1   **Constraints of applying strontium isotope stratigraphy in coastal and shallow marine**

2   **carbonates: insights from Lower Cretaceous carbonates deposited in an active tectonic**

3   **setting (N Iberian Basin, Spain).**

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Abstract

The Lower Cretaceous Leza Fm is an essentially carbonate unit deposited at the northernmost active margin of the Cameros Basin (N Spain) under an extensional tectonic regime. This unit is composed of freshwater, marine-influenced, marginal-marine and hypersaline marine carbonate facies, interbedded with variable amounts of alluvial deposits, mainly derived from the erosion of the Jurassic substrate. $^{87}Sr/^{86}Sr$, $\delta^{18}O$ and $\delta^{13}C$ analyses were obtained from carbonate facies of the Eastern and Western sectors of the basin. $\delta^{18}O$ values follow the expected trend in both sectors: they are more negative (down to -7.9‰) in freshwater carbonates and more positive (up to +2.8‰) in marginal-marine to hypersaline facies. However, independently of the seawater or freshwater influence, in the Western Sector the $^{87}Sr/^{86}Sr$ values (0.707373-0.707801) are significantly lower and closer to the published Lower Cretaceous seawater $^{87}Sr/^{86}Sr$ ratios, than those of the Eastern Sector (0.707988-0.709033), where the overall marine influence was relatively high and the alluvial input low. These data strongly suggest that $^{87}Sr/^{86}Sr$ ratios were mainly controlled by those of the riverine freshwater arriving to the coastal and marine areas after the weathering and erosion of the Jurassic carbonates or siliciclastic rocks, in the Western and Eastern sectors, respectively. Thus, data indicate that, in coastal and shallow marine carbonates the influence of the riverine water on the $^{87}Sr/^{86}Sr$ ratios should be systematically evaluated. This is particularly necessary in active tectonic settings, where the uplifted areas are significantly prone to weathering and erosion and where alluvial fan systems commonly developed, eventually discharging into coastal and shallow marine areas.

Keywords: Cameros Basin, coastal wetlands, carbon and oxygen isotopes, water-rock interaction

Resumen

La Formación Leza es una unidad esencialmente carbonática del Cretácico Inferior depositada en el borde norte de la cuenca de Cameros (N de España) en un contexto tectónico extensional. Está formada por facies carbonáticas de agua dulce, con influencia marina, marinas marginales e hipersalinas, intercaladas con cantidades variables de depósitos aluviales, procedentes de la erosión del sustrato Jurásico de la cuenca. Se han obtenido datos de $^{87}Sr/^{86}Sr$, $\delta^{18}O$ y $\delta^{13}C$ de las facies carbonáticas en las zonas Oriental y Occidental de la cuenca. Los valores de $\delta^{18}O$ siguen la tendencia esperable en ambas zonas: son más negativos (hasta-7.9‰) en los carbonatos de agua dulce y más positivos (hasta +2.8‰) en las facies marinas marginales e hipersalinas. Sin embargo, independientemente de la influencia marina o de agua dulce, los valores de $^{87}Sr/^{86}Sr$ de la zona Occidental (0.707373-0.707801) son significativamente inferiores y más próximos a los valores publicados para los carbonatos marinos del Cretácico Inferior, que los de la zona Oriental (0.707988-0.709033), donde la influencia marina fue, en general, relativamente mayor y el aporte aluvial menor. Estos resultados indican que las relaciones de $^{87}Sr/^{86}Sr$ estuvieron controladas principalmente por las del agua dulce fluvial que llegaba a la zonas costeras y marinas tras la meteorización y erosión del sustrato Jurásico de la cuenca, carbonático en el Sector Occidental y siliciclástico en el Oriental, y sugieren que, para la interpretación de las relaciones de $^{87}Sr/^{86}Sr$ en carbonatos costeros y marinos someros, sobre todo de aquéllos depositados en contextos tectónicamente activos, se debería evaluar sistemáticamente la influencia del agua dulce.

