Alpine ductile deformation of the upper Iberian collided margin
(Eaux-Chaudes massif, west-central Pyrenean hinterland, France)

Norbert Caldera¹, Antonio Teixell², Albert Griera¹, Pierre Labaume³, and Marc Guardia¹

¹Universitat Autònoma de Barcelona
²Universitat Autònoma de Barcelona
³Géosciences Montpellier, Université de Montpellier

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Abstract

The Eaux-Chaudes massif provides keys to unravel the deep-seated deformation of the Iberian rifted margin during the Alpine orogeny in the Pyrenees. The massif conforms to an inlier of upper Cretaceous carbonate rocks within the Paleozoic basement of the western Axial Zone, originally deposited in the upper margin shelf before the Cenozoic collision. New geological mapping and cross-section construction lead to the description of the lateral structural variation from a km-scale fold nappe in the west to a ductile, imbricate fold-thrust fan in the east. The transition from a Variscan pluton to Devonian metasediments underlying the autochthonous Cretaceous induced this structural change. Recumbent folding, which involved upper Paleozoic rocks, was facilitated by a lower detachment in Silurian slates and an upper detachment in an overlying Keuper shale and evaporite thrust sheet. Remains of this allochthonous sheet form shale and ophite bodies pinched within the upper Cretaceous carbonates, conforming unusual tertiary welds. Ductile shear in the overturned limb of the Eaux-Chaudes fold nappe imparted strong mylonitic foliation in carbonate rocks, often accompanied by N-S stretching lineation and top-to-the-south kinematic indicators. The burial of the massif by basement-involved thrust sheets and the Keuper sheet, along with their Mesozoic-Cenozoic cover, account for ductile deformation conditions and a structural style not reported hitherto for the Alpine Pyrenees. Two hypotheses for the tectonic restoration of this part of the Pyrenean hinterland are proposed in this work.

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Norbert Caldera¹, Antonio Teixell¹, Albert Griera¹, Pierre Labaume² and Marc Guardia¹

¹Departament de Geologia, Universitat Autònoma de Barcelona, 08193 Bellaterra (Barcelona), Spain
²Géosciences Montpellier, Université de Montpellier, CNRS, 34095 Montpellier, France

Corresponding author: Norbert Caldera (email: norbertcg4@gmail.com)

ABSTRACT

The Eaux-Chaudes massif provides keys to unravel the deep-seated deformation of the Iberian rifted margin during the Alpine orogeny in the Pyrenees. The massif conforms to an inlier of upper Cretaceous carbonate rocks within the Paleozoic basement of the western Axial Zone, originally deposited in the upper margin shelf before the Cenozoic collision. New geological mapping and cross-section construction lead to the description of the lateral structural variation from a km-scale fold nappe in the west to a ductile, imbricate fold-thrust fan in the east. The transition from a Variscan pluton to Devonian metasediments underlying the autochthonous Cretaceous induced this structural change. Recumbent folding, which involved upper Paleozoic rocks, was facilitated by a lower detachment in Silurian slates and an upper detachment in an
overlying Keuper shale and evaporite thrust sheet. Remains of this allochthonous sheet form shale and ophite bodies pinched within the upper Cretaceous carbonates, conforming unusual tertiary welds. Ductile shear in the overturned limb of the Eaux-Chaudes fold nappe imparted strong mylonitic foliation in carbonate rocks, often accompanied by N-S stretching lineation and top-to-the-south kinematic indicators. The burial of the massif by basement-involved thrust sheets and the Keuper sheet, along with their Mesozoic-Cenozoic cover, account for ductile deformation conditions and a structural style not reported hitherto for the Alpine Pyrenees. Two hypotheses for the tectonic restoration of this part of the Pyrenean hinterland are proposed in this work.

1. INTRODUCTION

How did inversion tectonics occur along collided continental margins? This is a complex question that depends on the specific geodynamic history within the Wilson Cycle (e.g. Manatschal et al., 2021). During the early stages of orogeny, tectonic inversion is mainly controlled by inherited factors such as the mechanical stratigraphy of the sedimentary cover and the nature of basement structures formed during previous tectonic events (e.g. Butler et al., 2006). At upper crust levels, contractional deformation typically occurs by the reactivation of extensional faults and by the development of detachment levels following weak mechanical horizons as salt and shale units. In foreland fold-and-thrust belts, synorogenic sediments give key information to decipher this early history, but in orogenic hinterlands, where polydeformed basement rocks dominate in outcrop, constraining the inversion tectonics of a particular event is challenged by the absence of unequivocal markers.
The Wilson cycle in the Pyrenees is well-documented and divided into two main stages. It commences with the Mesozoic rifting, which culminates at mid-Cretaceous times (Aptian to early Cenomanian) with hyper-extension of the Iberian and Eurasian rifted margins and mantle exhumation (e.g. Jammes et al., 2009; Lagabrielle et al., 2010). After a period considered as a post-rift stage, the extension cycle is followed from the late Santonian by the late Cretaceous-Cenozoic orogenic stage which can be subdivided into: (1) the initiation of the convergence involving mantle subduction, and (2) the main collision and deformation of the continental margins (Mouthereau et al., 2014; Teixell et al., 2016; Ford et al., 2022). Both compression stages are separated by a period of quiescence during the Paleocene (e.g. Ford et al., 2016, 2022; Ternois et al., 2019). The characteristic non-cylindricity of the Pyrenean orogen has been attributed to the extensional inheritance (e.g. Chevrot et al., 2018; Manatschal et al., 2021), especially accounting for the mechanical weakening of the basement. Sasbriturry et al. (2022) recently postulated crustal-scale transfer zones partitioning the western part of the Pyrenees in an ensemble of narrow segments favouring the lateral structural variation.

The purpose of this paper is to extend the structural study of the km-scale ductile fold nappe documented by Caldera et al. (2021) for a section of the Eaux-Chaudes massif (ECM) of the Pyrenean hinterland (western Axial Zone), which formerly constituted the upper part of the Iberian rifted margin. The ECM preserves an upper Cretaceous inlier between units of Paleozoic metasedimentary and igneous rocks, previously deformed by the Variscan orogeny (Ternet, 1965) (Fig. 1). The Cretaceous platform carbonate rocks of the ECM constituted the shelf of the Iberian margin during
the late Cretaceous post-rift stage (Fig. 1c), later deformed during the Pyrenean collision into a large fold nappe. The occurrence of the upper Cretaceous rocks in this part of the Pyrenean hinterland provides a clue to the Cenozoic deformation, often blurred by the dominant basement exposure of the Axial Zone (Fig. 1b). Ductile basement-involved folding and moderate temperature (around 350°C) reported by Caldera et al. (2021) in the ECM account for deformation conditions never reported hitherto for the Pyrenean orogeny.

Here, we show that the fold nappe reported by Caldera et al. (2021) passes laterally to a ductile fold-thrust imbricate fan in the upper Cretaceous, and we enlarge the study to the upper thrust sheets that buried the ECM, which favoured the observed ductility (Fig. 2). We argue that the lateral structural variation in the ECM is determined by lower (within the Paleozoic basement) and upper (within the Triassic of the upper thrust sheets) detachment levels and by the occurrence of a strong igneous body intruded in the autochthonous Paleozoic metasediments.

2. TECTONIC FRAMEWORK

Two rift stages (Permo-Triassic and late Jurassic-early Cretaceous) and two orogenic episodes (Variscan and Alpine-Pyrenean) have defined the structural architecture of the Pyrenees. The Variscan orogeny configured the Paleozoic basement structure between ca. 380 Ma – 280 Ma (Cochelin et al., 2017, and references therein), and culminated with the intrusion of granitic plutons around 300 Ma. The Permo-Triassic extension is recorded by terrestrial red beds, starting in the study area with siliciclastic sandstones and conglomerates of the Lower Triassic Buntsandstein facies. In the
Pyrenean domain, the Buntsandstein is overlain by red-green claystones and salt of Keuper facies (Biteau et al., 2006; Ortí et al., 2017), containing Muschelkalk marine limestone intercalations (Stevaux & Winnock, 1974). The Keuper facies host abundant subvolcanic bodies of dolerites (“ophites”). The main rifting in the Pyrenees occurred during early and mid-Cretaceous times inducing a strong crustal stretching (Lagabrielle & Bodinier, 2008; Jammes et al., 2009; Lagabrielle et al., 2010; Masini et al. 2014; Mouthereau et al., 2014; Tugend et al., 2014; Teixell et al., 2016; Grool et al., 2018; Espurt et al., 2019; Manatschal et al., 2021). As a result, the mantle was exhumed between the Iberian and Eurasian rifted margins with maximum basin subsidence in the Albian-early Cenomanian, and the pre- and syn-rift sediments where locally affected by HT-LP metamorphism (e.g. Golberg 1987; Golberg & Leyreloup, 1990; Lagabrielle et al., 2010; Clerc & Lagabrielle, 2014; Clerc et al., 2015; Ducoux et al., 2021). Today, the rift axis is represented by the Mesozoic sediments of the North Pyrenean Zone (NPZ) which was tectonically inverted as a large pop-up structure during the Pyrenean orogeny.

