

1 **Tidal influence in rebeds: a palaeoenvironmental and**  
2 **biochronostratigraphic reconstruction of the Lower Tresp Fm (South-**  
3 **Central Pyrenees, Spain) around the Cretaceous/Paleogene boundary**

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15  
16 **ABSTRACT**

17  
18 The Upper Cretaceous-Paleogene deposits of the lower Tresp Fm (South-Central Pyrenees)  
19 preserve an excellent record of sedimentological and palaeontological features that suggest a  
20 connection with marine settings and which allow the age of these deposits to be reviewed.

21 The deposits of three units of the Tresp Fm were studied: the Grey Unit, the Lower Red Unit  
22 and the Suterranya Limestone. The deduced sedimentary environments for the Grey Unit and  
23 the Suterranya Limestone - lagoonal and coastal lake environments respectively - agree with  
24 those proposed by previous authors. However, a new depositional setting is proposed for the  
25 Lower Red Unit, that of a mixed-energy zone in a tide-dominated delta. Earlier authors have  
26 interpreted this as a fluvial sedimentary environment. This new interpretation is based on the  
27 presence of inclined heterolithic stratification in point bar deposits, along with flaser and  
28 lenticular bedding, the nature of the interchannel deposits (which consist of intensely burrowed  
29 mudflat deposits), and the presence of *in situ* marine fossils - including those of planktonic

30 foraminifera - and glauconite grains. These foraminifera were almost certainly transported, as a  
31 suspended load, from the open sea into meandering channels on flood tides. It cannot be ruled  
32 out, however, that they were blown in on the wind or arrived with storm currents. Their  
33 associated biostratigraphy suggests a Maastrichtian age for the Grey Unit and Lower Red Unit,  
34 and a late Danian age for the Suterranya Limestone. There is a significant hiatus between the  
35 latter and former units that covers most of the Danian, and presumably includes the  
36 Cretaceous/Paleogene boundary. These new palaeoenvironmental and biostratigraphic data  
37 correlate the lower Tresp Fm with the Upper Cretaceous-Lower Paleogene marine deposits  
38 outcropping to the east in the South-Central Pyrenees.

39

40 **Key words:** Palaeoenvironment reconstruction, tidal influence, IHS, redbeds, planktonic  
41 foraminifera, K/Pg boundary

42

### 43 **HIGHLIGHTS**

44

45 A multidisciplinary approach was key in detecting marine influence in the Tresp Fm.

46 IHS, glauconite and *in situ* marine microfossils in redbeds suggest a tidal influence.

47 Planktonic foraminifera were transported as a suspension load in meandering channels.

48 The evidence suggests the presence of *in* and *ex situ* microfossils.

49 The ages for the lower Tresp Fm and K/Pg boundary location are established.

50

### 51 **1. INTRODUCTION**

52

53 Interpreting transitional depositional environments is difficult when sedimentary features  
54 associated with continental environments, such as reddish-coloured mudstone with abundant  
55 palaeosols or palaeochannel deposits, are profuse, and when sedimentary features and/or  
56 fossil evidence indicative of a marine influence is scant or absent. Under such conditions only a  
57 detailed, multidisciplinary study may allow accurate interpretations to be made. Such a study  
58 could provide better evidence of any marine influence masked by continental features.

59 Ancient transitional environments can be reconstructed via facies analysis and by taking note of  
60 the presence of marine fossils. When marine-continental fossils occur in settings that include  
61 eroded components, they can be misinterpreted as reworked grains from older rocks. A  
62 detailed petrographic and biostratigraphic study, however, helps avoid such mistakes. The late  
63 Cretaceous-early Paleogene Tremp Formation (Fm) (also known as the “Garumnian facies” and  
64 the Tremp Group [Cuevas, 1992]) in the South-Central Pyrenees (Spain), provides an example  
65 of such a setting. The Formation outcrops over some 1000 km<sup>2</sup> in a number of small basins  
66 produced by the uplifting of the Pyrenees (López-Martínez et al., 2006). It consists of greyish  
67 marl deposited in a transitional environment, followed by multicoloured marly-sandy deposits  
68 and subordinate conglomerates and limestone, all of which are given the name of ‘redbeds’.  
69 These deposits contain a remarkable record of dinosaur fossils, and are home to some of the  
70 youngest dinosaur-rich sites in the world (López-Martínez et al., 2001; Riera et al., 2009; Vila et  
71 al., 2012) as well as the youngest dinosaur tracksites in Europe (Vila et al., 2013). The  
72 redbeds’ abundant vertebrate remains have traditionally been regarded as having been  
73 deposited in alluvial, fluvial and lacustrine settings (Rosell, 1965; Nagtegaal et al., 1983;  
74 Cuevas, 1992; Rosell et al., 2001; Riera et al., 2009). Numerous sedimentological and  
75 palaeontological investigations have been performed in this area (see “Geological Setting” for  
76 references) where, in addition, the type-section of the Tremp Fm was defined (Rosell and  
77 Llompart, 1982).

78 The Tremp Fm has been assigned to the Late Cretaceous-Paleogene based on stratigraphic  
79 correlations, magnetostratigraphic data and the biostratigraphy suggested by rudists,  
80 charophytes and palynomorphs (Feist and Colombo, 1983; Porta et al., 1985; Médus et al.,  
81 1988; Ardèvol et al., 2000; López-Martínez et al., 2001; Vicens et al., 2004; Oms et al., 2009;  
82 Riera, 2010; Vila et al., 2012; Villalva-Breva and Martín-Closas, 2013). However agreement is  
83 not complete regarding the age of these deposits, in part because of a lack of precise  
84 biostratigraphic data. Thus, despite the importance of the Tremp Fm in understanding the  
85 extinction of the last European dinosaurs, there is no agreement on the exact position of the  
86 Cretaceous/Paleogene (K/Pg) boundary, nor on the age of the Tremp Fm (Riera et al., 2009).

87 This paper reports a sedimentological, micropalaeontological and petrographic study of the  
88 Upper Cretaceous-Lower Paleogene transitional-to-continental deposits of the Tremp Fm. The

89 data collected, including the discovery of non-reworked planktonic foraminifera, help refine our  
90 understanding of the Formation's depositional environments, provide new evidence regarding  
91 the age of the deposits of the lower Tremp Fm, and help identify the position of the K/Pg  
92 boundary.

93

## 94 **2. GEOLOGICAL SETTING**

95

96 The study area is located in the South-Central Pyrenees (Fig. 1), a region that corresponds to  
97 an alpine fold-thrust belt that formed during the Late Cretaceous to Early Miocene, which is  
98 classically, divided into three thrust sheets referred to as the Boixols, Montsec and Sierras  
99 Marginales. These thrust sheets controlled the sedimentation of an E-W orientated foreland  
100 basin (Teixell and Muñoz, 2000). The investigated area belongs to the Tremp-Graus Basin  
101 which is located to the east of this foreland basin, and is related to the evolution of the Boixols  
102 thrust sheet (Puigdefàbregas et al., 1992) (Fig. 1a). The Tremp-Graus Basin exposes Upper  
103 Cretaceous to Cenozoic deposits showing westward deepening and a transition from  
104 continental to marine facies. Eastwards, the Basin is structured as an E-W trending syncline -  
105 the Tremp syncline - which is limited northwards by the Sant Cornelli fault propagation anticline  
106 (the eastern termination of the Boixols thrust sheet). To the south it is limited by the Montsec  
107 thrust sheet (Fig. 1a).

108 The present study focuses on the northern flank of the Tremp syncline, near the town of Tremp  
109 (Fig. 1a). The studied outcrops (Fig. 1b) correspond to the lower part of the Tremp Fm (Mey et  
110 al., 1968) which overlies the Arén Fm (Mey et al., 1968). The Arén Fm consists of shallow,  
111 marine clastic deposits and shows progressive unconformities and facies variations related to  
112 the contemporaneous growth of the Sant Cornelli anticline (Garrido-Megias, 1973;  
113 Puigdefàbregas and Souquet, 1986; Simó, 1986; Deramond et al., 1993; Bond and McClay,  
114 1995; Arbués et al., 1996; Guillaume et al., 2008; Shackleton et al., 2011). The latter may have  
115 emerged as an island/peninsula during the Late Cretaceous (Nagtegaal et al., 1983). Díaz-  
116 Molina et al. (2007) interpreted the upper part of the Arén Fm as having been deposited in a  
117 marine littoral setting after distinguishing four major facies assemblages corresponding to  
118 shoreface, beachface, beach ridge plain and backbarrier-lagoon environments. The Arén Fm

119 shows a general northwestward prograding trend. It is gradually replaced landwards (towards  
120 the E and S) by lagoonal or estuarine and continental deposits of the lower Tremp Fm  
121 (Nagtegaal et al., 1983; Eichenseer and Krauss, 1985; Willems, 1985; Díaz-Molina, 1987;  
122 Eichenseer, 1987; Krauss, 1991; Ardèvol et al., 2000; Díaz-Molina et al., 2007; Riera et al.,  
123 2009; Vila et al., 2012).

124 The Tremp Fm is found throughout the entire Tremp-Graus Basin. It is predominantly  
125 composed of multicoloured mudstone deposits and subordinate sandstone, conglomerates and  
126 limestone (Fig. 1b). The Formation is divided into four informal lithological units known as the  
127 “Grey Unit”, “Lower Red Unit”, “Suterranya Limestone” and “Upper Red Unit (Rosell et al., 2001;  
128 Riera et al., 2009). The studied area includes the lower Tremp Fm, which is formed, from the  
129 base to the top, by the Grey Unit, the Lower Red Unit and the Suterranya Limestone (Fig. 2).