Palabras clave: Cuenca de Cameros, humedales costeros, isótopos de carbono y oxígeno, interacción agua-roca

1. Introduction

Strontium isotopes are commonly employed for dating and correlating marine carbonates and fossil shells based on the assumptions that the seawater $^{87}Sr/^{86}Sr$ ratios of the world´s oceans have changed through time, but they are, and have been, uniform for a given time (because its residence time is much greater than the time required for marine currents to mix waters) and that, in contrast to trace elements and C and O isotopes, there is no measurable fractionation of the Sr isotopes during precipitation of carbonates and fossil shells (Veizer and Compston 1974; Brass 1976; Burke et al. 1982; Banner 1995; Steuber and Veizer 2002; McArthur et al. 2012). Accordingly, many curves reflecting the $^{87}Sr/^{86}Sr$ variation of seawater through time have been published since the 70´s, and they have been progressively more detailed and based on a larger number of samples for a given period of time (e.g. Veizer and Compston,1974; Brass 1976; Burke et al. 1982; DePaolo and Ingram 1985; Koepnick et al. 1988; Jones et al. 1994; McArthur 1994; McArthur et al. 1994; 2001; 2007; 2012; Veizer et al. 1997; 1999; Jenkyns et al. 2002; Prokoph et al. 2008; Roveri et al. 2014; Korte and Ullmann 2016; Reghizzi et al. 2017; Wierzbowski et al. 2017). Based on those curves, the strontium isotope stratigraphy (SIS) has become a powerful tool, used for dating and correlating marine carbonate sequences (including deep to shallow and normal to restricted environments), as well as for estimating the duration of stratigraphic gaps, biozones or Stages, for constraining the age of condensed levels and as climatic indicator (e.g. DePaolo and Ingram 1985; Miller et al. 1988; Hess et al. 1989; McArthur et al. 1992; 1993, 2000; Brasier et al. 1996; Bralower et al. 1997; Barbieri et al. 1998; Weedon and Jenkyns 1999; Azmy et al. 1999; Scasso et al. 2001; Ebneth et al. 2001; Steuber 2001; Price and Grocke 2002; Nieto et al. 2008; Frijia and Parente 2008; Bodin et al. 2009; Lugli et al. 2010; Boix et al. 2011; Wehmiller et al. 2012; Williamson et al. 2012, Steuber and Schlüter 2012; Bonilla-Rodríguez et al. 2014, Frijia et al. 2015; Bover-Arnal et al. 2016; Caus et al. 2016; Zuo et al. 2018; Frau et al. 2018; Fan et al. 2020, among many others).

However, $^{87}Sr/^{86}Sr$ values of the riverine and lacustrine freshwater may vary significantly because they depend on the Sr isotopic values of the rocks that are being weathered and eroded and on their ^{87}Rb content, commonly high in silicate rocks, which, after its decay to ^{87}Sr, will significantly increase the $^{87}Sr/^{86}Sr$ ratio (Faure 1977; Stueber et al. 1984; Banner 1995).

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92   Because of that, some authors have attempted to distinguish between marine and non-marine

93   environments based on the Sr isotopes (Schmitz et al. 1991; Hofer et al. 2013; Gierlowski-

94   Kordesch and Cassle, 2015), and many other authors have studied and analysed the

95   importance of fresh- and seawater mixing and its relevance on the $^{87}Sr/^{86}Sr$ values in coastal to

96   shallow marine areas, close to the mainland (Müller et al. 1990; Müller and Mueller 1991;

97   Ingram and Sloan 1992; Andersson et al. 1992; Bryant et al. 1995; Banner 1995; Flecker et al.

98   2002; Flecker and Ellam 2006; Lugli et al. 2010; Topper et al. 2011; Sessa et al. 2012; Topper

99   and Meijer 2013; Roveri et al. 2014; Quijada et al. 2016a; Manzi et al. 2018; Meknassi et al.,

100 2018; Roveri et al. 2019; Madhavaraju et al. 2020). In this sense, it has been argued by some

101 authors that the seawater $^{87}Sr/^{86}Sr$ ratio is rarely altered by freshwater inputs if salinities are

102 maintained above 10 to $20^0/_{00}$ (Ingram and Sloan 1992; Bryant et al. 1995; McArthur et al.

103 2012), although it has also been highlighted, even by the same authors, that small inputs of

104 riverine waters may have significant effects on the $^{87}Sr/^{86}Sr$ values of carbonate rocks and

105 shells, and that it would be wise to evaluate whether the local riverine inputs have altered the

106 seawater signals (Bryant et al. 1995; Banner 1995; McArthur et al. 2012; Meknassi et al., 2018)

107 when analysing Sr isotopic compositions in coastal and shallow marine carbonates and shells.

108   In this study, we have attempted to evaluate this issue by analysing carbonates of the

109 Leza Fm (Late Barremian-Early Aptian, Cameros Basin, N Spain), a coastal and essentially

110 carbonate unit, deposited in the context of the Mesozoic Iberian Extensional System (Fig. 1).