Within the Cretaceous rift, a transition from syn- to post-rift sedimentation is ascribed to the mid-Cenomanian, recorded by a regional-scale unconformity (e.g. Debroas, 1987, 1990) on which expansive late Cenomanian deposits overlap the basement and lower Triassic rocks of the rift shoulders. During the Late Cretaceous, shallow platform carbonates (“Calcaires des Cañons”; Fournier, 1905) were widely developed in both the Iberian and the European upper margins, while the former rift axis still accumulated turbidite deposits (e.g. Cuvillier et al., 1964; Puigdefàbregas & Souquet, 1986; Floquet et al., 1988; Razin, 1989). Today these shelf carbonates
constitute the bulk of the Eaux-Chaudes massif, where they overlie Devonian metasediments and the late Carboniferous Eaux-Chaudes pluton (Debon, 1976, 1996; Ternet et al., 2004; Izquierdo-Llavall et al., 2012).

The Pyrenean orogeny took place from the late Santonian (ca. 84 Ma) to the early Miocene (ca. 20 Ma). It caused: 1) the subduction of the exhumed mantle tract and the overlying rift-axis inversion, including the shortening of previous salt diapirs, and the flexure-driven drowning of the post-rift platforms giving rise to flysch deposition, and 2) the collision of the margins, which led to the subduction of the Iberian lower crust and the development of a south-verging, basement-involved thrust stack in the Iberian upper crust. (Teixell et al., 2016, 2018). The ECM and overlying thrust sheets, now in the Pyrenean hinterland of the northern Axial Zone, uniquely record the compressional deformation of the Iberian margin, from the shelf to the hyperextended zones.

3. STRUCTURAL AND STRATIGRAPHIC DOMAINS IN THE STUDY AREA

The stratigraphic record of the ECM is well-constrained (e.g. Ternet et al., 2004) and is clue in the recognition of the structural setting. Below, we first expose the stratigraphy (section 3.1.), and then the tectonic configuration of the study area (section 3.2.), which consists of four main tectono-sedimentary domains (Fig. 3) arranged from bottom to top as: 1) The Gavarnie nappe with upper Cretaceous carbonate rocks unconformable on Paleozoic metasediments and granite, with scarce Buntsandstein remnants in between (Fig. 2), 2) the Eaux-Chaudes nappe (cf. Fig. 3 and text below), with allochthonous upper Cretaceous carbonates and Paleozoic metasediments involved in complex folding. 3) the Paleozoic-bearing thrust sheets overlying the ECM,
comprising metasedimentary basement rocks with local Buntsandstein pods and Keuper, and finally 4) the assemblage of allochthonous Keuper facies of the Bedous unit, overlying all the units described above (Fig. 1c), and the Chaînons Béarnais Belt of the North Pyrenean Zone consisting of a Jurassic and Lower Cretaceous succession detached on the Triassic Keuper. This last succession is affected by low-grade thermal metamorphism inherited from the Cretaceous rifting.

3.1. Stratigraphy of the Eaux-Chaudes massif and surroundings

3.1.1. Paleozoic basement and lower Triassic

The pre-Mesozoic basement around the ECM consists of upper Paleozoic low-grade metasedimentary rocks (Fig. 4). The oldest unit in the area corresponds to Silurian black slates (Miroprse, 1962), with interbedded thin black limestone layers. It is considered as the main regional detachment level for the Paleozoic of the Axial Zone (e.g. García-Sansegundo et al., 2011, and references therein). Above this unit, an approximately 400 to 500 m thick succession of interlayered pelites, limestones, sandstones and quartzites of Devonian age is observed, followed by a few hundred meters thick succession of clastic turbidites and limestones of Carboniferous age (Culm facies; Delvolvé, 1987). These rocks host the Eaux-Chaudes granitic pluton, which is late Carboniferous in age (301 +/- 9, Guerrot, 2001) (Fig. 2). In some thrust sheets overlying the ECM, an azoic succession of limestones and schists, with local sandstone layers, is tentatively attributed to the Carboniferous (Ternet et al., 2004; Labelled hCM in Fig. 4).
Discontinuous lower Triassic conglomeratic and sandy deposits (Buntsandstein facies) rest unconformably over the Paleozoic basement. In the ECM and overlying thrust units, pre-Cretaceous erosion removed a vast volume of Buntsandstein, but some pods have been preserved. They form useful markers to constrain boundaries of stratigraphic nature and polarity relationships between the upper Cretaceous and Devonian limestones of the ECM.

3.1.2. Allochthonous Triassic sheet

The middle-upper Triassic Keuper (Fig. 4) consists of a melange of claystones, cargneules, Muschelkalk limestones, and ophites (Ternet, 1965; Ternet et al., 2004). Salt is not observed at the surface but is well documented nearby in the subsurface in adjacent basins of the northern Pyrenees (e.g. Biteau et al., 2006; Ortí et al., 2017; Soto et al., 2017). The Keuper is not found along the main unconformity between the Paleozoic basement and the upper Cretaceous carbonates of the ECM but forms an allochthonous sheet (the Bedous unit) emplaced over the upper Cretaceous (Caldera et al., 2021; Figs. 2, 3).

3.1.3. Upper Cretaceous

The Cretaceous stratigraphy of the ECM has been thoroughly investigated in prior works (e.g. Casteras, 1956; Casteras & Souquet, 1964; Ternet, 1965; Alhamawi, 1992). It is characterized, from bottom to top by a carbonate platform succession (from Cenomanian to Santonian) followed by shale and flysch deposits (Campanian-Maastrichtian) (Fig. 4).
At the base of the upper Cretaceous stratigraphic succession, the Cenomanian with a maximum thickness of ca. 25 m, unconformably lies on the Paleozoic basement or the Buntsandstein. Occasionally, it begins with a quartz-rich microconglomerate or coarse-grained sandstone, followed by a succession of grainstones to mudstones and wackestones with *Praealveolina* and *Pseudocyclammina*. The transition to the Turonian is highlighted by packstone to mudstone deposits featuring a *Chrysalidina* and *Nezzazata* fossil content. Debris of echinoderms, *Pithonella*, *Halimeda elliotti* and *Globotruncan helvetica bolli* are also characteristic of this unit (Conard & Rioult, 1977). The Turonian limestone shows in general a varying thickness, with a maximum of 80 m (Alhamawi, 1992). This variation hampers the recognition of the transition to the Coniacian which corresponds to partially dolomitized grainstones and packstones with a maximum thickness of ca. 40 m (Ternet et al., 2004), and dominated at the base by debris of *Hippurites* rudists, polypers, gasteropods and foraminifera. To the top of the sequence, there is a succession of packstones to wackestones with benthic foraminifera, rudists, oysters, and polypers. In the southern flank of the Arcizettes Mountains (Fig. 2), a ~40 m thick layer of dark dolomitized limestones is observed constituting a reference horizon recognizable laterally along 2 km.

The Santonian is a massive white limestone unit, with a thickness of ca. 250 m (Ternet, 1965), forming the tallest reliefs of the ECM. It begins with microconglomerate or very coarse sandstone cemented by calcite and containing rounded quartz grains. The white limestone contains decimetric levels of slightly sandy packstones with high content of *Lacazina* and bivalve debris. The end of the Santonian is characterized by a 6 to 30 m layer of limestone with chert nodules, a characteristic key level in the western
Axial Zone (Souquet, 1967; Teixell et al., 2000) (Fig. 2), easy to recognize in the field. Locally, the Santonian limestone is followed by 10 to 15 m of calcareous shales with a wide variety of microfauna and fossils such as echinoids, benthic and pelagic foraminifera. The top of the upper Cretaceous sedimentary record of the ECM is composed of an alternation of pelites and sandstones up to several hundred meters thick referred to as the Campanian flysch. Sandstones show grain-size gradation and cross-stratification with quartz grains and white-mica slats, with mainly benthic microfauna in the sandstones (e.g. *Orbitoides media*, *O. tissoti*, *Nummofallotia cretacea*), and pelagic microfauna in the pelites (e.g. *Globotruncata elevata*, *G. rosetta*) (Ternet et al., 2004).