130 These units are also known in this area as the Posa Fm or Unit 1 (Grey Unit), the Conques and  
131 Talam Fms or Unit 2 (Lower Red Unit), and the Suterranya Fm or Unit 3 (Cuevas, 1992; Pujalte-  
132 Navarro and Schmitz, 2005; López-Martínez et al., 2006).

133 The Grey Unit consists of greyish marl with abundant carbonate pedogenic features and  
134 intercalations of coal, limestone and sandstone, all of which are interpreted as lagoonal or  
135 estuarine facies (Rosell, 1965; Nagtegaal et al., 1983; Cuevas 1992; Rosell et al., 2001; Riera  
136 et al., 2009). Liebau (1973) described it to contain the remains of many marine to freshwater  
137 taxonomic groups, such as charophytes, foraminifera, molluscs, ostracods, rudists, corals and  
138 vertebrates.

139 The Lower Red Unit is made of multicoloured (frequently mottled) and bioturbated mudstone  
140 interbedded with sandstone and conglomerates, all interpreted as floodplain and fluvial deposits  
141 (Cuevas, 1992; Rosell et al., 2001; Riera et al., 2009). The deposits of the Grey Unit and the  
142 Lower Red Unit contain fossilised dinosaur bones and tracks, and are home to world-renowned  
143 dinosaur fossil sites (for the locations of these sites see López-Martínez et al. [2001] and Riera  
144 et al. [2009]). The most modern sauropod record has recently been located in the Tremp  
145 section (Vila et al., 2012).

146 The top of the studied section is represented by the Suterranya Limestone (Figs. 1b and 2).  
147 This unit is formed by limestone and marl, contains charophytes, molluscs, ostracods and  
148 foraminifera, and shows abundant pedogenic features. The section top has been interpreted as

149 having been deposited in brackish-freshwater coastal lakes or ponds (López-Martínez et al.,  
150 2006).

151 The age of the Tremp Fm, and of the interfingering Arén Fm in the Tremp area, is not  
152 completely established because of the scarcity of guide fossils. According to the available  
153 palaeontological data, the depositional architecture of the Upper Cretaceous-Lower Paleogene  
154 strata of the Arén Fm, and the correlated continental deposits of the Tremp Fm, the studied  
155 section would have been deposited during the very late Campanian through to Danian times  
156 (Ardèvol et al., 2000; López-Martínez et al., 2001). This agrees with the biostratigraphic  
157 evidence, at least with respect to rudists as reported by Vicens et al. (2004). However, some  
158 authors have attributed a Maastrichtian age to the Grey Unit based on the study of charophytes  
159 (Feist and Colombo, 1983; Villalva-Breva and Martín-Closas, 2013) and palynomorphs (Porta et  
160 al., 1985; Médus et al., 1988). In addition, the dinosaur-rich Arén Fm sites located west of the  
161 Tremp syncline have been correlated - based on their planktonic foraminifera contents - with the  
162 upper Maastrichtian *Abathomphalus mayaroensis* Biozone (detected in deep marine sediments  
163 that outcrop westward near the town of Campo; see location in Fig. 1a). Other stratigraphic  
164 correlations, based on palaeomagnetostratigraphic studies of the lower part of the Tremp Fm,  
165 assign a Maastrichtian age to the Grey Unit deposits (Oms et al., 2009; Riera, 2010; Vila et al.,  
166 2012). The latter authors, however, all stress the difficulty in understanding the  
167 magnetostratigraphic evidence of the Tremp area.

168 The Suterranya Limestone and its equivalent stratigraphic units have been assigned to the  
169 Danian via their stratigraphic correlation with dated marine platform deposits in the Campo  
170 stratigraphic section (Fig. 1a) (López-Martínez et al., 2006). On the southern flank of the Tremp  
171 syncline, the limestone layers have also been dated as Danian, as suggested by their  
172 charophyte-containing biostratigraphy (Masriera and Ullastre, 1990). Correlations are difficult to  
173 see given the discontinuous exposure of the limestone layers and their low fossil content. Thus,  
174 different limestone layers of this unit (exposed in different areas of the Tremp syncline) have  
175 been described as Late Cretaceous (Díaz-Molina, 1987) or Thanetian (Feist and Colombo,  
176 1983; Masriera and Ullastre, 1983).

177 The K/Pg boundary is generally placed towards the top of the studied section, although there is  
178 no agreement on its exact position. According to different researchers, it lies at the top of the

179 Lower Red Unit (Eichenseer, 1987; Rosell et al., 2001) or above the Suterranya Limestone (e.g.  
180 Masriera and Ullastre, 1983).

181

### 182 **3. METHODS**

183

184 An area of 3 km<sup>2</sup> was mapped at a scale of 1:5000, based on field observations and satellite  
185 images, which were integrated using ArcGIS software (Fig. 1b). Detailed sedimentological,  
186 petrological and micropalaeontological data were gathered across the most complete and best  
187 exposed stratigraphic section in the area (Figs. 1b, 2 and 10).

188 For the petrographic study, 70 samples were collected; these came from all types of rock  
189 present, including hybrid arenite, limestone, conglomerate and sandy-marly limestone (Fig. 2).

190 A polished, uncovered thin section (30 µm) was prepared for each representative sample and  
191 petrographic analysis performed following standard techniques and using cathodoluminescence  
192 (CL) microscopy. The latter, which is essential for recognizing diagenetic processes and for  
193 discriminating between reworked and non-reworked fossils, was undertaken using a  
194 Technosyn® cold CL unit operating at 20–25 kV and with a 300–400 µA beam current. The  
195 terminology “*ex situ/in situ*” of Fernández-López (1991) was used for describing specimens that,  
196 respectively, had and had not been reworked from older rocks. Moreover, “*in situ*” specimens  
197 were differentiated as autochthonous or allochthonous according to the terminology proposed  
198 by Kidwell et al. (1986). Hybrid, siliciclastic and carbonate rocks were described using the  
199 arenite classification of Zuffa (1980). Carbonate texture was described following the  
200 classification of Dunham (1962).

201 For the micropalaeontological study, 48 samples of the sandy-marly limestone, the greyish marl  
202 and the limestone were collected at intervals of approximately 5-10 m (Fig. 2). The marly  
203 samples were processed using the standard disaggregating technique, i.e., placing in dilute  
204 (15%) hydrogen peroxide for 3 h to release the carbonate microfossils. The more lithified  
205 samples left behind were extracted following the technique of Lirer (2000), which includes  
206 sample disaggregation in a solution with 80% acetic acid and 20% H<sub>2</sub>O for 4 h. All samples  
207 were dried at ≤50°C, and sieved into 63 µm, 100 µm and 1 mm size fractions. The  
208 disaggregated samples were semi-quantitatively analysed to provide the relative abundance of

209 planktonic foraminifera, which was recorded as abundant, common, scarce or rare. Twenty-  
210 eight samples containing planktonic foraminifera were analysed to determine the assemblages  
211 present and the richness of the different species (Table 1). Representative specimens of all taxa  
212 were mounted on microscope slides to provide a permanent record. Some specimens were  
213 selected for scanning electron microscopy (SEM) analysis, using a JEOL JSM 6400 SEM at the  
214 Microscopy Service of the *Universidad de Zaragoza* (Spain). All residues, images and the  
215 chosen specimens themselves are stored at the *Departamento de Ciencias de la Tierra* of the  
216 *Universidad de Zaragoza* (Spain).

217 All collected samples were named with the initial letters of the geological unit from which they  
218 came, followed by the height (m) at which they were collected. For example, "LRU15.0"  
219 represents a sample from the Lower Red Unit, collected at 15 m from the base of the  
220 stratigraphic section.

221

#### 222 **4. DEPOSITIONAL FACIES AND SEDIMENTARY ENVIRONMENTS**

223

224 The studied section is 475 m thick and comprises the lower part of the Tremp Fm, including the  
225 Grey Unit, the Lower Red Unit and the Suterranya Limestone (Figs. 1b and 2). Four facies  
226 associations can be distinguished in these deposits: greyish marl with interbedded limestone in  
227 the Grey Unit, sandy-marly limestone, palaeochannel deposits in the Lower Red Unit, and  
228 bioclastic-brecciated limestone in the Suterranya Limestone (Figs. 1b and 2).

229

##### 230 4.1 Grey Unit: Greyish marl with interbedded limestone

231 The Grey Unit consists of a 46 m-thick stratigraphic succession of greyish marl with abundant  
232 carbonate horizons and three massive limestone layers (Fig. 2). The marl is typically greyish in  
233 colour, but it can become brownish towards the top of the Unit where it is mottled and there are  
234 signs of intense burrowing. Fossil ostracods, charophytes, plant remains, fragments of bivalves  
235 and benthonic foraminifera such as miliolids, as well as other indeterminate groups, are present.  
236 Some calcispheres and planktonic foraminifera are also seen. A distinctive feature of these  
237 deposits is the presence of several interbedded carbonate horizons with a lateral continuity of 3-  
238 100 m and a decimetric thickness (Fig. 3a). The carbonate horizons are composed of an



239 accumulation of vertically-orientated and subrounded carbonate nodules up to 10 cm in  
240 diameter. These nodules consist of mudstone with yellowish mottling and are also observed  
241 scattered within the marl.