111 This unit is composed of freshwater, marine-influenced and marginal-marine carbonates,

112 restricted marine carbonates and evaporites, and alluvial detrital deposits that mainly derive

113 from the erosion of the uplifted Upper Jurassic substrate, which is essentially carbonate or

114 essentially siliciclastic, depending of the sector of the basin (Durántez et al. 1982; Alonso and

115 Mas 1990; Hernández-Samaniego et al. 1990; Ramirez Merino et al. 1990; Suarez-Gonzalez et

116 al. 2013; 2015). Thus, the main aim of this work is to evaluate the influence of the riverine

117 waters on the $^{87}Sr/^{86}Sr$ ratios of carbonates deposited in the different depositional environments

118 (from freshwater to marine and hypersaline) of the Leza Fm, and to evaluate the significance of

119 the $^{87}Sr/^{86}Sr$ ratios of the Jurassic substrate, weathered and eroded during deposition, in

120 affecting the seawater $^{87}Sr/^{86}Sr$ ratios.

121 **2. Geological setting and stratigraphic framework**

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122   The Cameros Basin is the northernmost basin of the Mesozoic Iberian Extensional

123   System (Fig. 1A-B). It was developed from the Tithonian to the Early Albian and records up to

124   6,500 m of vertical thickness of sediments (Mas et al. 2011; Omodeo-Salé et al. 2014; 2015;

125   Mas et al. in Martin-Chivelet et al. 2019). During the Eocene to Early Miocene, the Cameros

126   Basin was tectonically inverted, leading to the development of the thrusts that now limit the

127   Cameros structural unit to the north and south (Fig. 1B; Platt 1990; Casas-Sainz and Simón-

128   Gómez 1992; Salas and Casas, 1993; Mas et al. 1993; 2011; Guimerà et al. 1995; Salas et a.,

129   2011; Mas et al. in Martin-Chivelet et al., 2019).

130   The sedimentary record of the Cameros Basin comprises eight depositional sequences

131   (DS) (Mas et al. 2002; 2011; Arribas et al. 2003; Fig. 1C), and is characterised by the overall

132   and progressive migration of the depocenters of the successive DS to the N, which results in an

133   onlapping geometry observed between the successive units and the underlying Jurassic and,

134   locally Upper Triassic, substrate (Fig. 2A; Guiraud 1983; Mas et al. 1993; Suarez-Gonzalez et

135   al. 2013; 2016a; Omodeo-Salé et al. 2014; Mas et al. in Martin-Chivelet et al. 2019). In general,

136   the sedimentary record of the Cameros Basin is gently folded, and it is apparently unaffected by

137   relevant internal deformation (Guiraud 1983; Guiraud and Seguret 1985; Mas et al. 1993;

138   Omodeo-Salé et al. 2015); however, to the N and NE margins of the basin, where this study has

139   been carried out, it has been interpreted that syn-sedimentary normal faults controlled the

140   generation of the accommodation space and the thickness of some DS (Guiraud, 1983; Gómez-

141   Fernández 1992; Quijada et al. 2013a; Suarez-Gonzalez et al. 2013; 2015; 2016a; Omodeo-

142   Salé et al. 2014). Specifically, in the studied N and NE Cameros Basin, Suarez-Gonzalez et al.

143   (2016a) have interpreted that small fault-limited tectonic depressions were formed during the

144   Late Barremian-Early Aptian due to the interaction of the general extensional direction (mainly

145   N-S) with the late-Variscan structure of the basement. Additionally, the irregular distribution of

146   the Triassic evaporites (Keuper Facies), and its association with the onlap geometry of DS 1–7

147   onto the Jurassic substrate and even onto the Keuper Facies (Fig. 2A), led Suárez-González et

148   al. (2016a) to interpret a probable role of salt-tectonics on the sedimentation at the northern part

149   of the basin.

150   The sedimentary infill of the basin includes continental and coastal siliciclastic,

151   carbonate and evaporite deposits (Fig. 1C). In general, facies distribution along the basin shows

152 a proximal-distal trend: proximal continental and detrital facies are located to the W and SW; the

153 distal facies, comprising coastal carbonates, mixed carbonate-siliciclastic or mixed carbonate-

154 evaporite deposits, are located to the E and NE of the basin (Mas et al. 1993; 2002; 2011; 2019;

155 Arribas et al. 2003; Quijada et al. 2013a, 2013b; 2014; 2016b; 2020; Suarez-Gonzalez et al.

156 2013; 2014; 2015; Sacristán-Horcajada et al. 2015; 2016).

