, Gratacós O, Ferrer O, *et al.* 2018. The structure of the South-Central-Pyrenean fold and thrust belt as constrained by subsurface data. *Geologica Acta* 16: 439–460. https://doi.org/10.1344/GeologicaActa2018.16.4.7.

Nijman W, Nio SD. 1975. The Eocene Montañana delta. In: Rosell J, Puigdefabregas C, eds. Sedimentary Evolution of the Paleogene South Pyrenean Basin. IAS 9th International Congress, Nice.

Ortí F, Pérez-López A, Salvany JM. 2017. Triassic evaporites of Iberia: Sedimentological and palaeogeographical implications for the western Neotethys evolution during the Middle Triassic – Earliest Jurassic. *Palaeogeography, Palaeoclimatology, Palaeoecology* 471: 157–180. https://doi.org/10.1016/j.palaeo.2017.01.025.

Ortuño M, Viaplana-Muzas M. 2018. Active fault control in the distribution of elevated low relief topography in the Central-Western Pyrenees. *Geologica Acta* 16: 499–518. https://doi.org/10.1344/GeologicaActa2018.16.4.10.

Peybernès B. 1976. Le Jurassique et le Crétacé inférieur des Pyrénées franco-espagnoles entre la Garonne et la Méditerranée. PhD thesis. Université Toulouse 3 (Paul Sabatier).

Reille JL. 1971. Les relations entre tectonogenése et sedimentation sur la vessant sud des Pyrenées Centrales. PhD thesis. Université de Montpellier.

Robles S, Ardévol L. 1984.Evolución paleogeográfica y sedimentológica de la cuenca palustre de Sossís (Eoceno superior, Prepirineo de Lérida): ejemplo de la influencia de su actividad de abanicos aluviales en el desarrollo de una cuenca lacustre asociada. *Publicaciones del departamento de estratigrafía de la UAB. Tomo homenaje a Luis Sánchez de la Torre* 20: 223–267.

Roigé M, Gómez-Gras D, Remacha E, Boya S, Viaplana-Muzas M, Teixell A. 2017. Recycling an uplifted early foreland basin fill: An example from the Jaca basin (Southern Pyrenees, Spain). *Sedimentary Geology* 360: 1–21. https://doi.org/10.1016/j.sedgeo.2017.08.007.

Rosell J, Gómez-Gras D, Luterbacher H, Llompart C. 1994a. Memoria del mapa geológico de la hoja n°252/33-11 (Tremp). 1:50.000 Segunda Serie (MAGNA). Primera edición. IGME.

Rosell J, Gómez-Gras D, Luterbacher H, Llompart C, Gabaldón V. 1994b. Mapa geológico de la hoja n°252 (Tremp), in: 1:50.000 Segunda Serie (MAGNA). Primera Edición. IGME.

Rosell J, Riba O. 1966. Nota sobre la disposición sedimentaria de los conglomerados de la Pobla de Segur (Província de Lérida). Zaragoza: Instituto de Estudios Pirenaicos, pp. 1–16.

Roure F, Choukroune P, Berástegui X, Muñoz JA, Villien A, Matheron P, *et al.* 1989. Ecors deep seismic data and balanced cross sections: Geometric constraints on the evolution of the Pyrenees. *Tectonics* 8: 41–50. https://doi.org/10.1029/TC008i001p00041.

Salvany JM, Bastida J. 2004. Análisis litoestratigráfico del keuper surpirenaico central. *Revista de la Sociedad Geológica de España* 17: 3–26.

Samsó JM, Cuevas JL, Mercadé L, Arbués P, Barberà X, Corregidor J, *et al.* 2010. 251-2-2 sheet, Espills, 1:25000 geological map.

Saura E. 2004. Anàlisi estructural de la zona de les Nogueres Pirineus Centrals. Tesi de la Universitat Autònoma de Barcelona.

Saura E, Ardèvol L, Teixell A, Vergés J. 2016. Rising and falling diapirs, shifting depocenters, and flap overturning in the Cretaceous Sopeira and Sant Gervàs subbasins (Ribagorça Basin, southern Pyrenees). *Tectonics* 35: 638–662. https://doi.org/10.1002/2015TC004001.