242 Three limestone layers can be seen interbedded with the greyish marl, one located at the base,  
243 one in the middle, and one at the top of the Unit (Figs. 2 and 3a). They have a tabular shape,  
244 show up to 600 m of lateral continuity (Fig. 1b), and their thickness ranges from 30 cm to 1.5 m.  
245 The limestone is grey-coloured, massive and shows signs of burrowing; the top of the bed is an  
246 irregular surface where root traces and occasional vertebrate footprints are preserved.

247 Petrographically, these limestone layers are wackestones and packstones, both of which  
248 contain small amounts of quartz, micrite intraclasts and bioclasts. The bioclasts have a micrite  
249 coating and include fragments of mollusc shell (bivalves and gastropods), foraminifera  
250 (orbitoids, miliolids, other indeterminate groups of benthonic foraminifera, and scarce planktonic  
251 foraminifera), ostracods, calcispheres and charophytes (Fig. 3b-c). Some samples contained  
252 scattered dasycladal algae and vertebrate remains.

253 The limestone layer at the top of the Grey Unit (Figs. 1b and 2) is discontinuous, up to 1.5 m  
254 thick, and it shows a flat top and a gentle erosive base. It has a remarkable lag of oncoids (up to  
255 10 cm) and with some dinosaur bone remains. Upwards, the limestone is composed of a  
256 packstone of micrite intraclasts and bioclasts similar to those described above. However, they  
257 also have variable amounts of oncoids between 2 mm and 3 cm in diameter. At the top, the  
258 layer is intensely burrowed.

259

### 260 *Interpretation*

261 The greyish marl and interbedded limestone of the Grey Unit were deposited in wide and  
262 shallow protected areas of variable salinity - perhaps part of lagoonal or estuarine settings  
263 (Rosell, 1965; Nagtegaal et al., 1983; Cuevas 1992; Rosell et al., 2001; Riera et al., 2009) or  
264 barrier island-lagoon systems (Díaz-Molina et al., 2007). The shallow and palustrine nature of  
265 these areas is suggested by the ubiquitous pedogenic features in the greyish marl, such as the  
266 abundant nodules and root traces, and the presence of micrite-coated grains at the top of the  
267 limestone layers (Esteban and Klappa, 1983; Alonso-Zarza, 2003). These shallow lagoonal  
268 areas appear to be traversed by oncoid-containing channels, indicating fluctuations in the water

269 level of this area. Similar oncoid-rich channels are very common components of modern and  
270 ancient carbonate fluvio-lacustrine systems (Arenas-Abad et al., 2010, and references therein).  
271 Variable salinity and/or brackish conditions are interpreted from the biotic assemblage since  
272 organisms of both marine affinity, such as foraminifera and dasycladal algae, and continental  
273 affinity, such as ostracods, charophytes, plant fragments and vertebrate remains, are observed  
274 together. The biotic assemblages of the Grey Unit have been described in detail by Libeau  
275 (1980), who interpreted these deposits as representing an area with brackish conditions.

276

#### 277 4.2 Lower Red Unit: palaeochannel deposits and sandy-marly limestone

278 This unit consists of 400 m of multicoloured sandy-marly limestone and subordinate  
279 palaeochannel deposits (Figs. 1b and 2).

280

##### 281 4.2.1 Palaeochannel deposits

282 The palaeochannel deposits consist of sandstone with subordinated conglomerate and sandy-  
283 marly limestone (Figs. 2 and 4). They show inclined heterolithic stratification (IHS, *sensu*  
284 Thomas *et al.* [1987]) and are interpreted as point bars (used here to indicate a composite bar  
285 formed by a set of conformable lateral accretion units [Díaz-Molina *et al.*, 1989]) or adjoined  
286 point bar bodies. They are interbedded with the marly-sandy limestone and form three clusters  
287 up to 150 m thick in which point bar bodies are more abundant (Figs. 1b and 2) and,  
288 occasionally, superimposed.

289 In the outcrops, the point bar bodies are 1-2 m thick and show different shapes in transverse  
290 and longitudinal section (*sensu* Díaz-Molina, 1993). In transverse section, they have a sigmoid  
291 outline (Fig. 4a), but in longitudinal section they take a convex side-upwards lenticular form.

292 Most of the meander loop deposits are formed by adjoining point bar bodies, laterally bound by  
293 erosional or non-erosional meander-bend reactivation surfaces (Díaz-Molina 1984 and 1993) or  
294 set boundaries (Thorne *et al.*, 1985). The boundaries between the bedsets of adjoined point  
295 bars are also distinguished by a discordance between them, or by the onlap of the younger  
296 point bar on the reactivation surface (Fig. 4a-b). In the study area, most of the meander loop  
297 deposits are formed by adjacent point bars and thus develop a lateral continuity up to 500 m  
298 long and 100 m thick (Figs. 1 and 4a). No scroll bar topography was identified. Most of the

299 inclined heterolithic strata pass gradually upwards and laterally into massive hybrid arenite and  
300 intensely burrowed sandy-marly limestone.

301 In these examples, the point bar deposit sequence is fining upwards, and two units can be  
302 identified: a lower conglomeratic unit, and an upper unit composed of more finely grained  
303 sediments (Figs. 2 and 4). The lower unit is up to 50 cm thick and consists of clast-supported  
304 conglomerates over a slightly erosive basal surface where load structures are present (Figs. 2  
305 and 4). Commonly, the conglomeratic unit shows large scale cross-bedding made by bed forms  
306 that moved up the bar and that are included in the inclined heterolithic strata. The upper unit of  
307 the bar is up to 1.50 m thick and consists of couplets of centimetric to decimetric hybrid arenite  
308 layers interbedded with centimetric sandy-marly limestone layers showing IHS (Figs. 4a-b). The  
309 thickness of the sandy marly limestone increases upwards along the lateral accretion units of  
310 the point bar. Frequently, the lateral accretion units are curved upwards and end up being  
311 horizontal. In the sandstone, large- and small-scale cross-bedding, climbing-ripple cross-  
312 bedding, flaser bedding (Fig. 4c) and parallel lamination are occasionally preserved. Most of  
313 palaeocurrent measurements indicate that bed forms moved up the bar. In some point bar  
314 bodies of the channel cluster in the middle of the section, the palaeocurrent measurements  
315 indicate transport by bidirectional currents (Fig. 2).

316 Burrowing and mottling are common in the point bar bodies (Figs. 2 and 4d), ranging from  
317 disperse to pervasive dotting. The intense burrowing can obliterate the original structure of the  
318 deposit (Fig. 4d). Where this occurs, the point bar deposits can be recognized only by their  
319 external shape (lenticular or sigmoid), although they sometimes maintain a blurred IHS. In  
320 addition, the point bar bodies of the uppermost channel cluster in the upper part of the section  
321 frequently show reddish root traces up to 1 m long. These roots may be found at the top of the  
322 lateral accretion units or throughout the entire point bar bodies (Figs. 2 and 4e). The  
323 sedimentary structures are exceptionally well preserved in some point bar bodies in clusters in  
324 the middle and upper parts of the section (Fig. 4c). Here, burrowing is restricted to the  
325 uppermost portion of the point bar deposits.

326 The clast-supported conglomerate found at the base of the IHS bodies is poorly to moderately  
327 well sorted with rounded to angular grains. The size of the pebbles varies between 2 mm and 2  
328 cm. These pebbles are lithoclasts, bivalve fragments and occasionally oncoids and vertebrate

329 remains. The matrix is formed by very fine to very coarse hybrid arenite, micrite and calcite  
330 cement which fills the interparticle porosity. The hybrid arenite of the matrix is composed of  
331 lithoclasts, quartz, fragments of bivalve shell, planktonic and benthonic foraminifera,  
332 calcispheres, and occasionally fragments of echinoderm, red algae, charophytes, ostracods,  
333 vertebrate remains (bones and eggshells) and glauconite.  
334 The hybrid arenite of the point bar deposits is composed of very fine to very coarse sand, poorly  
335 to moderately well sorted. The components of the hybrid arenite are similar to those that make  
336 up the conglomerate matrix (Fig. 5). The hybrid arenite typically contains an abundant micrite  
337 matrix, although in some samples from the lower cluster of the palaeochannel deposits, the  
338 inter- and intraparticle porosities are filled with sparitic or syntaxial cement, the latter always  
339 associated with the presence of echinoderm fragments.

340

#### 341 *Interpretation*

342 The palaeochannel deposits of the Lower Red Unit are interpreted as point bars of meandering  
343 channels. The bases for this interpretation are provided by the presence of fining upwards  
344 sequences, lateral accretion units, reactivation surfaces, and the external shape of the meander  
345 loop deposits. A similar interpretation for this sedimentary unit had been proposed in previous  
346 papers (Díaz-Molina, 1987; Cuevas, 1992; Rosell et al., 2001; Riera et al., 2009). However,  
347 certain features observed in the palaeochannel deposits suggest that these meandering  
348 channels were part of a tide-influenced sedimentary environment.