157   The syn-extensional record in the studied area, located at the northern and north-

158 eastern margin of the Cameros Basin (Figs. 1B; 2A), comprises deposits of the Urbión and

159 Enciso Groups (DS7; Late Barremian-Early Aptian in age) and of the Oliván Group (DS8; Late

160 Aptian-Early Albian in age) (Figs. 1B-C; 2A; Mas et al. 1993; 2002; 2011;; Suarez-Gonzalez et

161 al 2013; 2015; 2016b; Mas et al., in Martin-Chivelet et al. 2019). The Urbión Group is

162 represented in the studied area by deposits of the Jubera Fm (Figs. 1C; 2A-B), which is

163 composed of reddish conglomerate, sandstone and siliciclastic mudstone (*sensu* Friedman et

164 al., 1992) and is interpreted as deposited in alluvial fan systems (Alonso and Mas 1993; Mas et

165 al. 2002; 2011; Ochoa 2006; Suárez-González et al. 2013). The Enciso Group overlies and

166 passes laterally to the Urbión Group (Fig. 1C). In the studied area, the lower part of the Enciso

167 Group is represented by the Leza Fm, which overlies and passes laterally to the Jubera Fm,

168 and is the focus of this study (Figs. 1C; 2A-B). The Leza Fm is essentially composed of

169 carbonates, with variable marine influence and content of detrital deposits, and is interpreted as

170 deposited in a coastal-wetland system (Suarez-Gonzalez et al. 2013; 2015). The rest of the

171 Enciso Group, which overlie and pass laterally to deposits of the Leza Fm (Figs. 1C; 2A-B), is

172 composed of mixed carbonate-siliciclastic deposits interpreted as deposited in siliciclastic-

173 influenced lacustrine and palustrine systems (Mas et al. 1993; 2002; 2011). The Oliván Group is

174 composed of reddish to greenish sandstone and siliciclastic mudstone deposited in fluvial and

175 coastal systems (Mas et al. 2011; Mas et al., in Martin-Chivelet et al. 2019).

176   A relevant feature of the Jubera and Leza Fms is that their deposits show significant

177 variations in their thickness, as they were deposited in the above-mentioned small tectonic

178 depressions formed during the Late Barremian – Early Aptian by faulting of the basin substrate

179 (Fig. 2A-B; Alonso and Mas 1993; Suarez-Gonzalez et al. 2013; 2015; 2016a). The substrate of

180 the Cameros Basin is mainly composed of Jurassic, and locally Upper Triassic, rocks (Fig. 2A,

181 see below for details), which underlie syn-extensional deposits through an important

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182   unconformity (Alonso and Mas 1993; Mas et al. 1993; 2002; 2011; Benito et al., 2001; 2005;

183   Benito and Mas, 2002; 2006). Erosion of the faulted substrate led to deposition of alluvial fan

184   sediments throughout the Jubera Fm; in the Leza Fm, alluvial fan deposits were restricted to the

185   margins of the depressions, and they changed laterally to carbonate coastal wetland sediments

186   (Fig. 3; Suarez-Gonzalez et al. 2013; 2015). This coastal wetland system was composed of a

187   mosaic of diverse and interrelated environments with influence of both fresh- and sea-water, the

188   latter coming both from the North, from the Boreal Realm, and the South, from the Tethys Sea

189   (Fig. 3; Suarez-Gonzalez et al., 2013).

190   Two main sectors are distinguished in the studied area, the Western and the Eastern

191   (Figs. 2-3), which have important differences in the sedimentary features of both the Jurassic

192   substrate and the syn-extensional Jubera and Leza Fms.

193   In the Western Sector, the substrate of the Jubera-Leza Fms comprises Upper Triassic

194   to Upper Jurassic rocks (Fig. 2A-B; Suarez-Gonzalez et al. 2013; 2015; 2016a). The Triassic is

195   composed of the Keuper Facies, which includes evaporites (gypsum), reddish siliciclastic

196   mudstone and minor dolostone (Fig. 2A; Suarez-Gonzalez 2015; Suárez-González et al.,

197   2016a). The Keuper facies are largely deformed, and their thickness varies significantly along

198   the northern Cameros thrust (Fig. 2A). The Lower Jurassic is composed of approximately 150-

199   200 m-thick marine limestone and/or dolostone, which were deposited in shallow to very

200   shallow carbonate platforms (Mensink 1966; Bulard 1972; Ramírez-Merino et al. 1990;