The upper Cretaceous limestones represent the post-rift shelf in the upper Iberian margin. Relatively stable episodes of regression and transgression determined its facies deposition over time. The transition from the platform limestones to the shales and flysch-type sediments of the uppermost Cretaceous mark an abrupt deepening of the margin attributed to foreland flexure in the early steps of the Pyrenean orogeny (Teixell, 1996; Labaume et al., 2016).

### 3.2. Structural units

#### 3.2.1. The Gavarnie and Eaux-Chaudes nappes

The Eaux-Chaudes nappe (ECN) comprises the Eaux-Chaudes fold nappe (ECFN) and corresponds to the first allochthon unit with respect to the Gavarnie nappe (Fig. 3). The ECFN is observed on both sides of the Ossau Valley (Fig. 5) and described by Caldera et al. (2021). This fold involves the upper Cretaceous carbonates...
and the upper Paleozoic succession that occupies the fold core. The recumbent limb directly rests above the relative autochthonous upper Cretaceous carbonates of the Gavarnie nappe, preserving decametric pinched bodies of Keuper facies in between (Sup. 1). Large-scale recumbent folds have not been previously reported in the context of the Alpine Pyrenees but are documented in the Paleozoic basement where they are attributed to the Variscan orogeny (Aerden & Malavieille, 1999; Matte, 2002, and references therein; Bastida et al., 2014). Carbonates from the overturned limb attest for strong ductile deformation while the normal limb and the autochthon are lowly-deformed, preserving sedimentary textures and fossil content, and featuring a spaced pressure-solution cleavage (Caldera et al., 2021). The autochthonous upper Cretaceous carbonates continue to the west as a simple north-dipping monocline and limit the western termination of the Axial Zone (Fig. 1a, b).

To the east, in the Valentin valley, the upper Cretaceous of the ECN has been eroded and the unit comprises only Devonian sediments in the hanging-wall of the Eaux-Bonnes thrust (Bresson, 1903). In this area, it overrides the upper Cretaceous carbonates of the Gavarnie nappe affected by ductile deformation in the Pic de Ger fold-thrust fan (Figs. 2, 3, 5). The transition between the lowly-deformed autochthon, in the west, to the fold-thrust fan, in the east, occurs through a relatively narrow transfer zone, here named the Gourzy transfer zone, and located between the Pic du Gourzy and Montcouges, and passing by Les Eaux-Bonnes village to the north (Figs. 2, 3, 5). This transfer zone consists of a high-angle west-dipping tear fault system, which causes a recess of the ECN, passing from the far-reaching recumbent fold nappe to the west to the Devonian in the hanging wall of the Eaux-Bonnes thrust to the east. The Pic de Ger
ductile fold-thrust system is interpreted to partly take over the shortening of the ECFN to the east (see below).

3.2.2. The Paleozoic nappes above the Eaux-Chaudes fold nappe

The ECFN is overlain by a stack of basement-involved thrust sheets (Fig. 3), first reported by Majesté-Menjoulas (1968) and later mapped by Ternet et al. (2004). We define three units that are described below from bottom to top in the pile, using a description which partly differs from the previous reports. The first unit overlying the ECFN is the Montagnon d’Iseye fold nappe (MIN), located on the western edge of the massif (Laboume & Teixell, 2020; Caldera et al., 2021). The structure of the MIN corresponds in the southern part to a south-verging recumbent fold with a ~2 km-long overturned limb outlined by the Triassic Buntsandstein and cored by Carboniferous rocks, while in the northern part it comprises Devonian and Carboniferous strata. Late normal faults cut both the MIN and the Cretaceous and Paleozoic core of the underlying ECFN (Fig. 2). The second unit corresponds to the Montagne Verte nappe (MVN) (Fig. 3), formed by upper Devonian to Lower Carboniferous metasediments. From west to east, this unit widens cartographically up to ~3.5 km wide in the eastern limit of the study area (Fig. 3). No overturned limb was identified in this unit. The uppermost basement-involved unit is the Cinq-Monts nappe (5MN) (Fig. 3), which also contains an overturned limb at its front, defined by the Buntsandstein beds. In particular, the 5MN features a thrust fault mapped by Ternet et al. (2004) and sealed by the Buntsandstein which can be thus attributed to the Variscan orogeny (Fig. 2).
3.2.3. The Lakora thrust system and the Chaînons Béarnais Belt

The Eaux-Chaudes massif and the Paleozoic-bearing thrust sheets are overlain by the Lakora thrust system (red and blue lines in Fig. 3). The Lakora thrust system is related to the inversion of the Iberian rifted margin from the latest Cretaceous (Teixell, 1993, Teixell et al., 2016). The main Lakora thrust s.s. (as proposed by Teixell, 1993) in the study area carries the Jurassic-Lower Cretaceous sedimentary rocks of the Chaînons Béarnais Belt (CBB) from the North Pyrenean Zone (NPZ) to the south (red line in Fig. 3). At its base, it is possible to observe a thick Keuper horse (the Bedous Triassic unit of Labaume & Teixell, 2020) (Fig. 3), whose sole thrust is here referred to as the Lower Lakora thrust (LwLT; blue lines in Fig. 3). The CBB is a salt-detached fold-and-thrust system made of middle Triassic to lower Cretaceous rocks from the former rift axis, affected by diapiric structures and containing mantle (lherzolite) lenses (Labaume & Teixell, 2020). Two outliers of the CBB are preserved above the western termination of the Montagnon d’Iseye nappe (MIN): the Tacha and Bergon klippe (Figs. 2, 3a). Scarce remnants of siliciclastic conglomerates attributed to the Albian Mendibelza formation (Ternet, 1965), characteristic of the Lakora thrust sheet to the west of the Axial Zone, have been preserved over the Triassic Keuper or directly on the footwall upper Cretaceous (Figs. 2, 3, 5). In the study area, the characteristic shortcut of the Paleozoic underlying the Mendibelza conglomerate in the Iguntze massif to the west (Teixell, 1993), and shown in Figure 3b, is lacking.

4. STRUCTURAL SECTIONS OF THE EAUX-CHAUSES MASSIF
To describe the structure of the ECM and its lateral variation, we present six new cross-sections (Figs. 6, 8) and several interpreted outcrop images or panoramas (Figs. 7, 9). The sections are oriented approximately N-S, perpendicular to the dominant structural trend, and have been constructed from original field work and complemented by additional data from previous published maps and cross-sections (e.g. Ternet, 1965, Ternet et al., 2004, Labaume & Teixell, 2020, Caldera et al., 2021). The Move software (Petroleum Experts) was used for the managing of map data and to constrain surfaces and geolocation of structural data in 3D.

The description of the sections is divided into two parts to account for the different structural characteristics between the western and eastern sectors (Fig. 2). While in the western sector (Ossau Valley), the structure of the ECM is dominated by a large-scale allochthonous fold nappe, the ECFN involving the upper Cretaceous (Figs. 3, 6), in the eastern sector (Pic de Ger massif) the structure is characterized by an imbricate fold-thrust fan in the upper Cretaceous of the Gavarnie nappe (Fig. 8).

4.1. Western sector (Ossau Valley): the Eaux-Chaudes fold nappe

The general structure of the ECM has been classically interpreted as a duplex with a roof thrust carrying Paleozoic rocks over the upper Cretaceous (Ternet, 1965; Déramond et al., 1985; Dumont et al., 2015; Cochelin et al., 2017). Just a short, overturned fold limb was reported by Ternet (1965) in the front of the structure without continuity to the north. Recently, the structure of this western sector has been reinterpreted as a km-scale, south-vergent recumbent fold nappe with a large, overturned limb (Caldera et al., 2021) (Fig. 6). The Eaux-Chaudes section (S2 in Fig. 6)
has been improved from the one presented in Caldera et al. (2021). In this contribution, we further document the structure by enlarging the analysed area and providing new structural data and field images (Figs. 2, 5, 7, 9). Due to a general westward plunge, constraints for the upper thrust sheets are stronger to the west, while in the eastern sections, the structures projected above topography have larger uncertainties.

The autochthonous upper Cretaceous (i.e. the Mesozoic cover of the Gavarnie nappe, Figs. 2, 5) lies unconformably on the Eaux-Chaudes granite and remains weakly deformed along this sector, preserving sedimentary textures and unstrained large fossils such as rudists or gastropods (Ternet, 1965; Caldera et al., 2021). In the ECFN, the upper Cretaceous succession is not always complete but locally preserved up to the Campanian flysch (i.e. below the Montagnon d’Iseye thrust in S1). The normal limb is weakly deformed while features observed in the upper Cretaceous carbonates of the overturned limb indicate top to the south shearing, developed under ductile conditions and moderate temperatures (315°C to 328°C in the normal limb; 334°C to 355°C in the overturned limb and autochthonous; Caldera et al., 2021). Examples of this ductility at large and small scales are evidenced by bedding-parallel mylonitic foliation, mineral stretching lineation, S-C composite fabrics and other asymmetric kinematic indicators (i.e. calcite crystal-shape fabrics, dolomite porphyroclasts).