349 IHS (Fig. 4a-b) is mainly the result of the lateral accretion of point bars in the meandering  
350 channels of both fluvial and tide-influenced settings (Thomas et al., 1987). However, it is mainly  
351 associated with tide-influenced marginal marine deposits (Smith, 1987). In fluvial environments,  
352 IHS occurs in the point bars of rivers carrying an abundant, fine-grained load (Jackson, 1978).  
353 For instance, it has been identified within the inner accretionary bank of the meanders of the  
354 River Endrick (Bluck, 1971), the benches of the Barwon River (Taylor and Woodyer, 1978), the  
355 meanders of the Murrumbidgee River in Australia (Page et al., 2003), and in the counter-point-  
356 bar of the Peace-Athabasca Delta in Canada (Smith et al., 2011). Many examples have been  
357 documented from modern mesotidal creeks (Bridges and Leeder, 1976, Mowbray, 1983), and  
358 estuaries (Smith, 1987; Choi et al., 2004; Gingras et al., 1999; Choi, 2011; Sisulak & Dashtgard,

2012), in which the architecture of IHS bodies seems to be primarily governed by the combined effects of fluvial, tidal and seasonal control (Choi et al., 2004, Hovikoski et al., 2008; Choi, 2011) or by the shifting of the turbidity maximum due to fluctuations in continental discharge (Smith, 1987; Gingras et al., 1999). Lateral accretion units that curve upwards and end up being horizontal have been observed by other authors in tidal creeks (Bridges and Leeder, 1976; Mowbray, 1983) and in mixed and suspended-load rivers (Page et al., 2003).

In the studied outcrops, the presence of flaser bedding (Fig. 4c) and bidirectional cross-beds in the IHS suggest a tidal influence on these ancient fluvial deposits. The deposition of mud drapes and bidirectional currents suggest that bedforms formed and migrated under the influence of flood tide currents. Another characteristic observed in modern tide-influenced point bars, and also present in these ancient examples, is the upwards increase of the mud bed thickness (Smith, 1987). In modern examples of meandering channels with tidal influence, the scroll bar topography is replaced by overbank marsh mud (Smith, 1987), showing tidal flat sediments (Mowbray, 1983; Choi et al., 2004) or channel-related tidal flats (Dalrymple, 2010) where the sediment adjacent to the channel is typically sandy. This passes gradually into mud near the high-tide line. In the studied examples, however, the intertidal deposits that develop on the top of the tide-influenced point bars are represented by massive and intensely burrowed hybrid arenite (Fig. 4d).

The reactivation surfaces between different point bar deposits mean the displacement direction of the meandering channel changed, the result of episodic channel adjustments in response to the development of critical curvatures (Díaz-Molina 1984 and 1993). Similar truncation surfaces have also been noticed in tide-influenced point bars (Bridges and Leeder, 1976), but they differ from other erosion surfaces described in intertidal mudflat channels (Mowbray, 1983) in that the reactivation surfaces go through the entire bar and are tens of meters apart.

Additional support for the interpretation of tidal influence comes from the presence, in the point bar deposits, of foraminifera, grains of glauconite, and fragments of red algae and echinoderms (Fig. 5). These elements are transportable as a suspension load by flood tide currents (see below).

#### 4.2.2 Non-channelized sandy-marly limestone

389 The meander loop deposits are interbedded with sandy-marly limestone, the dominant deposit  
390 in the lower Tremp Fm (Figs. 1b and 2). These sandy-marly limestone deposits show a variety  
391 of colours, from yellowish to purplish, throughout the studied section. Two types of interbedded  
392 facies are distinguishable (Figs. 2 and 6a): yellowish sandy-marly limestone (SML1, Fig. 6b) and  
393 reddish sandy-marly limestone (SML2, Fig. 6c). Facies SML1 is more abundant in the lower part  
394 of the stratigraphic section, interbedded with the palaeochannel deposits. SML2 is more  
395 dominant in the upper part. Exceptionally, thin layers of greyish marl up to 2 m thick are  
396 interbedded with this facies (Fig. 2).

397 Facies SML1 is mainly composed of mudstone or wackestone with very fine sand and silt-sized  
398 grains. It is intensely burrowed, has a yellowish colour and orange to reddish mottling (Fig. 6b).  
399 Some reddish horizons with abundant root traces are observed; these are more abundant  
400 towards the top of the stratigraphic section (Fig. 2). No sedimentary structures can be  
401 recognized in facies SML1, largely due to the intense bioturbation, except for in the lower part of  
402 the stratigraphic section where lenticular bedding is occasionally observed (Fig. 2). In this  
403 lenticular bedding, the small-scale cross-bedded arenite has petrological features very similar to  
404 those described for the point bar deposits. However, SML1 has more glauconite, which  
405 appears as dispersed, rounded grains, as infill in the remaining interparticle porosity (Fig. 6d),  
406 and as a replacement for the micrite matrix.

407 The components of facies SML1 are quartz, fragments of mollusc shell, planktonic foraminifera,  
408 calcispheres and, commonly, ostracods and charophytes (Fig. 6e). Nodulization and iron oxide  
409 mottling are ubiquitous.

410 Facies SML2 differs from SML1 in its colour, which is typically reddish to purplish. In addition, it  
411 shows slightly less burrowing and more scattered centimetric carbonate nodules and root traces  
412 (Fig. 6c). These root traces are mainly observed at the top of the Lower Red Unit. The  
413 components are similar to those described for facies SML1, except that planktonic foraminifera  
414 are less abundant.

415

#### 416 *Interpretation*

417 The sandy-marly limestone is interpreted as overbank facies deposited on mudflats laterally  
418 associated with the tide-influenced meandering channels. The amount of carbonate in this

419 facies, particularly in the form of micrite, indicates that the precipitation of carbonate in these  
420 areas was a predominant process. Sand-sized siliciclastic components were probably  
421 transported as bedload and deposited by currents (e.g., spring tides and fluvial floodings), while  
422 the finer siliciclastic components were deposited from the settling of the suspension load.  
423 However, no sedimentary structures are typically observed in this facies, probably due to the  
424 intense burrowing it has undergone (Fig. 6b). This intense burrowing, the precipitation of  
425 carbonate, and the absence of mudcracks, together suggest that the sandy-marly limestones  
426 originated in mudflats under dominantly sub-aquatic or humid conditions through the flooding of  
427 the fluvial system and/or the action of flood tides.

428 Scattered carbonate nodules and root traces, mainly within facies SML2 (Fig. 5c), indicate  
429 pedogenic processes (Esteban and Klappa, 1983; Alonso-Zarza, 2003). The mud flats were,  
430 therefore, eventually sub-aerially exposed.

431 The presence of glauconite, as well as that of fully-marine microfossils, suggests these areas  
432 were affected by sea water. Glauconite is formed under marine conditions in outer shelf and  
433 slope deposits (Odin and Fullagar, 1988), under very shallow-water to tidal flat conditions  
434 (Chafetz and Reid, 2000), and in carbonate deposits of lagoonal and estuarine environments (El  
435 Albani et al., 2005). The glauconite grains in facies SML1 may have been transported from  
436 marine towards overbank areas via the channels. However, the environmental conditions for  
437 glauconite precipitation (e.g., a saline, redox environment), must have been maintained in the  
438 overbank areas since glauconite is also observed filling the interparticle porosity and replacing  
439 the micrite matrix (Fig. 6d).

440

#### 441 4.3 Suterranya Limestone: Bioclastic and brecciated limestone

442 Two limestone layers, 1 and 1.5 m thick respectively, interbedded with grey and reddish marl,  
443 lie at the top of the studied section (Fig. 2). The limestone is greyish-coloured, tabular and  
444 massive, and at the top becomes nodular and brecciated (Fig. 7a).

445 Petrographically, the limestone can be grouped into two facies, a bioclastic packstone at the  
446 base of each layer (Fig. 7b), and nodular and/or brecciated limestone to the top. The packstone  
447 contains intraclasts and smaller components such as mollusc (gastropods and bivalves) shell  
448 fragments, fragments of dasycladal algae, small benthonic foraminifera, planktonic foraminifera,

449 charophytes, quartz (less than 5%), calcispheres and ostracods (Figs. 7b-c). Burrowing  
450 structures and root traces are common, as are nodulization and/or brecciation, micritization and  
451 mottling (Figs. 7b). Breccias can be seen floating in a wackestone texture matrix. Both the  
452 breccias and matrix have similar components described above as bioclastic packstone. Within  
453 the marl, foraminifera, calcispheres and charophytes are rarely observed.

454

#### 455 *Interpretation*

456 The bioclastic and brecciated limestones were deposited in shallow lakes of variable salinity in a  
457 coastal environment, as interpreted by Lopez-Martinez et al. (2006). The latter authors studied  
458 different outcrops of the Suterranya Limestone throughout the Tremp syncline, concluding it to  
459 have been thus deposited. Particularly in the Tremp section, they inferred brackish conditions  
460 based on the biotic assemblage formed by benthonic foraminifera, charophytes, ostracods and  
461 molluscs. The present samples also include dasycladal algae, calcispheres and planktonic  
462 foraminifera. Dasycladal algae typically inhabit euhaline seawater (Berger and Kaever, 1992;  
463 Flügel, 2010), as do planktonic foraminifera, indicating that the coastal lakes were, at least at  
464 some point, open to the sea. Coastal lakes with water of normal marine salinity have been  
465 reported for recent environments (Britton and Podlejski, 1980), as well as in ancient  
466 environments showing salinity fluctuations (Monty and Hardie, 1976; Muller et al., 2008; Suárez-  
467 González et al., 2013). The Suterranya coastal lakes would have developed as shallow water  
468 bodies within relatively flat depressions with a gentle gradient and low energy margins (Plat and  
469 Wright, 1991), as inferred from the abundance of palustrine features such as nodulization and  
470 brecciation (Alonso-Zarza, 2003). Fluctuations in salinity from freshwater to brackish and  
471 marine conditions would have occurred during their deposition.