Saura E, Teixell A. 2006. Inversion of small basins: effects on structural variations at the leading edge of the Axial Zone antiformal stack (Southern Pyrenees, Spain). *Journal of Structural Geology* 28: 1909–1920. https://doi.org/10.1016/j.jsg.2006.06.005.

Séguret M. 1972. Étude tectonique des nappeset séries décollées de la partie centrale du vessant sud des Pyrénées. Caractère synsédimentaire, rôle de la compresion et de la gravité. PhD thesis. Univ. de Montpellier.

Séguret M. 1969. Carte géologique des têtes plongeantes des Nogueras : versant sud des Pyrénées centrales.

Sinclair HD, Gibson M, Naylor M, Morris RG. 2005. Asymmetric growth of the Pyrenees revealed through measurement and modeling of orogenic fluxes. *American Journal of Science* 305: 369–406. https://doi.org/10.2475/ajs.305.5.369.

Teixell A, Labaume P, Ayarza P, Espurt N, de Saint Blanquat M, Lagabrielle Y. 2018. Crustal structure and evolution of the Pyrenean-Cantabrian belt: A review and new interpretations from recent concepts and data. *Tectonophysics* 724–725: 146–170. https://doi.org/10.1016/j.tecto.2018.01.009.

Teixell A, Muñoz JA. 2000. Evolución tectono-sediementaria Pirineo meridional durante el terciario: Una síntesis basada en la transversal del río Noguera Ribagorçana. *Revista de la Sociedad Geológica de España* 13: 251–264.

Trusheim F. 1960. Mechanism of salt migration in Northern Germany. *AAPG Bulletin* 44: 1519–1540.

Vacherat A, Mouthereau F, Pik R, Bellahsen N, Gautheron C, Bernet M, *et al.* 2016. Rift-to-collision transition recorded by tectono-thermal evolution of the northern Pyrenees Rift-to-collision transition recorded by tectonothermal evolution of the northern Pyrenees. *Tectonics* 35: 907–933. https://doi.org/10.1002/2015TC004016.

Vergés J. 1993. Estudi geològic del vessant sud del Pirineu oriental i central. Evolució cinemàtica en 3D. PhD thesis. Universitat de Barcelona.

Vergés J, Muñoz JA. 1990. Thrust sequences in the southern central Pyrenees. *Bulletin de la Societé Geologique de la France* 8: 265–271.

Vincent SJ. 2001. The Sis palaeovalley: a record of proximal fluvial sedimentation and drainage basin development in response to Pyrenean mountain building. *Sedimentology* 48: 1235–1276.

Whitchurch AL, Carter A, Sinclair HD, Duller RA, Whittaker AC, Allen PA. 2011. Sediment routing system evolution within a diachronously uplifting orogen: Insights from detrital zircon thermochronological analyses from the South-Central pyrenees. *American Journal of Science* 311: 442–482. https://doi.org/10.2475/05.2011.03.

Williams GD, Fischer MW. 1984. A balanced section across the Pyrenean Orogenic Belt. *Tectonics* 3: 773–780. https://doi.org/10.1029/TC003i007p00773.

Yelland AJ. 1991. Thermo-tectonics of the Pyrenees and Provence from fission track studies. PhD thesis from Birkbeck College. University of London.