201   Hernández-Samaniego et al. 1990). The Middle Jurassic comprises approximately 300 m-thick

202   marine limestone, including a thick Bathonian sequence (up to 150 m thick) mainly composed of

203   oolitic deposits with minor siliciclastics, which were deposited in a shallow carbonate platform

204   (Benke 1981; Benke et al. 1981; Wilde 1990; Ramírez-Merino et al. 1990; Hernández-

205   Samaniego et al. 1990; García-Frank et al. 2008). The pre-extensional Upper Jurassic record

206   (Oxfordian and Kimmeridgian) is composed of relatively thin shallow marine units (down to less

207   than 50 m thick), which include abundant coral reef deposits of Kimmeridgian age and minor

208   siliciclastic marine deposits (Benke et al. 1981; Alonso and Mas 1988; 1990; Errenst 1990;

209   Benito and Mas 2006). The overlying syn-extensional sedimentary record of the Jubera and

210   Leza Fms in the Western Sector, although highly variable, reaches up to approximately 500 m

211   of thickness (Fig. 2B; Suarez-Gonzalez et al. 2013). In this sector, the detrital facies of both

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212   units are mainly composed of carbonate clasts coming from the erosion of the different units of

213   the Jurassic, mainly from the Bathonian to the Kimmeridgian units (Fig. 4A-B; Alonso and Mas

214   1993; Ochoa 2006; Suarez-Gonzalez et al. 2013; 2015); moreover, in the Western Sector the

215   overall detrital influence in the Leza Fm is higher than in the Eastern Sector (Suarez-Gonzalez

216   et al., 2015; see bellow and details in Section 4).

217   In the Eastern Sector, the substrate of the Jubera-Leza Fms is composed of Upper

218   Jurassic rocks (Figs. 2A-B; Suarez-Gonzalez et al. 2013; 2015). The Upper Triassic Keuper

219   Facies (which include very scarce and local outcrops of volcanic to subvolcanic rocks, less than

220   0.01 Km^2) and the Lower and Middle Jurassic carbonate rocks are also observed in this sector,

221   but they do not directly underlie the syn-extensional sedimentary record (Fig. 2A; Suarez-

222   Gonzalez et al., 2016a) and, thus, they probably they did not crop out during sedimentation of

223   the Jubera and Leza Fms. In the Eastern Sector, deposits from the Upper Triassic to the

224   Bathonian are equivalent to those observed in the Western Sector (Mensink 1966; Bulard 1972;

225   Durántez et al. 1982; Hernández-Samaniego et al. 1990). However, and in contrast to what is

226   observed in the Western Sector, in the Eastern Sector the Callovian to Kimmeridgian

227   sedimentary record is mainly composed of marine sandy limestone, sandstone and quartzite

228   conglomerates, which reach up to around 150 m (Benke 1981; Benke et al. 1981; Durántez et

229   al. 1982; Alonso and Mas 1988; 1990; Wilde 1990; Hernández-Samaniego et al. 1990; García-

230   Frank et al. 2008). The syn-extensional sedimentary record of the Jubera and Leza Fms in the

231   Eastern Sector, although also variable, is overall thinner (up to 300 m) than in the Western

232   Sector (Fig. 2B; Alonso and Mas 1993; Suarez-Gonzalez at al. 2013; 2015); moreover in the

233   Eastern Sector, detrital deposits of both the Jubera and Leza Fms came from the erosion of the

234   Callovian and the Upper Jurassic units, which are mainly composed of quartzite conglomerate

235   and sandstone, with minor detrital carbonate fraction (Fig. 4C-D; Suarez-Gonzalez et al. 2015).

236   Additionally, the overall detrital content of the Leza Fm deposits is lower in the Eastern Sector

237   than in the Western Sector (see details in Section 4).

238   **3. Materials and methods**

239   Two selected stratigraphic sections of the Leza Fm, one from the Eastern Sector of the

240   northern Cameros Basin (Préjano section), and another one from the Western Sector (the Leza

241   River section) have been used for this study (Figs. 2, 5). A total of 341 rock samples from the

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242   Leza Fm (214 limestone or marly limestone, 49 dolostone, 57 sandstone or sandy limestone, 21

243   conglomerate) were collected for laboratory studies (see Suarez-Gonzalez, 2015 for details

244   regarding the facies and samples). For each sample, a polished and uncovered thin section was

245   prepared to 30 μm thickness for petrographic analysis utilizing standard petrographic

246   techniques and cathodoluminescence petrography. For 75 samples, a polished 150-200 μm

247   thick section, matching the 30 μm thin section, was prepared for isotopic analyses.