The fold nappe plunges to the west following the general trend of the western Axial Zone. Although there exist some small differences in the fold shape across the three sections (Fig. 6), the overall geometry is consistent. The overturned stratigraphy is constrained by the presence of Buntsandstein pods, which show way-up criteria (crossbedding, grain-size grading) indicating a reverse polarity (Caldera et al., 2021),
along the contact between Paleozoic and upper Cretaceous rocks of the fold core. It is worth mentioning the strong thinning of the upper Cretaceous in the overturned limb eastwards from section 1 to section 3 (Fig. 6).

The hinge zone of the recumbent fold is box-shaped featuring ductile deformation in the Cretaceous rocks evidenced by stretched fossils and grain recrystallization observable in thin sections, while these rocks remained weakly deformed in the normal limb. A complex network of calcite veins is also observed along the unconformity between the Paleozoic and upper Cretaceous. The thrusted syncline of the ECFN is linked in depth and eastwards with the Eaux-Bonnes thrust (e.g. Bresson, 1903, Ternet et al., 2004), well-traced in the Valentin valley (“accident du Valentin” in Ternet, 1965) (Fig. 2). Several Keuper facies and ophite bodies remain trapped in between the overturned limb of the ECFN and the autochthon (Figs. 2, 5 and Sup. 1, in supplementary material), which are remains of the allochthonous Keuper sheet (Bedous unit) of the overlying Lakora unit pinched in the synformal zone between both limbs (i.e. a tertiary weld sensu Jackson & Hudec, 2017) (Caldera et al., 2021). In the Paleozoic core of the fold, inherited Variscan folds of the stratigraphy can be recognized (light grey lines in Fig. 7a).

South of the recumbent fold hinge, the autochthonous upper Cretaceous features small steep north-vergent back-thrusts (Caldera et al., 2021) (Figs. 6, 7), associated with the tilting of the northern Axial Zone. These thrusts are visible in the western side of the Ossau Valley, where they offset the Paleozoic basement and the upper Cretaceous alike (section S1 in Fig. 6 and Fig. 7a; Caldera et al., 2021). The number of these north-vergent structures increases from west to east, evolving from a simple back-thrust (S1)
to a small antiformal stack (section S3 in Fig. 6 and Fig. 7b). On the eastern side of the Ossau Valley, on the southern slopes of the Pic du Cézy, they cause repetitions of the upper Cretaceous and Keuper thrust sheet (Sections S2 and S3 in Fig. 6 and Fig. 7b). Ophite bodies are also pinched between the hinge of the ECFN and the imbricate sheets.

The Paleozoic stratigraphy involved in the ECFN follows the large anticlinal geometry, but inherited Variscan folds determine more complex features (Fig. 6). Silurian slates form the fold core but they are locally directly in contact with the overturned upper Cretaceous (see S2 section), and to the north, they are pinched by the Devonian limestones accommodating top-to-the-south shearing.

Over the ECFN in this sector, we have represented the Paleozoic upper thrust sheets reported above (i.e. the Montagnon d'Iseye, Montagne Verte and Cinq Monts nappes). The MIN and 5MN show overturned fold limbs defined by the Buntsandstein. Frequent Keuper pods are pinched between the thrust units, derived from the overlying Lakora thrust sheet. Over the Keuper, the Lakora unit carries the whole stratigraphy of the CBB together with Mendibelza conglomerate inliers (e.g. Figs. 3, 6, 8), which we interpret separated by the Licq fault as is observed more to the west (Labaume & Teixell, 2020). Of the Paleozoic nappes, the first unit over the ECFN (i.e. the MIN) keeps Keuper remains in its footwall, corresponding to the Bedous allochthonous sheet previously emplaced by the Lower Lakora thrust.

4.2. Eastern sector (Pic de Ger massif): The ductile fold-thrust system
The cross-sections and field-interpreted images from the eastern sector are shown in Figs. 8 and 9, respectively. In this area, constraints for the upper thrust sheets are scarce, except for the klippes of Keuper and Mendibelza conglomerates carried by the Lakora thrust system on top of the upper Cretaceous (cropping out south of Plateau d'Anouilhas, Fig. 5 and Sup.2 for location). Although intensely folded, as reported by Ternet (1965), the upper Cretaceous is broadly in a right-way-up attitude, and in contrast with the western sector, a long-overturned panel is not observed.

The structure equivalent to the allochthonous Eaux-Chaudes fold nappe is largely eroded, and the continuation of its basal thrust, the Eaux-Bonnes thrust, brings the Paleozoic on top of the upper Cretaceous in the Valentin valley (Figs. 2, 8). The hanging wall fold structure represented in the sections is speculative and is addressed in the discussion. Paleozoic-bearing thrust sheets (MIN and MVN) are completely eroded above the ECM and are not represented in these sections. The upper Cretaceous of this eastern sector, which is considered as autochthonous to the ECFN, is notwithstanding affected by strong ductile deformation (folding, foliation and stretching lineation), in contrast with the western autochthon. Cross-sections S4 to S6 and field images (Figs. 8, 9) illustrate a strain gradient in the autochthonous rocks that increases from west to east.

In section S4, from south to north, the first main structure recognized is a north-vergent syncline (Fig. 8a) in the Paleozoic basement and the overlying upper Cretaceous rocks of the Petite Arcizette peak (Fig. 9a; peak location labelled “Pte. Acz.” in Fig. 5), with intensely folded Campanian flysch rocks in its core (e.g. Dumont et al., 2015). This structure, trending E-W, is rapidly damped to the east. It follows to the
north a subhorizontal or north-dipping kilometric-scale panel, cut by steeply dipping normal faults and affected by hectometre-scale south-verging folds (Fig., 8a). An asymmetric E-W trending graben in Plateau d'Anouilhas (Fig. 5, 8a and Sup. 2) preserves Keuper rocks of the Bedous unit, which are allochthonous over the upper Cretaceous. A few hundreds of meters to the west of section S4, two larger klippes are observed, one carrying the Keuper rocks and the other the Mendibelza conglomerates (Ternet, 1965) (Figs 2, 5, 8a), also interpreted to have been carried by the Lakora thrust system (Fig. 3).

Further to the east (e.g. S5, Fig. 8), folding of the upper Cretaceous becomes more intense in the Pic de Ger fold-thrust fan. Two large-scale south-verging similar folds (the tight anticline-syncline pair shown in Fig. 9b), are beautifully exposed on the western slopes of Pic de Ger, and separated by a complex north-dipping thrust fault obliterated by a penetrative schistosity. The axial planes are inclined to the north by ~30° degrees (Figs. 8b, 9b). The fold limbs are strongly stretched, the hinges are thickened, and a penetrative axial plane foliation is well-developed. South-verging internal detachments within the upper Cretaceous are locally observed. The most illustrative examples are represented in section S6 in Fig. 8 and in Figs. 9c, d. The detachment is quite evident by the triangular shape of the Cenomanian limestones which have been ductily squeezed in a thrust footwall. Asymmetric, tight disharmonic folds are recognized north of the exposed detachment (Fig. 9d), evidencing a large amount of shortening. Penetrative foliation and stretching lineation are well-developed. Dolostone levels within the dominant limestones appear stretched and boudinaged.
Large-scale, heterogeneous dolostone boudins are folded and imbricated (Fig. 9d) and foliation wraps around these bodies, which occasionally resemble large porphyroclasts.

Several steeply-dipping fault surfaces cutting the upper Cretaceous and Paleozoic rocks contain pinched bodies of Keuper and ophites on top of them, resembling salt welds (e.g. the southern border of Pic de Ger; section S5 in Fig. 8). These unusual structures, which origin is discussed below, were reported by Ternet et al. (2004) and exhibit lateral continuity in W-E direction along the eastern sector of the ECM (Fig. 5). An example of that is the large ophite body located south of Pic de Breque (Fig. 5 for location) and the continuous welded structure passing eastwards through the Montcogues-Pambassibé peaks and Pic de Ger massif (Figs. 2, 5). To the east, these faults rapidly fade and are not observed in S6. On the other hand, the unconformity between Paleozoic and Mesozoic rocks is locally affected by small south-verging imbricate thrusts affecting the upper part of the Devonian and the Cenomanian under the main detachment level (S6 in Fig. 8 and Fig. 9d).