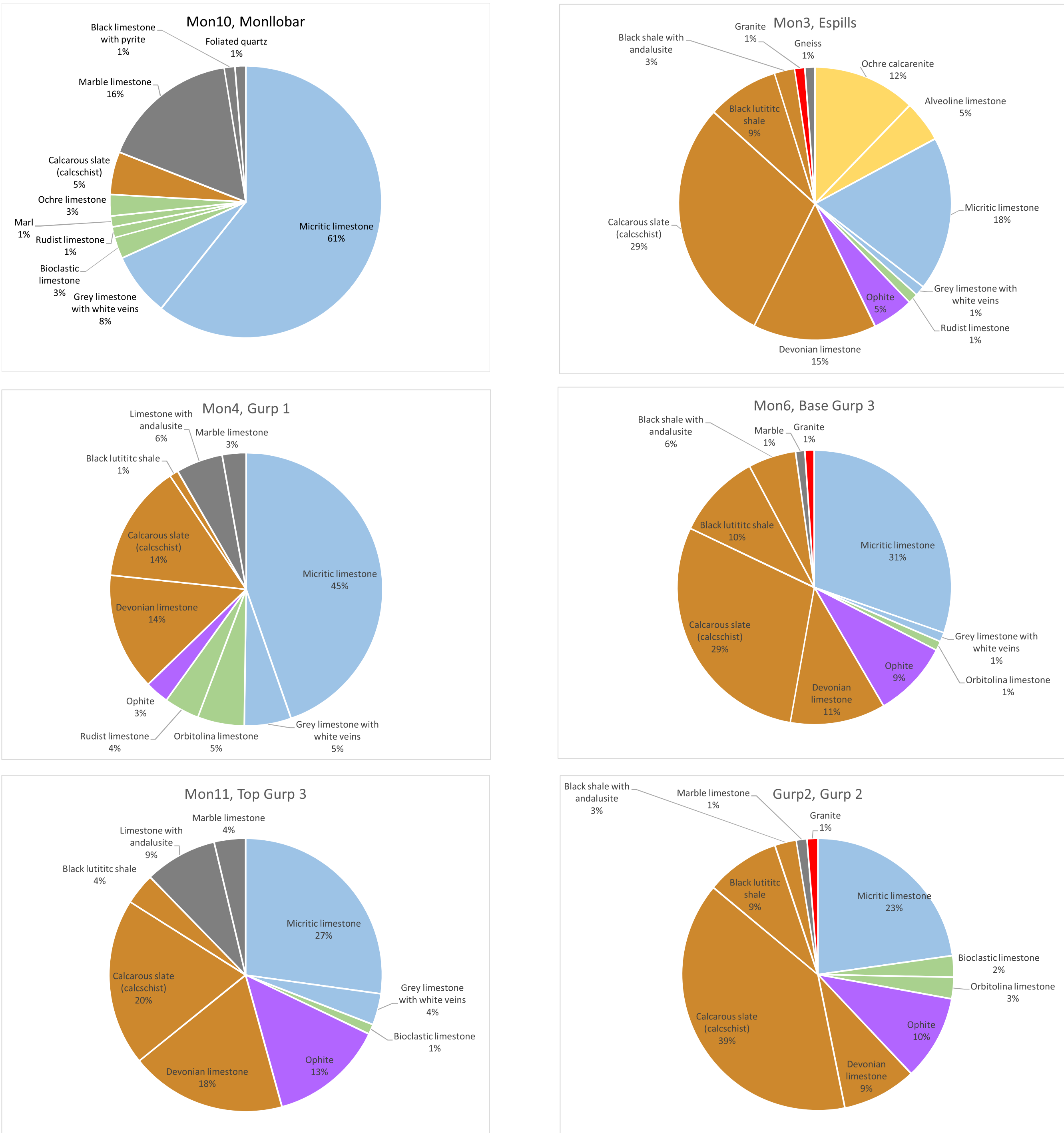
Zwart HJ. 1979. The Geology of the Central Pyrenees. *Leidse Geologische Mededelingen* 1–74.