472

#### 473 **5. TAPHONOMIC STUDY: DETERMINING THE *IN SITU* OR *EX SITU* NATURE OF THE** 474 **MARINE FOSSILS**

475

476 Given the hybrid and detrital nature of most of the studied rocks, it is hard to initially determine  
477 whether the fossil component is the result of the erosion of older rocks (*ex situ* specimens  
478 appearing through reworking *sensu* Fernández-López [1991]) or reflects *in situ* specimens



479 (*sensu* Fernández-López, 1991). *In situ* fossils may represent organisms that grew locally or  
480 that were transported in (autochthonous and allochthonous specimens *sensu* Kidwell et al.  
481 [1986]). The taphonomic study of these fossils is therefore required if they are to be used for  
482 biostratigraphic purposes and sedimentary environment reconstruction. In the present work, a  
483 detailed petrographic study, including cathodoluminescence (CL) microscopy, was undertaken  
484 to distinguish between *in situ* and *ex situ* specimens.

485 The transmitted light and CL microscopy procedures showed some bioclasts that may have  
486 been reworked from older rocks (*ex situ* specimens). These are observed in the hybrid arenite  
487 and sandy-marly limestone but not in the limestone beds of the Grey Unit or the Suterranya  
488 Limestone. *Ex situ* specimens are sometimes included within lithoclasts (making their  
489 identification easy), and/or randomly distributed within the sediment, as seen for some  
490 calcispheres, echinoderm fragments and foraminifera (Fig. 8a, black arrows). When randomly  
491 distributed, they are commonly fragmented, and under transmitted light show a brownish to  
492 reddish colour caused by the precipitation of iron oxides. Under CL, the calcite cement filling  
493 the intrabioclast porosity, and that filling the interparticle porosity, show different luminescence  
494 patterns (Fig. 8a, black arrows). These differences indicate that the bioclasts were cemented  
495 before deposition; they were therefore reworked.

496 However, there are other bioclasts (both fragmented and unfragmented), such as those derived  
497 from gastropod shells, charophytes, dasycladal algae, some calcispheres and most of the  
498 foraminifera, which show identical luminescence patterns in the calcite cement filling the  
499 intrabioclast and interparticle porosities (Figs. 8 and 9). This suggests that both cements  
500 precipitated at the same time in a similar diagenetic environment (Machel and Burton, 1991),  
501 and that these bioclasts were unfilled when deposited. Thus, it is probable that these are *in situ*  
502 specimens and not reworked.

503 The small intraparticle pores of the echinoderm fragments and red algae make difficult to  
504 observe the characteristics of the intraparticle cement or compare it with interparticle cement.  
505 For the echinoderms, it might be possible to demonstrate their *ex situ* origin if they were to show  
506 preserved broken and/or eroded syntaxial cement. However most of the echinoderms of the  
507 lower Tremp Fm show no such thing; they are only cemented by syntaxial cement which has a  
508 CL pattern similar to that precipitated in the interparticle porosities (Fig. 8c).

509

## 510 6. BIOSTRATIGRAPHY DETERMINED VIA THE EXAMINATION OF PLANKTONIC

### 511 FORAMINIFERA

512

513 The preservation of the external surface of the tests of the planktonic foraminifera in the studied  
514 section is only poor to moderately good. In addition, the quantity of planktonic foraminifera  
515 varies from rare to abundant. Although the species richness was generally low, it was quite high  
516 in some samples (Fig. 10 and Table 1).

517 In the Cretaceous part of the Tremp Fm, 49 planktonic foraminifera species were identified.

518 From the point of view of their biochronological distributions and according to Nederbragt  
519 (1991), Arz and Molina (2002), Pérez-Rodríguez et al. (2012) and Gradstein et al. (2012), three  
520 groups can be distinguished:

521 1) Exclusively Maastrichtian species (marked with green circles in Fig. 10): *Pseudoguembelina*  
522 *kempensis*, *Psg. aff. hariaensis*, *Planoglobulina acervulinoides*, *Globotruncanella minuta* and  
523 *Globotruncanita fareedi*.

524 2) Species with an older first appearance but present in the Maastrichtian (marked with black  
525 circles in Fig. 10): *Guembelitria cretacea*, *Gb. trifolia*, *Heterohelix globulosa*, *Htx. planata*, *Htx.*  
526 *labellosa*, *Htx. glabrans*, *Htx. pulchra*, *Htx. navarroensis*, *Pseudotextularia nutalli*,  
527 *Planoglobulina riograndensis*, *Pseudoguembelina costulata*, *Gublerina acuta*, *Globigerinelloides*  
528 *yaucoensis*, *Gdes. prairiehillensis*, *Gdes. volutus*, *Gdes. multispina*, *Gdes. rosebudensis*, *Gdes.*  
529 *bollii*, *Herbergella holmdelensis*, *Hd. monmouthensis*, *Hd. planispira*, *Globotruncanella*  
530 *petaloidea*, *Gella. havanensis*, *Gella. pschadae*, *Rugoglobigerina rugosa*, *Archaeoglogigerina*  
531 *cretacea*, *A. blowi*, *Globotruncana arca*, *Gna. aegyptiaca*, *Gna. bulloides*, *Gna. linneiana*, *Gna.*  
532 *mariei*, *Gna. orientalis*, *Gna. ventricosa*, *Globotruncanita stuartiformis*, *Contusotruncana*  
533 *fornicata*, *C. plummerae* and *C. patelliformis*.

534 3) Species with last appearance older than Maastrichtian (marked with red circles in Fig. 10):  
535 *Ventilabrella eggery*, *Sigalia deflaensis*, *Hedbergella faldrini*, *Hd. simplex*, *Whiteinella baltica*  
536 and *W. paradubia*. Specimens of these species are very scarce, *ex situ*, and come from  
537 reworked material mainly of Santonian age.

538 The biochronological scale of Pérez-Rodríguez et al. (2012) was used for dating purposes; this  
539 scale was established by examination of the well-exposed and continuous uppermost  
540 Cretaceous coastal section of Zumaia (Basque Country, northern Spain) in the western  
541 Pyrenees. For these hemipelagic facies, which are the same age as those of the Tremp Fm,  
542 Pérez-Rodríguez et al. (2012) proposed five Partial-Range Zones for the Maastrichtian. These  
543 zones are based on the oldest occurrence of the marker species: 1) *Pseudoguembelina*  
544 *palpebra* and *Planoglobulina acervulinoides* of the lower Maastrichtian, 2) *Racemiguembelina*  
545 *fructicosa*, *Abathomhalus mayaroensis*, and 3) *Pseudoguembelina hariaensis* of the upper  
546 Maastrichtian. The ages of the different planktonic foraminifera were based on those obtained  
547 by Huber et al. (2008) for the upper Campanian-Maastrichtian pelagic sediments cored at the  
548 DSDP/ODP Sites 390A/1049, 1050, and 1052 (Blake Nose, subtropical western Atlantic Ocean)  
549 and the Cretaceous planktonic foraminiferal biochronological calibrations proposed by  
550 Gradstein et al. (2012).

551 In the Paleogene part of the Tremp Fm, 13 planktonic foraminifera species were identified. The  
552 biozonation systems of Berggren and Pearson (2005) and Arenillas (2011), and the Paleogene  
553 biochronological calibrations proposed by Gradstein et al. (2012), were used to identify two  
554 biozones in the Danian-Selandian transition: P2 and P3 (the last being subdivided into two  
555 subzones: P3a and P3b). These biozones and subzones are approximately equivalent to the  
556 *Acarinina uncinata* (=P2), *Morozovella angulata* (=P3a) and *Morozovella pusilla* (=P3b) Zones  
557 of Arenillas (2011). The Danian/Selandian boundary was placed in the middle part of  
558 *Morozovella pusilla* Zone or P3b (Schmitz et al., 2011). The planktonic foraminiferal  
559 biostratigraphy of each unit of the lower Tremp Fm is described below.

560

#### 561 6.1 Grey Unit

562 Villalba-Breva and Martín-Closas (2013) proposed the Grey Unit to belong to the charophyte  
563 *Septorella ultima* Zone, and suggested an early Maastrichtian age for the Barranc de la Posa  
564 section that outcrops in the eastern part of the Tremp-Graus Basin. In the present study, only  
565 one of the analysed samples showed planktonic foraminifera. The assemblage consisted of  
566 species of no biostratigraphic interest, although it was compatible with the age assigned to the  
567 Grey Unit by Villalba-Breva and Martín-Closas (2013).

568

569 6.2 Lower Red Unit

570 Feist and Colombo (1983) found it difficult to identify many biostratigraphic levels of the Lower  
571 Red Unit because of the scant abundance of charophytes. The study of the planktonic  
572 foraminifera record, however, allows more accurate biochronological results to be obtained.  
573 Planktonic foraminifera are more abundant in the samples of facies SML1, their abundance  
574 decreasing towards the top of the Lower Red Unit. Three stratigraphic intervals show a higher  
575 relative abundance of planktonic foraminifera, allowing different planktonic foraminiferal zones  
576 to be discerned (Fig. 10). These very nearly coincide perfectly with the clusters of meander loop  
577 deposits in the section's lower and middle parts (Fig. 2 and Table 1), in which petrographic  
578 evidence of *in situ* specimens can be seen (marked with red asterisks in Fig. 10).