5. DISCUSSION

Field observations and the cross-sections of the ECM indicate a complex ductile deformation of the Iberian margin during the Pyrenean collision. A marked difference in tectonic style is observed between the eastern and western sectors of the massif: from a large-scale recumbent fold nappe, the ECFN, in the west with high strain localized in the overturned limb, the structure changes eastwards to a simple thrust, the Eaux-Bonnes thrust, overlying a fold-thrust fan in the footwall with strong ductile deformation accommodated in the autochthonous Cretaceous succession. Several factors may have
contributed to the complex structure depicted in the cross-sections: 1) the structural inheritance of the Paleozoic basement due to the Variscan orogeny, 2) the geometry and thermal gradient of the Iberian margin due to the mid-Cretaceous hyperextension, 3) the mechanical stratigraphy of both the Mesozoic and Paleozoic rocks, and 4) the tectonic burial by the emplacement of the upper thrust sheets. During the inversion of the rifted margin, the structural configuration of the basement and sedimentary cover induced the reactivation of ancient structures and the activation of several detachment levels (Silurian, Keuper and intra-Cenomanian). We focus the discussion on two major key questions: 1) the factors influencing the lateral variation of the ECM structure and 2) the tectonic evolution of the ECM and overlying thrust units using sequential restoration of two sections (S1 and S4).

5.1. What caused the structural contrast between the fold nappe and the fold-thrust domain? Constraints from the recumbent fold

The structural variation of the fold nappe to the fold-thrust system observed in the eastern sector is quite sudden and occurs through a relatively narrow transfer zone near Gourzy (Figs. 2, 5, 6). The fold nappe domain coincides with the existence of the Eaux-Chaudes granite pluton under the autochthon (Fig. 3). We infer from our observations that the Gourzy transfer zone accommodates a structural variation where the development of the recumbent fold to the west was thus favoured by the nature of the footwall basement, coupled with the existence of mechanically weak layers that induced both a lower and an upper detachment, i.e. the Silurian of the fold core and the allochthonous Keuper emplaced over the Upper Cretaceous.
The Paleozoic basement underlying the ECM is constituted by two clearly differentiated lithological units: the upper Paleozoic metasediments and the Carboniferous granite pluton (Figs. 2, 5, 6). While the recumbent fold largely coincides with the lateral extent of the granite, the eastern fold-and-thrust fan overlies Devonian rocks (interlayered slates and black limestones), which are mechanically weaker (Figs. 2, 5, 8). The deformation in the Eaux-Chaudes granite is of low strain, with occasional minor back-thrusts, whereas the Paleozoic rocks show strong ductile deformation expressed by crenulation and folding superpositions, with a late-phase pervasive folding with southern vergence from minor to large scale. Although the age of the different folding phases (i.e. Variscan vs. Alpine) has not been unequivocally demonstrated, we suggest that the Paleozoic rocks may have experienced superposed shortening from both orogenic cycles (e.g. Sup. 3, showing Alpine foliation crossing the unconformity between the Paleozoic and upper Cretaceous), as also hinted by Ternet (1965).

We postulate that the granite acted as a forestop, producing a strain shadow zone to the autochthon Mesozoic cover directly overlying it and enabling the transport of the fold nappe involving Paleozoic metasediments originally north of the granite. We must point out that Bresson (1906) already invoked the role of the basement granites for the nucleation of thrust nappes in the area and Ternet (1965) suggested the importance of the granite in the overall deformation.

The ECFN is bounded by two mechanically weak units, the Silurian black slates at its bottom, and the allochthonous Keuper sheet on the top of the structure, which both acted as lower and upper detachment, respectively. The Silurian detachment allowed a relatively thin upper Paleozoic section to be entrained in the fold core by top-
to-the-south shearing as proposed in Fig. 6, which in turn enabled the recumbent folding. The Silurian slates, reported as well as the basal detachment of the Gavarnie thrust (Bresson, 1903; Séguret, 1972), have also been proposed to be an effective Alpine detachment eastward of MVN in the Chiroulet and Lesponne domes (Cochelin et al., 2021). Likewise, we interpret that the upper Paleozoic thrust sheets of the study zone (MIN, MVN, 5MN) are also detached in the Silurian slates.

The allochthonous Keuper sheet, which probably contained a large proportion of salt, was also key in causing the decoupling of the upper Cretaceous from the overlying thrust sheets. This unit was attributed to the infill of an early Triassic graben later inverted (Teixell, 1993, Labaume & Teixell, 2020), to an olistostrome (Stevaux & Zolnai, 1975; Lagabrielle et al., 2010), or to an extruded salt sheet (García-Senz et al. 2019). We postulate that it was carried by the Lakora thrust system on top of the upper Cretaceous limestones previous to the activation of the Paleozoic and Eaux-Chaudes nappes. Indeed, the Keuper on the upper Cretaceous limestones was also crucial in enabling recumbent folding of the ECNF and was expelled from the underlying faulted syncline as attested by few pinched remnants (Caldera et al., 2021; Sup. 1). Hence, the combination of two detachments (the Silurian in the upper Paleozoic and the allochthonous Keuper) with the Eaux-Chaudes granite buttress effect accounts for the intense top-to-the-south shear leading to the development of the Eaux-Chaudes recumbent fold that characterizes the western part of the massif, while a deformable Paleozoic basement and a weak horizon in the lower part of the upper Cretaceous carbonates favoured the ductile fold-thrust fan in the eastern part.
5.2. Weld structures within the upper Cretaceous

A singularity of the ECM is the existence of pieces of Triassic ophite, Keuper shale and cargneule pinched within the upper Cretaceous limestones. Two main occurrences are recognised: 1) in the tight syncline between the overturned limb of the ECFN and its relative autochthon (Sup. 1), and 2) in steep fault zones cutting the right-way up succession of the eastern upper Cretaceous limestones of the massif (Figs. 5, 6).

A first-order interpretation for the origin of these features can invoke salt tectonics, assimilating the structures that host the Triassic slivers to salt welds. It could be speculated that pre-existing diapirs sourced in Keuper salt originally located under the upper Cretaceous were squeezed during the convergence producing the salt welds. This scenario could be similar to the interpreted salt structures observed in the Jurassic and lower Cretaceous rocks of the CBB (Labause & Teixell, 2020). However, Keuper rocks are nowhere observed under the upper Cretaceous of the ECM, which is seen always unconformable directly over Paleozoic rocks or small Buntsandstein pods. Hence, we consider that the salt welds do not derive from the squeezing of regular diapirs that originally pierced the Cretaceous succession as previously interpreted by Ternet (1965) or Dumont et al. (2015), but rather must be tertiary welds derived from the squeezing of the allochthonous Keuper sheet of the overlying Lakora unit. Caldera et al. (2021) interpreted in this way the Keuper and ophite slivers in the sheared, isoclinal synform between the fold nappe and its autochthon. During the growth and amplification of synform, there was an extreme expulsion of the Triassic sheet from the fold core, producing the weld between autochthon and overturned fold limb, and favouring the
accumulation of Keuper facies south of the ECFN hinge (Fig. 6). Similarly, in the steep
welds of the eastern part of the ECM, the Keuper and ophite bodies are observed in the
upper part of the upper Cretaceous limestones, associated to high-angle faults (Fig. 10)
and just below to the Lakora detachment. These faults, that currently may show normal
or reverse offsets, are interpreted as former extensional faults synchronous to, or post-
dating, the emplacement of the Lakora thrust sheet, as for example observed in the
Anouilhas graben (Fig. 5 and Sup. 2), that were subsequently shortened during the
deformation of the ECM. The faults often show drag folds on both walls, which can be
described as a-type flanking folds according to the classification by Passchier (2001),
consistent with early extensional slip. The origin of these extensional faults is unclear,
but they may be attributed to flexural load by the overlying thrust sheets to the north
(Lakora system and Paleozoic-bearing thrust sheets). Within this context, the ophites
and Keuper were down-dropped along the flanking folds associated to the normal faults.
Subsequent shortening led to fault steepening and tightening of the flanking folds,
expelling the Keuper and ophites, which were locally pinched forming the observed
weld-like structures (Figs. 8, 11). Again, they represent an unusual kind of tertiary salt
welds, where the remains of an allochthonous sheet are not in the contact between the
subsalt and suprasalt layers, but were entrained between tightly folded subsalt rocks.

5.3. Sequential evolution of the upper Iberian margin: the Eaux-Chaudes fold
nappe and the eastern Eaux-Chaudes fold-thrust system

Restorations of sections S1 and S4 are shown in Fig. 12 and Fig. 13. The
sequential evolution diagrams are started at the immediate pre-orogenic stage (Mid-
Santonian) of the upper Iberian margin. The reconstructions are based on our field observations, structural cross-sections and data compilation from previous works on the west-central Pyrenees, mainly from Teixell et al. (2016) and Labaume & Teixell (2020).