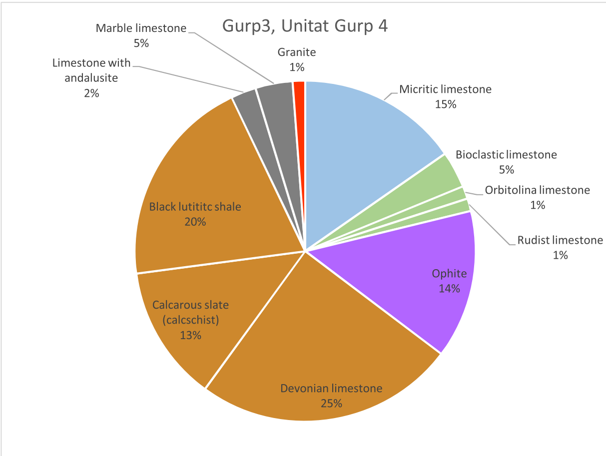
Appendix 1

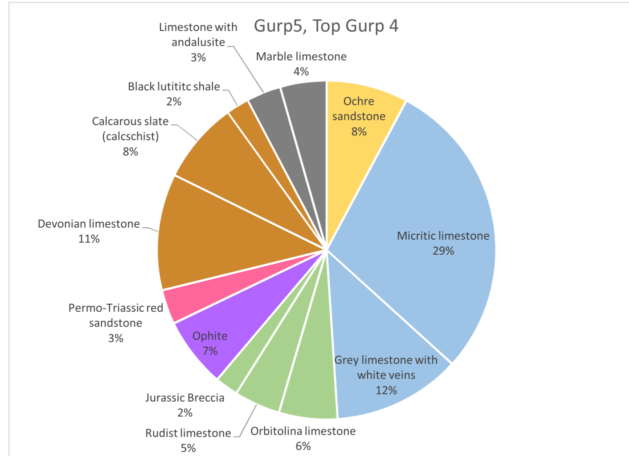
Sample	Mon10	Mon3	Mon4	Mon6	Mon11	Gurp2	Gurp3	Gurp5	Gurp6	Gurp8	Gurp9	Sent1	Sent2	Sent3	Montsor1	Montsor2	Montsor3	Montsor4
Unit	Monllobar	Espills	Gurp1	Base Gurp3	Top Gurp3	Gurp2	Gurp4	Top Gurp4	Ermita	Camporan1	Camporan 1	Senterada1	Senterada2	Senterada loca	Mont ophite la	Montsor middl	Montsor top	Montsor base
Ochre sandstone	0	0	0	0	0	0	0	7.8	15.6	0	5.9	0	0	0	0	0	0	0
Ochre calcarenite	0	12.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Alveoline limestone	0	4.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Micritic limestone	57.1	18.3	42.7	30.3	27.2	21.4	15.3	28.9	33.3	36.1	38.8	9	2.2	21.5	36.6	19.8	6.1	4.3
Grey limestone with white veins	7.1	1.2	5.3	1.1	3.7	0	0	12.2	8.9	7.2	4.7	0	0	0	0	0	0	3.2
Ochre bioclastic limestone	0	0	0	0	0	0	0	0	0	0	1.2	0	0	0	0	0	0	0
Bioclastic limestone	2.4	0	4	0	1.2	2.4	3.5	0	27.8	2.1	0	0	0	0	2	0	0	1.1
Orbitolina limestone	0	0	5.3	1.1	0	2.4	1.2	5.6	0	5.2	2.4	0	0	0	1	1	0	0
White limestone	0	0	0	0	0	0	0	0	4.4	0	0	0	0	0	0	0	0	0
Sparitic white limestone	0	0	0	0	0	0	0	0	2.2	0	0	0	0	0	0	0	0	0
Rudist limestone	1.2	1.2	4	0	0	6	1.2	4.4	1.1	4.1	0	0	0	0	0	0	0	0
Jurassic Breccia	0	0	0	0	0	0	0	2.2	0	0	0	0	0	0	2	0	0	1.1
Marl	1.2	0	0	0	0	0	0	0	2.2	0	0	0	0	0	0	0	0	0
Intraformational mudstone	0	0	0	0	0	0	0	0	1.1	0	0	0	0	0	0	0	0	0
Black dolomite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0
Ophite	0	4.9	2.7	9	13.6	9.5	14.1	6.7	1.1	3.1	0	1	0	0	24.8	0	0	0
Buntsandstein congomerate	0	0	0	0	0	0	0	0	0	2.1	7.1	7	6.7	1.1	1	5.2	20.4	3.2
Quartz	0	0	0	0	0	0	0	0	0	1	0	3	4.5	2.2	0	3.1	10.2	0
Permo-Triassic red sandstone	0	0	0	0	0	0	0	3.3	0	12.4	14.1	57	5.6	7.5	6.9	10.4	26.5	44.1
Buntsandstein white sandstone	0	0	0	0	0	0	0	0	0	1	10.6	8	3.4	1.1	0	3.1	5.1	8.6
Pumite	0	0	0	0	0	0	0	0	0	0	0	0	1.1	0	0	0	0	0
Permo-Triassic breccia	0	0	0	0	0	0	0	0	0	1	2.4	0	0	0	0	0	0	0
Permo-Triassic Caliche	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0
Griotte limestone	0	0	0	0	0	0	0	0	0	0	0	0	1.1	1.1	0	2.1	1	0
Red limestone	0	0	0	0	0	0	0	0	2.2	0	0	0	0	0	0	0	0	0
Orxidized devonian limestone	0	0	0	0	0	0	0	0	0	0	0	2	4.5	0	0	0	0	0
Devonian limestone	6	14.6	13.3	11.2	18.5	8.3	24.7	11.1	0	19.6	11.8	10	58.4	48.4	5.9	33.3	22.4	18.3
Ochre limestone	2.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Devonian limestone with chrinoids	0	0	0	0	0	0	0	0	0	0	0	0	7.9	2.2	0	0	0	0
Calcarous slate (calcschist)	4.8	29.3	13.3	29.2	19.8	36.9	12.9	7.8	0	4.1	0	0	4.5	12.9	0	0	1	0
Culm sandstone	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	19.8	6.1	16.1
Carboniferous slate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Black lutititc shale	0	8.5	1	10.1	3.7	8.3	20	2.2	0	1	0	0	0	0	0	0	0	0
Black shale with andalusite	0	2.4	0	5.6	0	2.4	0	0	0	0	0	0	0	0	0	0	0	0
Limestone with andalusite	0	0	5.3	0	8.6	0	2.4	3.3	0	0	1.2	0	0	0	0	0	0	0
Marble	0	0	0	1.1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Marble limestone	15.5	0	2.7	0	3.7	1.2	3.5	4.4	0	0	0	0	0	0	0	0	0	0
Black limestone with pyrite	1.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Foliated quartz	1.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gneiss	0	1.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cambro-ordovician Schist	0	0	0	0	0	0	0	0	0	0	0	0	0	1.1	0	0	0	0
Quarsita	0	0	0	0	0	0	0	0	0	0	0	0	0	1.1	0	0	0	0
Granite	0	1.2	0	1.1	0	1.2	1.2	0	0	0	0	0	0	0	10.9	2.1	1	0
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