579 The first stratigraphic interval rich in non-reworked planktonic foraminifera is limited by the  
580 samples LRU 89.4 to LRU 105.1. The presence of *Psg. kempensis* (Fig. 11.1a-b) reveals its  
581 early Maastrichtian age; the first appearance of this species was 71.50 Ma ago (Huber et al.,  
582 2008), a little after the Campanian/Maastrichtian boundary (72.1 Ma, according to Voigt et al.  
583 [2012], and Gradstein et al. [2012]). Accordingly, the lower part of the Lower Red Unit belongs  
584 to the lower part of the *Psg. palpebra* Zone whose base is dated at 71.64 Ma (Huber et al.,  
585 2008). This biozone was proposed by Huber et al. (2008) to replace the standard *Gansserina*  
586 *gansseri* Zone in localities where *Gansserina gansseri* is absent, such as in the Pyrenean Basin  
587 (Arz, 1996). Although, *Psg. palpebra* is absent in the section, the identification of specimens  
588 intermediate between *Psg. palpebra* and its descendant *Psg. hariaensis* (which first appeared  
589 67.3 Ma ago [Gradstein et al., 2012]) confirms the studied deposits to belong to the *Psg.*  
590 *palpebra* Zone. The name of *Psg. aff. hariaensis* has been provisionally given to the  
591 intermediate morphotypes identified (Fig. 11.2a-b; Appendix 1).

592 The second stratigraphic interval rich in non-reworked planktonic foraminifera is that limited by  
593 samples LRU231.1 to LRU293.5. These materials correspond to the upper-middle part of the  
594 *Psg. palpebra* Zone, where the lowest stratigraphic evidence of *Gita. fareedi* was found in  
595 LRU232.5 in a similar stratigraphic position to that recorded in Zumaia (Pérez-Rodríguez et al.,  
596 2012). Specimens of dwarf globotruncanids are relatively common in this interval. Keller and

597 Abramovich (2009) relate the size reduction in planktonic foraminifera seen in the late  
598 Maastrichtian, during which they reached reproductive adulthood at a size below normal, to the  
599 high-stress conditions of mesotrophic restricted basins and shallow marginal settings.  
600 The last biostratigraphically important level corresponds to that from which LRU339.3 was  
601 collected. This level has a high species richness, including 30 species of planktonic  
602 foraminifera (Table 1). The co-occurrence of *Pl. acervulinooides* (Fig. 11.3) and *Pl. riograndensis*  
603 (Fig. 11.4) indicates these materials to belong to the lowest part of the *Pl. acervulinooides* Zone  
604 (Pérez-Rodríguez et al., 2012). These species first appeared 69.55 Ma ago (Huber et al., 2008),  
605 so this horizon can be placed close to the Lower/Upper Maastrichtian boundary.  
606 In the Upper Maastrichtian, planktonic foraminifera are very scarce and the index-species are  
607 not found; the last Cretaceous biozones could therefore not be recognized. The species  
608 richness is reduced in this interval, with 5 to 12 species detected per sample (Table 1). The  
609 absence of Danian planktonic foraminifera species is noticeable; the Lower Red Unit in the  
610 studied section may therefore be exclusively Maastrichtian.

611

### 612 6.3 The Suterranya Limestone

613 In the Paleocene, planktonic foraminifera are very scarce or rare, and show poorly preserved  
614 external surfaces. Except for some obviously reworked Cretaceous specimens, such as *Hd.*  
615 *holmdelensis* and *Hd. monmouthensis*, the Paleocene specimens can be considered *in situ*, as  
616 suggested by the results of the taphonomic analysis (Fig. 9). Thus, the identified assemblages  
617 of planktonic foraminifera were used to propose the most likely age of the Suterranya  
618 Limestone. According to the taxonomy of Arenillas (2012), the Paleocene planktonic  
619 foraminifera assemblages identified (samples SL495.3 to SL497.9) consist of the following  
620 species (Table 1): *Parasubbotina pseudobulloides* (Fig. 12.1a-c), *P. varianta*, *P. quadrilocula*,  
621 *Subbotina triloculinooides* (Fig. 12.5a-c), *Sb. compressaformis*, *Globanomalina compressa*, *G.*  
622 *haunsbergensis*, *Praemurica inconstans* (Fig. 12.2a-c), *Acarinina trinidadensis* (Fig. 12.3a-c),  
623 *Ac. praepentacamerata* (or *Acarinina praeangulata*; Fig. 12.4a-c), *Ac. hansbolli*, *Ac. triplex* and  
624 *Morozovella simulatilis* (biconvex morphotypes are included in *Morozovella angulata* by other  
625 authors such as Olsson et al. [1999]; Fig. 12.6a-c).

626 Until now, the age of the Suterranya Limestone has never been directly established since no  
627 guide fossils had ever been found (López-Martínez et al., 2006). Palaeomagnetic data (the  
628 identification of chrons 27r, 27n and 26r by Galbrun *et al.* [1993]) as well as charophyte and  
629 vertebrate assemblages (López-Martínez *et al.*, 1998) from equivalent units in the nearby  
630 Fontllonga section, suggest the Suterranya Limestone (Unit 3 of the Tremp Fm) to be late  
631 Danian (López-Martínez et al., 2006). The present planktonic foraminifera assemblage results  
632 support the idea that the Suterranya Limestone belongs to the upper Danian *M. angulata* Zone  
633 of Arenillas (2011) or P3a of Berggren and Pearson (2005). Therefore, at least the first 4 million  
634 years of the Danian are absent in the Tremp Fm according to the Geological Time Scale  
635 proposed by Gradstein et al. (2012).

636 The K/Pg boundary has never been identified in the Tremp Fm (López-Martínez et al., 2006),  
637 except via indirect evidence. For example, in the Tremp Fm, and throughout Europe, no  
638 changes are observed in the palaeoflora over the K-Pg transition, so there are no palynological  
639 successions with which to fix the K/Pg boundary (Médus et al., 1992; López-Martínez et al.,  
640 1999; Fernández-Marrón et al., 2004). Some authors have used the abundance of *Microcodium*  
641 as a biomarker of the Paleogene, but this taxon also appears frequently in Upper Cretaceous  
642 deposits of the Tremp Fm; it is not, therefore, a very useful chronostratigraphic marker  
643 (Llompart and Krauss, 1982; Rosell et al., 2001; Díaz-Molina et al., 2007). The typical iridium  
644 anomaly of the K/Pg boundary has never been identified in the Tremp Fm, leading some  
645 authors to suggest a hiatus comprising the K-Pg transition to exist (Baceta et al., 2004). Close  
646 to the studied section in the Fontllonga, Benabarre and Figuerola sections, a reduction in  $\delta^{13}\text{C}$   
647 isotope values might mark the K/Pg boundary (López-Martínez et al., 1998 and 1999). In these  
648 sections, the isotope horizon is located towards the top of what, in the Tremp Fm, would be the  
649 Lower Red Unit, below levels with Danian vertebrates such as the fish *Coelodus laurenti* and  
650 the mammal *Hainina pyrenaica* (De la Peña and Soler-Gijón, 1996; Peláez-Campomanes et al.,  
651 2000), and above levels with dinosaur fossils (López-Martínez et al., 1998 and 1999;  
652 Casanovas et al., 1999). Nevertheless, the isotope record is a problematic chronostratigraphic  
653 marker since it provides no age. Moreover, frequent transitional environments may have altered  
654 the isotope signal.

655 According to the planktonic foraminifera assemblages identified in this work, the K/Pg boundary  
656 lies between the layers from which samples LRU493.8 (Lower Red Unit) and SL495.3  
657 (Suterranya Limestone) were collected. Thus, in the studied section, the K/Pg boundary might  
658 be placed between the Lower Red Unit and the base of the Suterranya Limestone, although the  
659 significant hiatus leaves us with no sign of the K-Pg transition nor indeed of any record of most  
660 of the Danian. It is likely, therefore, that there is no physical K/Pg boundary to be found.

661

## 662 **6. *IN SITU* PLANKTONIC FORAMINIFERA: THE ROLE OF TIDES**

663

664 The petrographic analysis suggested that most of the marine bioclasts could be considered *in*  
665 *situ*. However, *in situ* specimens can be allochthonous or autochthonous. The present work  
666 focused on the analysis of planktonic foraminifera, since these provided evidence for both  
667 biostratigraphic and palaeoenvironmental reconstructions. The observation under CL  
668 microscopy of similar cements filling both the interparticle porosity and the intraparticle porosity  
669 of planktonic foraminifera (Figs. 8 and 9) implies that, if they were reworked, these organisms  
670 were deposited after erosion without being cemented. Such preservation is unusual given the  
671 fragility of foraminiferal tests (Herrero and Canales, 2002).

672 The presence in the studied section of *in situ* planktonic foraminifera - inhabitants of open, fully-  
673 marine areas - must be understood as evidence of allochthony *sensu* Kidwell et al. (1986).

674 These organisms must have appeared in the study area by their landward transport after death.

675 The landward transport of foraminifera tests has commonly been overlooked in

676 palaeoecological studies, but there are both recent (Murray et al., 1982; Wang and Chappell,

677 2001) and ancient examples (Holcová, 1996; Murray, 2006) of this process. Murray et al.

678 (1982), who collected samples of foraminifera in the water column of the western English

679 Channel, reported their samples to be very rich in dead outer-shelf foraminifera that must have

680 been brought to the coast by tides, waves and storms. The small, globular planktonic

681 foraminifera in the Tremp Fm deposits were probably transported as a suspended load from the

682 open sea towards the land by currents. However, transport by wind cannot be ruled out since

683 foraminifera have been observed in recent aeolian dunes (Goudie and Sperling, 1977; Murray,

684 2009).