Dashed lines in the sketches indicate the trace of the future faults in the next step. Red arrows on the right border of the pictures illustrate the compressional stage while blue arrows indicate the post-orogenic exhumation.

5.3.1. Sequential evolution of the Eaux-Chaudes fold nappe (Fig. 12)

The evolution is shown in seven steps, spanning from the mid-Santonian to the present-day.

a) During the Mid-Santonian, the Iberian margin is interpreted as a post-rift shallow-water carbonate shelf (i.e. Calcaires des Cañons), directly covering the Paleozoic basement in the future ECM or the Keuper of the Bedous unit in the future Paleozoic nappes MIN, MVN and 5MN. The boundaries between these units are interpreted as inherited late-Variscan or Mesozoic extensional faults dipping to the north.

The Bedous unit was limited to the north by the shelf edge and slope rupture of the Iberian platform. Northwards in the basin, the Mendibelza conglomerates onlap the Paleozoic basement on the necking zone of the continental margin, limited to the north by a diapiric structure which will become the Licq fault. This limit is interpreted to correspond to the southern limit of the CBB, which occupy the former Cretaceous rift axis (Labaume & Teixell, 2020).

b) The early stages of the Pyrenean orogeny were marked by the deepening of the upper Cretaceous shelf and sedimentation of the Campanian-Maastrichtian flysch, the
first syn-orogenic sediments. The inversion of the basin started with the transport to the
south of the salt-detached fold-and-thrust system of CBB by the thin-skinned Lakora
thrust (red line) (Teixell et al., 2016, Labaume & Teixell, 2020).

c) Near synchronous with the Lakora s.s. thrust, there was the activation of the Lower
Lakora thrust (blue line) which emplaced a horse carrying most of the Bedous evaporitic
unit over the future ECM. During or immediately after this stage, the sole detachment on
the Silurian of the 5MN (brown line) was active and started to override the southern
segment of the Bedous basement.

d-e) Progressively, the northern Paleozoic thrust sheets (MIN, MVN and 5MN) were
emplaced by a propagating basement-involved thin-skinned (Pfiffner, 2017) thrust
system, in a piggy-back sequence. The nappe stacking in combination with the Iberian
margin flexure (e.g. Labaume et al., 2016) and the foredeep sedimentation enhanced
the burial, placing the ECM at a depth of ca. 10 km. The deepest nappe in the stack, the
ECFN, was the latter to be activated. While the compression progressed, the Eaux-
Chaudes granite faced opposition to deformation, which was transmitted upwards and
also to the rear. This fact triggered the nucleation of the antiformal fold cored by Silurian
slates and Devonian layered and foliated metasediments. The persistent shortening
kept the progression of the structure to a fold nappe by the hinge migration mechanism
as discussed by Guardia et al. (2020).

The temperatures reached by the burial, and possibly enhanced by an inherited
high geothermal gradient (Bellahsen et al., 2019; Caldera et al., 2021), facilitated the
dominant ductile deformation associated with the ECFN. Meanwhile, the progressive
advance of the upper units (basement units and CBB) created a regional south-directed
shearing favouring the hinge migration of the anticlines which turned into recumbent folds. The overturned limbs of the MIN and the 5MN, formed at relatively lower burial than the ECFN, are defined by siliciclastic rocks of the Buntsandstein and display a short (<1 km in 5MN) to moderate length (>2 km in MIN).

The stacking and folding of the Paleozoic units and the ECFN provoked the folding of the Keuper sheet previously emplaced on their top. The progressive growth of the overturned limbs and tightening of the synclines resulted in the Keuper expulsion and weld between limbs, as proposed by Caldera et al. (2021).

Based on tectonic-sedimentation relationships in the Jaca foreland basin, it has been proposed that the Lakora and the Eaux-Chaudes nappes remained active up to Mid-Eocene times (Labaume et al., 2016), by the system propagating in a broad piggy-back sequence.

f) The southward displacement and development of the ECFN and Paleozoic-bearing units were followed, from the Late Eocene, by the emplacement of the Gavarnie nappe which corresponds to a change in the deformation style by the accretion of a footwall sequence of thick-skinned thrusts favouring the antiformal structure of the Axial Zone (Teixell, 1996; Jolivet et al., 2007; Labaume et al., 2016; Teixell et al., 2016) (Fig. 1b).

This stage is inferred to correspond to the full crustal collision between the Iberian and European plates which developed from the Late Eocene to Early Miocene (Teixell et al., 2016). It induced the uplift and arching of the previous structures, which were tilted to the north in the northern limb of the Axial Zone antiform. We interpret that in the ECM, local structural features such as north-verging back-thrust systems, back-folds, and sub-vertical foliation were related to the Gavarnie nappe emplacement.
Further uplift of the ECM and adjoining areas by the emplacement of the Guarga thrust are constrained by thermochronology during the Late Eocene-Miocene (Bosch et al. 2016). Consequently, a large amount of recycled, earlier syn-orogenic deposits and Axial Zone rocks were shed into both the Jaca (Puigdefàbregas, 1975; Labaume et al., 2016; Roigé et al., 2016) and Aquitaine foreland basins (Biteau et al., 2006) (Fig. 1a).

During the post-orogenic stage in the Axial Zone, there was the development of extensional faults affecting the whole stack, from the ECFN to the CBB. These faults down-dropped the 5MN and MVN to the north to a lower structural elevation than the MIN and were probably formed in the final steps of Gavarnie-related arching (Teixell, 1996) and reactivated in Quaternary times by isostatic readjusting induced by erosion (e.g. Lacan, 2008; Lacan & Ortuño, 2012; Dumont et al., 2015).

5.3.2. Sequential evolution of the eastern Eaux-Chaudes fold-thrust fan (Fig. 13)

We highlight here the most important differences from the western sector (Fig. 12). The eastern sector is characterized by Paleozoic-bearing thrust units above the ECN where the Cretaceous has been eroded. For the purpose of simplification, the post-rift stage shows a shorter basement of the Bedous unit, only represented by the future MVN and 5MN; the Triassic is inferred from the klippe observed in the eastern ECM.

During the orogenic stages, deformation was spread in the autochthonous Mesozoic and Paleozoic rocks of the eastern ECM, due to the weaker basement because of its anisotropic behaviour and the absence of the granitic pluton. In relation to the flexure of the margin by thrust sheet loading, two scenarios could explain the current
structural configuration involving Keuper rocks: 1) pre-alpine inherited extensional structures in the Paleozoic were reactivated or 2) extensional faults were neoformed. We interpret that those extensional structures were activated in the initial stages of the inversion, caused by the emplacement of the northernmost thrust sheets, and previous to the climax of ductile deformation in the ECM, which favoured the development of the Pic de Ger fold-thrust fan and the fault reactivation.

The overturned limb of the ECFN is not preserved and is interpreted as a simple hanging-wall anticline above the Eaux-Bonnes thrust, with a moderately-developed overturned limb in the upper Cretaceous. Indeed, at variance to the western part, the autochthonous upper Cretaceous is strongly ductily deformed, indicating a larger accommodation of the deformation in the footwall of the ECN.

The eastern north-verging syncline of the Petite Arcizette (S4 in Fig. 8) represents a fault-propagation fold from the back-thrust system associated with the Gavarnie thrust. Further east, the steep attitude of the basement-upper Cretaceous unconformity, south of i.e. Pêne Médaa (Figs. 8, 9), corresponds to the continuation of the same back-folding of the Gavarnie nappe.