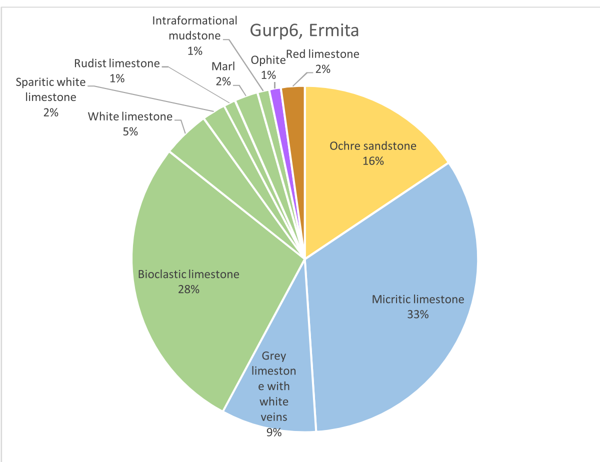
Categories

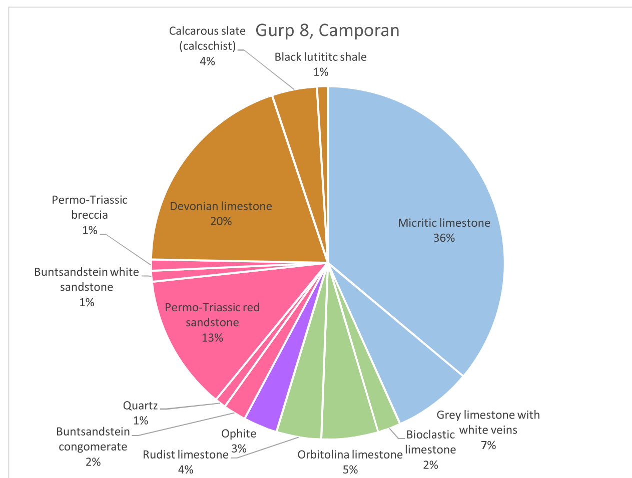
- a. Tertiary limestones and sandstones
- b. Mesozoic carbonates
- c. Micritic limestone
- d. Triassic dolerites
- e. Permo-triassic clasts
- f. Carboniferous
- g. Silurian and Devonian
- h. Paleozoic granites
- i. Paleozoic metasediments