685 In the Lower Red Unit, the great abundance and diversity of planktonic foraminifera in the point  
686 bars and mudflats close to the meander belts, plus with lesser development of palaeosols,  
687 suggests the transport of foraminifera through the channels. The importance of these processes  
688 has been documented in the recent macrotidal South Alligator River in Australia where the  
689 influence of the tide reaches 80 km landwards. Here, small foraminifera prone to float can be  
690 collected along the entire length of the tide-influenced channel (Wang and Chappell, 2001). The  
691 latter authors cite similar situations for the Yangtse and Qiangtan Rivers (Asia), the Elbe and  
692 Ems Rivers (Europe), and the Daly River (Australia). The flat shape of the red algae and  
693 echinoderm fragments would also allow these bioclasts to float.

694

695 In palaeogeographic terms, the ancient tide-influenced meandering channels may have been  
696 part of a multiple channel system (Schumm, 1977) filling the synorogenic Tremp syncline (Fig.  
697 1a). The source area of the meandering channels would be the synsedimentary Sant Cornelli  
698 anticline (Fig. 1a), as indicated by the extrabasinal origin of the clasts (Nagtegaal et al., 1983)  
699 and the presence of *ex situ* Santonian planktonic foraminifera in the studied deposits (Santonian  
700 rocks outcrop in the Sant Cornelli anticline [Roca and Miranda, 2010, p. 228-229]).

701 The stratigraphic succession of the Lower Red Unit shows an upwards progradational trend and  
702 consequently a regressive shoreline is inferred. The progradational trend is indicated by the  
703 upwards reduction in the quantity of glauconite and marine fossils, and the increase in  
704 pedogenic features. This supports the interpretation of the deposits of the Lower Red Unit as a  
705 mixed-energy zone of a tide-dominated delta (Dalrymple and Choi, 2007). This setting  
706 developed during the early-late Maastrichtian when delta deposits of the Tremp area were  
707 laterally related to shallow marine environments in the western area of Campo (Fig. 1a), where,  
708 in addition, a progradational trend has been deduced (Baceta et al., 2004). This progradational  
709 stage was followed by two retrogradational stages, the last occurring during the late Danian  
710 (Baceta et al., 2004; Baceta et al., 2005; López-Martínez et al., 2006). In the study area, the last  
711 retrogradational unit would correspond to the deposits of the Suterranya Limestone.

712 The wide development of transitional conditions in the late Cretaceous-early Paleogene  
713 palaeoenvironments of the South-Central Pyrenees may be associated with the epeiric nature  
714 of the seas of the Cretaceous, small sea level fluctuations of which would have affected large



715 areas landwards. Thus, transitional environments may be more widespread in the Tremp Fm  
716 than previously thought.

717

## 718 **9. CONCLUDING REMARKS**

719

720 The lower Tremp Fm records deposits of a shallow, lagoonal environment (Grey Unit), a tide-  
721 dominated delta (Lower Red Unit), and coastal lakes (Suterranya Limestone), where *in situ* and  
722 allochthonous planktonic foraminifera were deposited after being transported landwards from  
723 the outer/inner shelf. In the Lower Red Unit in particular, foraminifera were mainly transported  
724 landwards via the meandering channels by tidal currents, as recorded in many macrotidally-  
725 influenced recent rivers. However, transportation by the wind and/or storm induced currents  
726 cannot be ruled out.

727 *In situ* assemblages indicate an early to late Maastrichtian age for the Grey Unit and the Lower  
728 Red Unit of the Tremp Fm. The planktonic foraminifera assemblage in the Suterranya  
729 Limestone, however, indicates this to be of late Danian age.

730 The K/Pg boundary might be located at the top of the Lower Red Unit or not be there at all since  
731 there is a hiatus of at least 4 Ma between the top of the Lower Red Unit and the overlying  
732 Suterranya Limestone.

733 In palaeogeographic terms, the stratigraphic succession and vertical evolution of the lower  
734 Tremp Fm correlates with that observed in the western foreland basin of South-Central  
735 Pyrenees for early Maastrichtian to late Danian times.

736

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738

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749

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- 1061

1062 **Appendix 1: Taxonomic notes**

1063 *Pseudoguembelina hariaensis* was defined by Nederbragt (1991) as a heterohelcid with test  
1064 biserial throughout or followed by one or two, rarely more, sets of small multiserial chamberlets.  
1065 While lacking accessory apertures, Nederbragt included this species within *Pseudoguembelina*,  
1066 given its suspected phylogenetic relation with *Pseudoguembelina palpebra* Brönnimann and  
1067 Brown 1953 from which it differs “by having thinner costae, less inflated chambers, more sets of  
1068 multiserial chamberlets, and no accessory apertures”. The specimen in Figure 11.2a-b (sample  
1069 LRU84.9), named *Pseudoguembelina* aff. *hariaensis*, is very similar to the paratype for *P.*  
1070 *hariaensis* reported by Nederbragt (1991, Figure 1, Plate 9) but differs from it and from *P.*  
1071 *palpebra* by the presence of accessory apertures covered by an eye-shaped lip directed away  
1072 from the median suture.

- 1073 **Appendix 2: List of planktonic foraminifera**
- 1074 *Acarinina hansbollii* (Blow and Banner, 1962)
- 1075 *Acarinina praeangulata* Blow, 1979
- 1076 *Acarinina praecursoria* Morozova, 1957
- 1077 *Acarinina praepentacamerata* (Shutskaya, 1956)
- 1078 *Acarinina trinidadensis* (Bolli, 1957)
- 1079 *Acarinina triplex* Subbotina, 1953
- 1080 *Archaeoglobigerina blowi* Pessagno, 1967
- 1081 *Archaeoglobigerina cretacea* (d'Orbigny, 1840)
- 1082 *Chiloguembelina subcylindrica* Beckmann, 1957
- 1083 *Contusotruncana fornicata* (Plummer, 1931)
- 1084 *Contusotruncana plummerae* (Gandolfi, 1955)
- 1085 *Contusotruncana patelliformis* (Gandolfi, 1955)
- 1086 *Contusotruncana plummerae* (Gandolfi, 1955)
- 1087 *Globanomalina compressa* (Plummer, 1926)
- 1088 *Globanomalina haunsbergensis* (Gohrbandt, 1963)
- 1089 *Globigerinelloides bollii* (Pessagno, 1967)
- 1090 *Globigerinelloides multispina* (Lalicker, 1948)
- 1091 *Globigerinelloides praeriehillensis* (Pessagno, 1967)
- 1092 *Globigerinelloides rosebudensis* Smith and Pessagno, 1973
- 1093 *Globigerinelloides volutus* (White, 1928)
- 1094 *Globigerinelloides yaucoensis* (Pessagno, 1960)
- 1095 *Globotruncana aegyptiaca* Nakkady, 1950
- 1096 *Globotruncana arca* (Cushman, 1926)
- 1097 *Globotruncana bulloides* Vogler, 1941
- 1098 *Globotruncana linneiana* (d'Orbigny, 1839)
- 1099 *Globotruncana mariei* Banner and Blow, 1960
- 1100 *Globotruncana orientalis* El Naggari, 1966
- 1101 *Globotruncana ventricosa* White, 1928
- 1102 *Globotruncanella havanensis* (Voorwijk, 1937)

- 1103 *Globo truncanella minuta* Caron and González Donoso, 1984
- 1104 *Globo truncanella pschadae* (Keller, 1946)
- 1105 *Globo truncanella petaloidea* (Gandolfi, 1955)
- 1106 *Globo truncanita fareedi* (El Naggar, 1966)
- 1107 *Globo truncanita stuartiformis* (Dalbiez, 1955)
- 1108 *Gublerina acuta* de Klash, 1953
- 1109 *Guembelitra blowi* Arz, Arenillas and Nájuez, 2010
- 1110 *Guembelitra cretacea* Cushman, 1933
- 1111 *Hedbergella faldrini* Porthault, 1970
- 1112 *Hedbergella holmdelensis* Olsson, 1964
- 1113 *Hedbergella monmouthensis* (Olsson, 1960)
- 1114 *Hedbergella planispira* (Tappan, 1940)
- 1115 *Hedbergella simplex* (Morrow, 1934)
- 1116 *Heterohelix glabrans* (Cushman, 1938)
- 1117 *Heterohelix globulosa* (Ehrenberg, 1840)
- 1118 *Heterohelix labellosa* Nederbragt, 1991
- 1119 *Heterohelix navarroensis* (Loeblich, 1951)
- 1120 *Heterohelix planata* (Cushman, 1938)
- 1121 *Heterohelix pulchra* (Brotzen, 1936)
- 1122 *Morozovella angulata* (White, 1928)
- 1123 *Morozovella simulatilis* (Schwager, 1883)
- 1124 *Parasubbotina quadrilocula* (Blow, 1979)
- 1125 *Parasubbotina pseudobulloides* (Plummer, 1926)
- 1126 *Parasubbotina varianta* (Subbotina, 1953)
- 1127 *Planoglobulina acervulinoidea* (Egger, 1899)
- 1128 *Planoglobulina riograndensis* (Martin, 1972)
- 1129 *Praemurica inconstans* (Subbotina, 1953)
- 1130 *Pseudoguembelina* aff. *hariaensis*
- 1131 *Pseudoguembelina costulata* (Cushman, 1938)
- 1132 *Pseudoguembelina kempensis* Esker, 1968

- 1133 *Pseudotextularia nuttalli* (Voorwijk, 1937)  
1134 *Rugoglobigerina rugosa* (Plumier, 1926)  
1135 *Sigalia deflaensis* (Sigal, 1952)  
1136 *Subbotina compressaformis* (Khalilov, 1956)  
1137 *Subbotina triloculinooides* (Plummer, 1926)  
1138 *Ventilabrella eggery* (Cushman, 1928)  
1139 *Whiteinella baltica* Douglas y Rankin, 1969  
1140 *Whiteinella paradubia* (Sigal, 1952)  
1141  
1142



1143 **Figure 1:** a) Map of the eastern South-Central Pyrenees, showing the position of this area in  
1144 the Iberian Peninsula, and the exact location of the studied area (square). Note the location of  
1145 the Tremp syncline (Tremp-Graus Basin) and its margins, the Sant Cornelli anticline, the Boixols  
1146 Range and the Montsec Range. The asterisk indicates the location of Upper Cretaceous-Lower  
1147 Paleogene shallow-deep marine deposits. b) Geological map of the study area. The black  
1148 arrows point out the base and top of the composite stratigraphic section in Figure 2.