5.4. Implications on the collision of the Iberian margin during the Pyrenean orogeny

The Alpine Pyrenees are characterized by two main types of tectonic structures: 1) thick-skinned thrusts (e.g. Gavarnie, Guarga, Broto) detached in depth and enhancing the structural relief along the belt, and 2) thin-skinned thrusts (e.g. Lakora, Larra, Monte Perdido, Cotiella) with shallower detachments in the Mesozoic cover or in
the upper Paleozoic (basement short-cuts, e.g. Teixell 1993), sometimes being able to
carry sheets over long distances (e.g. Teixell et al., 2018; Espurt et al., 2019). The Axial
Zone of the Pyrenees is usually assumed as weakly deformed in dominant brittle or
brittle-ductile conditions during the Alpine orogeny. From our study of the ECM
Mesozoic rocks in the Pyrenean hinterland, we conclude that the recumbent fold nappe
resulted from “ductile” thin-skinned basement-involved tectonics (nomenclature by
Pfiffner, 2017), in an intense simple shear deformation regime associated with
detachment in the upper Paleozoic (see Figs. 6, 12). This scenario also prevails for the
basement units MIN, MVN and 5MN which are also detached on the Silurian,
ocasionally featuring recumbent folds on their front. All these structures represent the
transition between dominant thin-skinned tectonics (i.e. Lakora thrust) to thick-skinned
tectonics (i.e. Gavarnie thrust), and were formed in greenschist metamorphic conditions
favoured by considerable burial. The hypothesis of ca. 10 km of burial and the
consequent thermal state are consistent and supported by the (U-Th)/he
thermochronology of the western Axial Zone (including the ECM) which yielded Miocene
cooling ages of reset zircon grains (Bosch et al., 2016). Accounting for that, the thermal
reset of the Paleozoic basement may have been acquired during the Pyrenean orogeny
by a combination of structural stacking and syntectonic sedimentation burial. Indeed,
recently Curry et al. (2021) proposed larger exhumation (17-19 km) for the whole Axial
Zone of the Pyrenees, perhaps unrealistic values with our observations and

The tectonic style at Eaux-Chaudes has not been reported thus-far in the Alpine
Pyrenees, evidencing basement-involved, ductile thin-skinned folding and thrusting.
Similar ductile alpine structures may have been unperceived so-far in other parts of the Paleozoic basement of the Axial Zone. The Eaux-Chaudes deformation structures may be extended ~40 km to the east (cf. Fig. 1) conforming the northern wall of the Néouvielle shear zones dated at the early Eocene (circa 50-48 Ma) by radiochronologic methods (Wayne & McCaig, 1998; Jolivet et al. 2007). In the Néouvielle granite, Jolivet et al. (2007) obtained Oligocene to Miocene fission-track cooling ages, similar to the results of Bosch et al. (2016), supporting a deep regional burial, resetting of thermochronometers, followed by a rapid Alpine exhumation. The tilting of the Axial Zone to the west also affects the ECM, covered by the Bedous Triassic sheet and the Igountze and Mendibelza massifs westwards (cf. Fig. 1a). From a regional point of view, the reconciliation with the structure of the Basque massifs is not straightforward due to the tilting and the rapid structural variation related to the influence of transverse structures such as N-S transfer zones (e.g. Saspiturry et al., 2022), similar to what occurs at a smaller scale in the ECM with the Gourzy transfer zone.

6. CONCLUSIONS

Six new cross-sections pose the scope of the remarkable structural variability within the upper Cretaceous of the Eaux-Chaudes massif along strike. The structure passes from an allochthonous, large-scale recumbent fold core by Paleozoic sediments to the west, into a detached ductile fold-and-thrust fan in the eastern autochthon, separated by the high-angle Gourzy transfer fault. The rheology of the Paleozoic basement underlying the upper Cretaceous is key to this abrupt change in the deformation style. While the Eaux-Chaudes granite leads the localization of deformation
on top of it, placing the recumbent fold nappe, the eastern upper Paleozoic
metasediments (Devonian limestones and schists) spread the deformation all over the
stratigraphic pile including the upper Cretaceous.

There is no evidence of autochthonous Keuper remnants in between the
Paleozoic basement and the Cretaceous rocks of the Eaux-Chaudes massif, but an
allochthonous Keuper sheet emplaced on the upper Cretaceous by the Lower Lakora
thrust in the beginning of the Pyrenean tectonic inversion, facilitated an upper
detachment of the structure and the tightening of the recumbent fold. Detachment in
Silurian slates was also instrumental in the development of the Eaux-Chaudes tight fold
structure, allowing the upper Paleozoic to be entrained in the fold nappe core.

Detachment in the Silurian is also inferred for the basement-involved thrust sheets that
overlie the Eaux-Chaudes structure (Montagnon d’Iseye, Montagne Verte, Cinq Monts).
Small intra-Cretaceous detachments and along the unconformity with the Paleozoic
metasediments enhanced the shearing within the large-scale.

Unusual tertiary weld-like structures, marked by ophite and claystone/cargneule
pinched slivers, attest for the allochthonous Keuper sheet. Unlike common tertiary
welds, these are not localized between the subsalt and suprasalt rocks, but within tight
synforms of the upper Cretaceous subsalt rocks, from which the bulk of the salt sheet
was expelled. Weld-like structures also formed where slivers of the allochthonous
Keuper sheet were pinched along former normal faults during their inversion.

Not only the western Eaux-Chaudes nappe conforms to a large recumbent fold
evidencing Alpine ductile deformation in this segment of the Pyrenean hinterland, but
also the Paleozoic basement units of Cinq Monts and Montagnon d’Iseye show
moderately large, overturned limbs delineated by post-Variscan, lower Triassic rocks. The deformation observed is consistent with the moderate paleotemperatures recorded in the post-Paleozoic rocks (300-360°C) (Caldera et al., 2021). The nappe stacking at Eaux-Chaudes and surroundings represents a tectonic style not reported hitherto in the Alpine Pyrenees, evidencing relatively deep burial and/or high inherited thermal gradients during deformation, and basement-involved thin-skinned thrusting. This tectonic style characterizes the inversion of the previous Cretaceous rift during the early stages of the Pyrenean orogeny, at variance to the thick-skinned fan which structured the Axial Zone of the central Pyrenees during the subsequent fully-developed continental collision. It also warns on so-far unperceived Alpine ductile deformation in the basement of the Pyrenean hinterland.

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DATA AVAILABILITY STATEMENT
Further data that support the conclusions of this study are available from the corresponding author upon request.

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**Figure captions**
1. (a) Geologic sketch map of the Pyrenees showing the location of the Eaux-Chaudes massif. Red frame indicates the mapped area (Figs. 2, 3) and red line indicates cross-section in Fig. 1b.

(b) Crustal cross-section of the Pyrenees west of the study area (simplified from Teixell et al., 2016) showing the tectonic setting of the Eaux-Chaudes structures (red frame). Black frame indicates the part of the section used to show the Lakora thrust system trace in Fig. 3b. (c) Restored crustal cross-section of the Iberian margin and rift axis to the Late Cretaceous (Santonian) from Fig. 1b (modified from Teixell et al., 2016). CBB: Chaînons Béarnais Belt; IM: Igoutze and Mendibelza massifs; GT: Gavarnie thrust; LT: Lakora thrust; NPZ: North Pyrenean Zone; NPF: North Pyrenean Fault; NPFT: North Pyrenean Frontal thrust; SPFT: South Pyrenean Frontal thrust.
Fig. 2. Geological map of the Eaux-Chaudes massif and surrounding areas (location in Fig. 1a).

Data compiled from published maps (Ternet, 1965; Ternet et al., 2004; Labaume & Teixell, 2020; Caldera et al., 2021), and own field observations. White frame indicates the mapped area amplified in Fig. 5. S1 to S3: cross-sections in Fig. 6. S4 to S6: cross-sections in Fig. 8.

Indicated in the legend with a question mark is an azoic succession of limestones and slates attributed tentatively to the Carboniferous by Ternet et al. (2004) and labelled hCM in Fig. 4.
Fig. 3. (a) Simplified tectonic map of the Eaux-Chaudes massif and southern edge of the Chaînons Béarnais Belt showing the structural units referred to in the text. Bedous unit corresponds to the upper Triassic carried by the Lower Lakora thrust. MIN: Montagnon d’Iseye nappe; GTZ: Gourzy Transfer Zone. (b) Detail of the cross-section in Fig. 1b from the Gavarnie nappe and its overlying tectonic units indicating the structural position of the Lower Lakora thrust and Lakora thrust s.s.
**Fig. 4.** Simplified stratigraphic logs of the Paleozoic and Mesozoic of the Eaux-Chaudes massif (based on Ternet, 1965, and own data).

**Fig. 5.** Detailed geological map of the Eaux-Chaudes massif (from Fig. 2) showing structural data and the situation of the main localities referred to in the text. PCy: Pic de Cézy; PGz: Pic du Gourzy; PB: Pic de Brèque; Pl An: Plateau d’Anouilhas; Pte Acz: Petite Arcizette; Mtcg: Montcogues; Pss: Pambassibé; PG: Pic de Ger; Pn M: Pêne Médaa.
**Fig. 6.** Geological cross-sections of the western sector of the Eaux-Chaudes massif presenting the lateral variation of the Eaux-Chaudes unit from west to east (S1 – S3). See location in Fig. 2. Red asterisk in S2 shows the location of the allochthon Keuper pinched in the welded syncline of the recumbent fold, shown in Sup. 1. Mblz Cngl: Mendibelza Conglomerates; LqF: Licq Fault; MIN: Montagnon d’Iseye nappe; 5MN: Cinq Monts nappe; MVN: Montagne Verte nappe; CBB: Chaînons Béarnais Belt; BU: Bedous Unit (carried by the Lower Lakora thrust). Jurassic and Lower Cretaceous rocks of the CBB in section 1 are based on Labaume & Teixell, 2020.