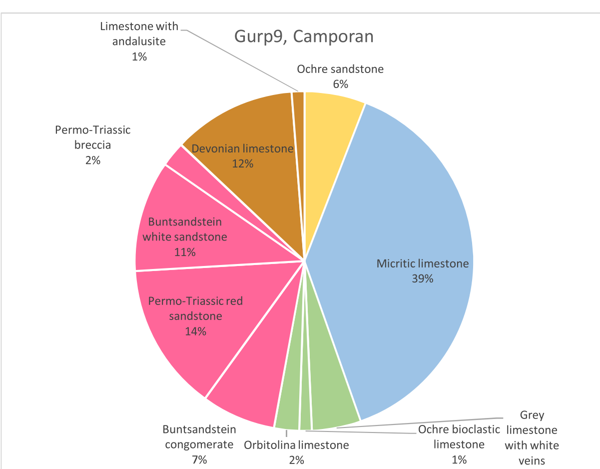

Mon10, Monllobar
Black limestone with pyrite 1%
Foliated quartz 1%
Marble limestone 16%
Calcarous slate (calcschist) 5%
Ochre limestone 3%
Marl 1%
Rudist limestone 1%
Bioclastic limestone 3%
Grey limestone with white veins 8%
Micritic limestone 61%
Mon3, Espills
Granite 1%
Black shale with andalusite 3%
Gneiss 1%
Ochre calcarenite 12%
Alveoline limestone 5%
Black lutititc shale 9%
Micritic limestone 18%
Calcarous slate (calcschist) 29%
Grey limestone with white veins 1%
Ophite 5%
Rudist limestone 1%
Devonian limestone 15%
Mon4, Gurp 1
Limestone with andalusite 6%
Marble limestone 3%
Black lutititc shale 1%
Calcarous slate (calcschist) 14%
Micritic limestone 45%
Devonian limestone 14%
Ophite 3%
Rudist limestone 4%
Orbitolina limestone 5%
Grey limestone with white veins 5%
Mon6, Base Gurp 3
Black shale with andalusite 6%
Marble 1%
Granite 1%
Black lutititc shale 10%
Micritic limestone 31%
Calcarous slate (calcschist) 29%
Grey limestone with white veins 1%
Ophite 9%
Orbitolina limestone 1%
Devonian limestone 11%
Mon11, Top Gurp 3
Marble limestone 4%
Limestone with andalusite 9%
Black lutititc shale 4%
Micritic limestone 27%
Calcarous slate (calcschist) 20%
Grey limestone with white veins 4%
Bioclastic limestone 1%
Ophite 13%
Devonian limestone 18%
Gurp2, Gurp 2
Black shale with andalusite 3%
Marble limestone 1%
Granite 1%
Black lutititc shale 9%
Micritic limestone 23%
Bioclastic limestone 2%
Orbitolina limestone 3%
Calcarous slate (calcschist) 39%
Ophite 10%
Devonian limestone 9%

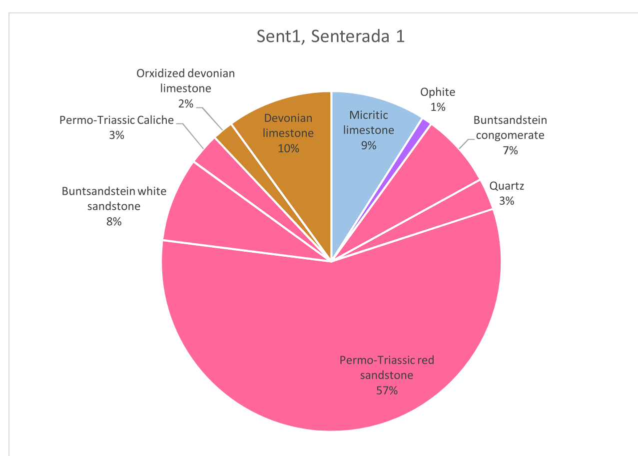

Gurp3, Unitat Gurp 4
Marble limestone 5%
Granite 1%
Limestone with andalusite 2%
Micritic limestone 15%
Bioclastic limestone 5%
Orbitolina limestone 1%
Rudist limestone 1%
Black lutititc shale 20%
Ophite 14%
Calcarous slate (calcschist) 13%
Devonian limestone 25%