1149

1150 **Figure 2:** Composite stratigraphic section of the studied outcrops (see Fig. 1b for location),  
1151 Letters a, b, c and d correspond to detailed logs of palaeochannel deposits. Facies  
1152 associations: (A) greyish marl and interbedded limestone, (B) non-channelized sandy-marly  
1153 limestone (C), palaeochannel deposits and (D) bioclastic and brecciated limestone.

1154

1155 **Figure 3:** Sedimentological and palaeontological features of the Grey Unit. a) Field photograph  
1156 of the greyish marl (M) showing carbonate horizons formed by the accumulation of carbonate  
1157 nodules (C). Note the limestone layer (L) located at the base of the section. b) Planktonic  
1158 foraminifera in a limestone layer under transmitted light microscopy, sample GU21.7. c)  
1159 Limestone under transmitted light microscopy, sample GU21.7. Note the benthonic foraminifera  
1160 (BF), ostracods (O) and gastropods (G).

1161

1162 **Figure 4:** Palaeochannel deposits. a) Adjoined point bar bodies interbedded with sandy-marly  
1163 limestone; detailed view (left), and a synthetic stratigraphic section (right) of two point bar  
1164 bodies (PB 1 and PB 2) separated by a reactivation surface (RS) and showing IHS. Note the  
1165 onlap of PB 2 on the reactivation surface. b) IHS of a point bar body (white arrows). c) Flaser  
1166 bedding within the IHS. d) Burrowing and mottling affecting the whole of the point bar deposits.  
1167 e) Root traces and mottling towards the upper part of the Lower Red Unit.

1168

1169 **Figure 5:** Hybrid arenite of the point bar deposits under transmitted (top) and polarized (bottom)  
1170 light microscopy (sample LRU73.6). The sample is composed of lithoclasts (Lt), quartz (Q),  
1171 bivalve fragments (B), planktonic foraminifera (PF), calcispheres (Ca) and glauconite (Gl).

1172

1173 **Figure 6:** a) Field photograph of the yellowish and reddish sandy-marly limestone. b) Intense  
1174 burrowing and mottling of yellowish facies SML 1. c) Carbonate nodules of reddish facies SML  
1175 2. d) Detail of glauconite (G) found in lenticular bedding preserved in facies SML1. Note that the  
1176 glauconite has precipitated within a small fracture (black arrow) (sample LRU68.8). d) Bivalve  
1177 fragments (B) and foraminifera (F) in the sandy-marly limestone (sample LRU112.0). Images d)  
1178 and e) were taken under a transmitted light microscope.

1179

1180 **Figure 7:** Suterranya Limestone. a) Field photograph. b) Transmitted light photomicrograph.  
1181 Packstone (sample SL495.3) of planktonic foraminifera (PF), fragments of dasycladal algae  
1182 (Ds), and calcispheres (Ca). Note the abundance of intraclasts, particularly pelloids. c) Detail of  
1183 a planktonic foraminifer under transmitted light microscopy, sample SL495.3.

1184

1185 **Figure 8:** Photomicrographs of hybrid arenite from the Lower Red Unit. a) Transmitted light  
1186 (top) and CL (bottom) photomicrographs of a hybrid arenite containing calcispheres (Ca),  
1187 planktonic foraminifera (PF) and benthonic foraminifera (BF). Calcite cement precipitated in the  
1188 intrabioclast porosity of the calcispheres and the foraminifera. Some of the bioclasts (black  
1189 arrows) show a dark brownish luminescence that differs from the bright orange of the cement  
1190 precipitated in the interparticle porosity. Note that the brownish cement filling one of the  
1191 calcispheres (number 1) is broken and eroded. However, the intraparticle cement that  
1192 precipitated in some of the planktonic foraminifera (white arrows) has the same bright orange  
1193 luminescence as that in the interparticle porosity, indicating that these foraminifera were  
1194 uncemented during deposition. Note that this cement is even present in the pores of the test  
1195 since it is seen in the foraminifer identified as *Hedbergella monmouthensis* (number 2), sample  
1196 LRU95.4. b) *Globotruncana* sp. showing cement in its chamber porosity identical to the  
1197 surrounding interparticle cement (above, under transmitted light, and below, under CL), sample  
1198 LRU73.6, planktonic foraminifera (PF). c) Some images captured under transmitted light (left),  
1199 polarized light (centre) and under CL (right) (sample LRU395). Echinoderm fragments (Eq) and  
1200 intraclasts (Ic) in hybrid arenite. Syntaxial cement (1) precipitated around echinoderm fragments  
1201 and sparitic cement (2) precipitated around lithoclasts fill the interparticle porosity. Note that the

1202 CL pattern (the brownish-orange area) is identical in both the syntaxial (1) and sparitic cement  
1203 (2).

1204

1205 **Figure 9:** Photomicrographs of the Suterranya Limestone. a) Planktonic foraminifera (PF) under  
1206 transmitted light (above) and under CL (below). Note that the CL pattern of the calcite cement  
1207 precipitated in both the intraparticle (PF) and interparticle porosities (Po) is dark brownish and  
1208 identical in both cases (sample SL495.3). b) Bioclasts of the same sample (SL495.6) under  
1209 transmitted light (above) and under CL (below). Charophyte (Ch) and planktonic foraminifera  
1210 (PF) show an identical CL pattern (orange to brownish) for their intrabioclast cements.

1211

1212 **Figure 10:** Biozones inferred from planktonic foraminiferal species collected in the lower Tremp  
1213 Fm (Grey Unit, Lower Red Unit and Suterranya Limestone). Red circles indicate species older  
1214 than the Maastrichtian (reworked). Green circles are species exclusively Maastrichtian. Red  
1215 asterisks indicate levels with evidence of non-reworked planktonic foraminifera assemblages.

1216

1217 **Figure 11:** Upper Cretaceous planktonic foraminifera species identified in the Grey and Lower  
1218 Red Units (Scale bar = 100  $\mu$ m): 1a-b: *Psg. kempensis* Esker, 1968, sample LRU84.9. 2a-b:  
1219 *Psg. aff. hariaensis*, sample LRU84.9. 3: *Pl. acervulinoides* (Egger, 1899), sample LRU339.3. 4:  
1220 *Pl. riograndensis* (Martin, 1972), sample LRU339.3. 5a-b: *Htx. labellosa* Nederbragt, 1991,  
1221 sample GU39.1. 6a-c: *Gella. minuta* Caron and González Donoso, 1984, sample LRU268.8. 7a-  
1222 b: *Gdes. prairiehillensis* (Pessagno, 1967), sample LRU363.9. 8a-c: *Gella. havanensis*  
1223 (Voorwijk, 1937), sample LRU105.1. 9a-c: *Gna. arca* (Cushman, 1926), sample LRU257. 10a-c:  
1224 *Gna. aegyptiaca* Nakkady, 1950, sample LRU105.1. 11a-c: *Gna. linneiana* (d'Orbigny, 1839),  
1225 sample LRU339.3. 12a-c: *Gna. bulloides* Vogler, 1941, sample LRU339.3. 13a-c: *C. fornicata*  
1226 (Plummer, 1931), sample LRU105.1. 14a-b: *S. deflaensis* (Sigal, 1952), sample LRU261.4. 15a-  
1227 c: *W. paradubia* (Sigal, 1952), sample LRU39.1. 16a-c: *Hd. simplex* (Morrow, 1934), sample  
1228 LRU493.8.

1229

1230 **Figure 12:** Paleocene planktonic foraminifera identified in the Suterranya Limestone (Scale bar  
1231 = 100  $\mu$ m): 1a-c: *P. pseudobulloides* (Plummer, 1926), sample SL495.3. 2a-c: *Pr. inconstans*

1232 (Subbotina, 1953), sample SL495.3. 3a-c: *Ac. trinidadensis* (Bolli, 1957), sample SL497.9. 4a-c:  
1233 *Ac. praepentacamerata* (Shutskaya, 1956) (also known as *Ac. praeangulata* Blow, 1979),  
1234 sample SL495.3. 5a-c: *Sb. triloculinoides* (Plummer, 1926), sample SL495.3. 6a-c: *M. simulatilis*  
1235 (Schwager, 1883) (also known as *M. angulata* [White, 1928]), sample SL495.3.

1236

1237 **Table 1:** Distribution of planktonic foraminifera in the studied section. The planktonic  
1238 foraminiferal richness was calculated excluding those species that became extinct prior to the  
1239 Maastrichtian. Relative abundances for planktonic foraminifera in the samples are indicated  
1240 according to the following scale: A (abundant); C (common); F (scarce) and R (rare).

1241

1242