**Fig. 7.** Interpreted panoramas showing different examples of deformation in the upper Cretaceous of the western part of the Eaux-Chaudes massif (location of views in Fig. 2). (a) Interpreted panorama of the Eaux-Chaudes recumbent fold and overlying tectonic units (MIN, Lower Lakora and Lakora thrusts, 5MN, CBB, MVN; for explanation of acronyms, refer to the legend of the previous figure) in the Ossau Valley from an eastern viewpoint. It corresponds to the southern part of sections 1 and 2 (Fig. 6). (b) Interpreted panorama of the Pic de Cézy from an eastern viewpoint. It corresponds to the southern termination of the recumbent fold in section 3 (Fig. 6). The system of late backthrusts (black) overprints the Lower Lakora thrust (blue), which is marked by Keuper and ophite bodies.
Fig. 8. Geological cross-sections of the eastern sector of the Eaux-Chaudes massif featuring the strong ductile deformation in the autochthonous upper Cretaceous. See location in Fig. 2.

Mblz Cngl: Mendibelza Conglomerates; LqF: Licq Fault; CBB: Chaî nons Béarnais Belt; LwLt: Lower Lakora thrust; BU: Bedous Unit (carried by the Lower Lakora thrust); EBT: Eaux-Bonnes Thrust; PG: Pic de Ger in S5. The Eaux-Chaudes fold nappe illustrated in sections in Fig. 6 is tentatively interpreted to be replaced in these transects by a simple thrust-related ramp anticline, whereas much of the deformation is transferred to its footwall.
Fig. 9. Interpreted panoramas showing different examples of deformation in the upper Cretaceous of the eastern part of the Eaux-Chaudes massif (location of views in Fig. 2). (a) View from the west of the Petite Arcizette north-verging syncline. (b) View from the west of the Pic de Ger. A large-scale isoclinal anticline-syncline pair with an intervening thrust attests for a strong component of ductile deformation in the upper Cretaceous. A view of the syncline on the eastern slope of the Pic de Ger is in Fig. 10c. (c) View from the east of the Pène Médaa showing an intra-Cretaceous detachment at the level of the Cenomanian. Ductile deformation
led to folding and squeezing of the lower limestone units. (d) View from the east of the northern slope of Pêne Médâa showing large-scale dolomitic bodies affected by boudinage, folds and thrusts evidencing intense deformation in this area. Widespread mylonitic foliation in the host limestones is indicated by black lines. Small thrusts affect the basal unconformity.

Fig. 10. Interpreted panoramas of salt weld-like structures in the eastern Eaux-Chaudes massif (see location of pictures in Fig. 2). Weld structures are marked by ophite or Keuper shale slivers enclosed in the upper Cretaceous limestone and were mapped originally by Ternet (1965), who interpreted them as squeezed diapiric structures coming from below. Here we interpret them as tertiary welds coming from the overlying, allochthonous Keuper sheet (Bedous unit, see text for explanation). (a) View from the west of the Pic de Brèque with the large ophite body in the autochthon of the Eaux-Chaudes fold nappe. The autochthon is deformed by the inversion of an extensional small graben which originally cut the Lower Lakora thrust (see text for explanation).
(b) View from the west of the Montcouges and Pambassibé mountains, showing a large, detached anticline limited to the north and south by former extensional faults tectonically inverted. Ophite rocks are pinched in faults, witnessing their compressional tightening. The tightening of the fold is accompanied by foliation in the carbonates. (c) View from the east of the Pic de Ger ridge showing the prominent syncline imaged in Fig. 9b and faulted contacts to the south that are marked by Triassic slivers. Strong ductility is evidenced by the penetrative mylonitic foliation which is folded by the syncline. A vertical foliation (blue dashed lines), which is oblique to the axial plane of the fold developed during a later deformation episode.
**Fig. 11.** Cartoons explaining the occurrence of pinched Keuper and ophite bodies in the upper Cretaceous carbonates in two sections of the Eaux-Chaudes massif (cf. Fig. 5 for location and 10 for illustration). In the first step the Lower Lakora thrust emplaced the allochthon Keuper sheet (Bedous unit) over the upper Cretaceous. In a second step, extensional structures were formed and/or enhanced inheritance reactivation by the flexure associated to the thrust load, resulting in the mobilisation of the Keuper rocks into depressed areas. Finally, in the shortening step, structures related with salt were welded when small bodies of upper Triassic got trapped in the core of the previous extensional structures and deformed by flattening and inversion. The overlying Eaux-Chaudes nappe and subsequent upper nappes are not represented to simplify the illustration. In a) orange line correspond to the Gourzy Transfer Zone.
Fig. 12. Sketch illustrating the proposed sequence for the compressional inversion of the uppermost Iberian margin in the western Eaux-Chaudes massif, including the structural stacking of the upper thrust units. Red line corresponds to the Lakora thrust carrying the detached CBB
and Mendibelza conglomerates. Blue line corresponds to the lower branch of the Lakora thrust carrying the allochthonous Keuper sheet (horse) of the Bedous unit on the ECFN. Dashed lines show the location of future faults in the following steps. The structure of the pre-inversion stage (a) is modified from the model of hyper-extension of Teixell et al. (2016). The last stage (f) is based on the cross-sections S1 and S2 from Fig. 6 for the ECFN, MIN, 5MN and MVN. The kinematic evolution of the CBB is taken from Labaume & Teixell (2020). ECFN: Eaux-Chaudes fold nappe; MIN: Montagnon d’Iseye nappe; 5MN: 5 Monts nappe; MVN: Montagne Verte nappe; CBB: Chaînons Béarnais Belt; Mblz. Cngl: Mendibelza Conglomerates.

Fig. 13. Sketch illustrating the proposed sequence for the inversion of the uppermost Iberian margin in the eastern Eaux-Chaudes massif. It features the deformation of the footwall upper Cretaceous rocks in conjunction with the underlying Paleozoic metasediments and the overlying allochthonous Keuper sheet of the Bedous unit. Red line corresponds to the Lakora thrust
carrying the detached CBB and Mendibelza conglomerates. Blue line corresponds to the lower branch of the Lakora thrust carrying the allochthonous Keuper sheet on the ECU. Dashed lines show the location of future faults in the following steps. The structure of the pre-inversion stage (a) is modified from the model of hyper-extension of Teixell et al. (2016). The last stage (d-e-f) is based on the cross-section S4 from Fig. 8 for the ECN, MVN and 5MN. The kinematic evolution of the CBB is taken from Labaume & Teixell (2020). For explanation of acronyms, refer to the legend of the previous figure.
Sup. 1. Interpreted panorama of a pinched slice of hectometre-scale allochthon Keuper in the welded syncline conformed by the upper Cretaceous from the overturned limb and from the autochthon of the ECFN. The contact between the Keuper and autochthon upper Cretaceous is interpreted. The emplacement of the Keuper is performed by the Lower Lakora thrust at early stages of the Alpine compression.
Sup. 2. Interpreted panorama of the transition from the western to the eastern sector of the ECM. At the bottom of the image the Eaux-Chaudes fold nappe is represented by the overturned polarity of the upper Cretaceous and the Paleozoic rocks. The transition to the east is defined by the orange line which conforms the Gourzy Transfer Zone. The eastern sector is characterized by fold structures with E-W-trend fold axis identified by yellow dashed lines. The
presence of the allochthon upper Triassic (Keuper facies) is substantially more representative and emplaced by the Lower Lakora thrust. A small outcrop of Mendibelza conglomerates, Albian in age, remain partially on the Keuper and on the Campanian flysch, carried by the Lakora thrust s.l. The Eaux-Bonnes thrust outcrops at the upper left edge of the image carrying the Paleozoic basement on top of the deformed autochthon upper Cretaceous. At the right border of the image the back thrust structure coetaneous to the emplacement of the Gavarnie nappe at the full-compression stage is interpreted. EBT: Eaux-Bonnes thrust; LT: Lakora thrust; LwLT: Lower Lakora thrust; GTZ: Gourzy Transfer Zone.

Sup. 3. Interpreted outcrops of the main unconformity between the Paleozoic basement and the upper Cretaceous where it is possible to recognize the refraction of the Alpine foliation along the
transition. This effect is enhanced in the areas where the unconformity is defined by a quartz vein.