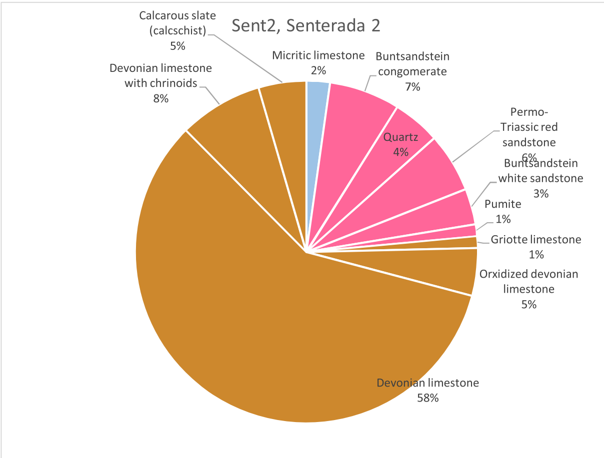

Gurp5, Top Gurp 4
Limestone with andalusite 3%
Marble limestone 4%
Black lutititc shale 2%
Ochre sandstone 8%
Calcarous slate (calcschist) 8%
Devonian limestone 11%
Micritic limestone 29%
Permo-Triassic red sandstone 3%
Ophite 7%
Grey limestone with white veins 12%
Jurassic Breccia 2%
Rudist limestone 5%
Orbitolina limestone 6%

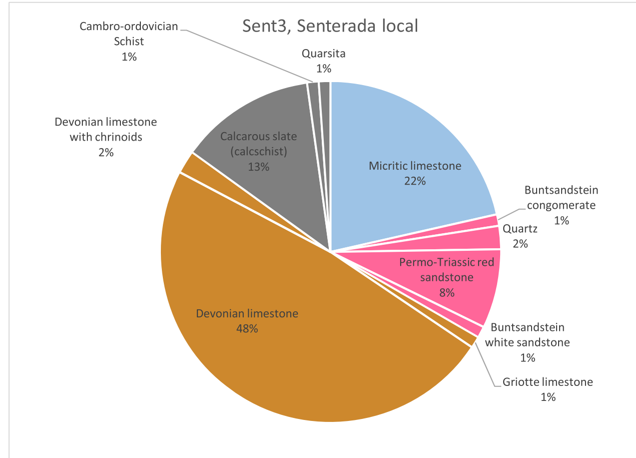

Gurp6, Ermita
Intraformational mudstone 1%
Rudist limestone 1%
Marl 2%
Ophite 1%
Red limestone 2%
Sparitic white limestone 2%
White limestone 5%
Ochre sandstone 16%
Bioclastic limestone 28%
Micritic limestone 33%
Grey limeston e with white veins 9%

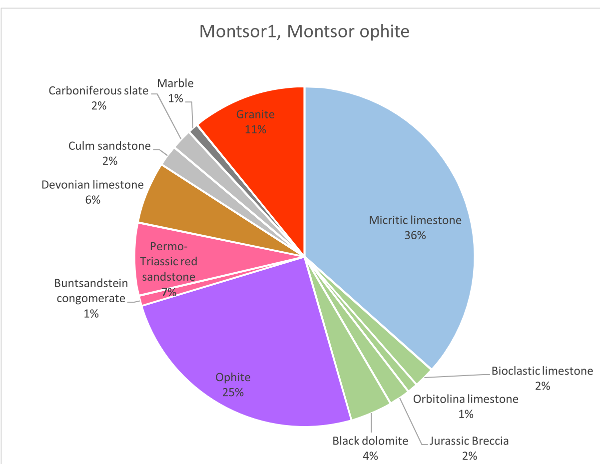

Gurp 8, Camporan
Calcarous slate (calcschist) 4%
Black lutititc shale 1%
Devonian limestone 20%
Micritic limestone 36%
Permo-Triassic breccia 1%
Buntsandstein white sandstone 1%
Permo-Triassic red sandstone 13%
Quartz 1%
Buntsandstein congomerate 2%
Ophite 3%
Rudist limestone 4%
Orbitolina limestone 5%
Bioclastic limestone 2%
Grey limestone with white veins 7%

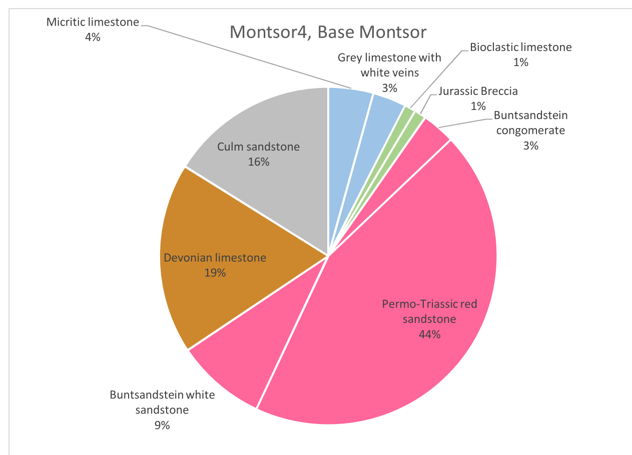

Gurp9, Camporan
Limestone with andalusite 1%
Ochre sandstone 6%
Permo-Triassic breccia 2%
Devonian limestone 12%
Buntsandstein white sandstone 11%
Micritic limestone 39%
Permo-Triassic red sandstone 14%
Buntsandstein congomerate 7%
Orbitolina limestone 2%
Ochre bioclastic limestone 1%
Grey limestone with white veins

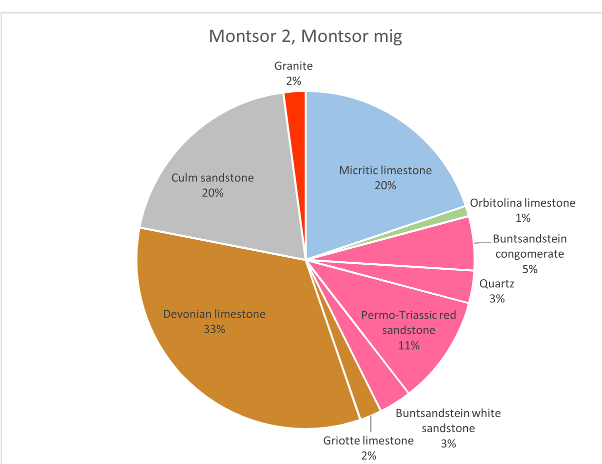

Sent1, Senterada 1
Orxidized devonian limestone 2%
Ophite 1%
Permo-Triassic Caliche 3%
Devonian limestone 10%
Micritic limestone 9%
Buntsandstein congomerate 7%
Buntsandstein white sandstone 8%
Quartz 3%
Permo-Triassic red sandstone 57%

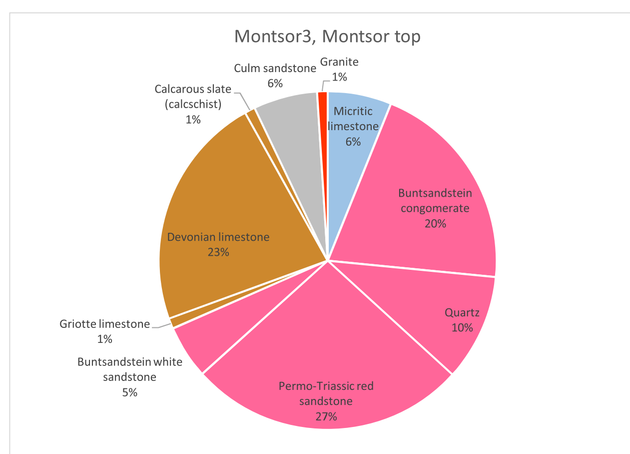












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