248   Cathodoluminescence (CL) examination was carried out using a Technosyn® cold

249   cathodoluminescence unit operating at 20-25 kV with 300-400 μA beam current. Following

250   examination with CL, thin sections were stained with Alizarin Red S and potassium ferricyanide

251   (Dickson, 1966) for identification of carbonate minerals.

252   After petrographic examination and staining, well-preserved micritic or dolomicritic

253   samples (samples displaying mudstone to wackestone texture *sensu* Dunham, 1962), lacking

254   detrital input and petrographic evidence of diagenetic alteration, were selected for isotope

255   analyses and microsampled directly from thick sections using a microscope-mounted drilling

256   system, using 0.3 mm in diameter dental burs. When possible, approximately 20 mg of

257   powdered samples were obtained, from which 100-150 μg were used for C and O isotopic

258   analyses, and the rest for $^{87}Sr/^{86}Sr$ determinations.

259   62 analyses for $\delta^{13}C$ and $\delta^{18}O$ determinations were performed in the Stable Isotope

260   Laboratory at the University of Michigan. Sample powders reacted at 73 °C during 6 and 12

261   minutes (for calcite and dolomite, respectively) in an automated carbonate reaction system

262   (CarboKiel-IV) coupled directly to the inlet of a Thermo MAT 253 gas ratio mass spectrometer.

263   Isotopic ratios were corrected for ^{17}O contribution and are reported in per mil notation relative to

264   the VPDB standard. Values were calibrated utilizing NBS 19 as the primary standard, and

265   analytical precision was monitored by daily analysis of NBS powdered carbonate standards.

266   Precision was better than 0.1 ‰ for both $\delta^{13}C$ and $\delta^{18}O$ measurements.

267   58 $^{87}Sr/^{86}Sr$ ratios were determined on an automated multicollector TIMS-Phoenix®

268   mass spectrometer at the Geochronology and Isotope Geochemistry Centre of the

269   Complutense University of Madrid. Carbonate powder was dissolved in 5 ml of 0.5M acetic acid.

270   Once dried, 1 ml of 3M HNO_3 (Merk-Suparapur™) was added to the sample and dried again.

271   3ml of 3M HNO_3 (Merk-Suparapur^{TM}) were then added to the samples, which were

272   subsequently centrifuged at 4000 r.p.m. during 10 minutes, in order to eliminate the solid

273   residue (clay minerals, quartz, etc). For the Sr chromatographic separation, an extraction resin

274   SrResinTM (Trisken International) was employed. The Sr was recovered with 0.05M HNO_3 as

275   eluent. The fraction in which Sr was concentrated was recovered and dried for analysing in the

276   mass spectrometer. Sr analyses have been corrected for possible interference of ^{87}Rb and they

277   have been normalized to the value $^{88}Sr/^{86}Sr=0.1194$. Analytical precision was monitored by

278   analysis of the NBS 987 standard (the mean value obtained for 7 samples were 0.710247; $2\sigma=$

279   0.000008). Analytical uncertainties (referred to 2σ) were 0.01% for $^{87}Sr/^{86}Sr$ ratios. Blanks of Sr

280   preparations were lower than 0.05 ng/ml. The standard error for each sample was equal to or

281   lower than 3.

282   **4. Results: The sedimentary record and isotopes of the Leza Fm.**

283   The Leza Fm is a predominantly carbonate coastal unit, which has variable content of

284   detrital sediment and also shows a general trend of upwards increase in marine influence in

285   both the Eastern and Western sectors (Fig. 5; see detailed facies descriptions and

286   interpretations in Suarez-Gonzalez et al. 2013; 2014; 2015; 2016b; 2019). According to these

287   authors, tectonic activity caused significant variations in subsidence and thickness the unit

288   (which ranges from 20 m to 280 m) and in the lateral distribution of its facies, which include a

289   wide variety of interrelated deposits (Fig. 3), grouped into five facies associations (FA, Figs. 5-

290   6):

291   The alluvial fan FA is characterised by conglomerates and sandstones. As pointed out

292   above (Section 2), in both the Eastern and the Western sectors, the main components of these

293   facies are lithoclasts of the Middle and Upper Jurassic (Bathonian to Kimmeridgian) rocks of the

294   basin substrate, which are mainly marine sandstone and quartzite conglomerates with minor

295   limestone in the Eastern Sector, and marine limestone in the Western Sector (Fig. 4). Deposits

296   of the alluvial fan FA are interbedded with freshwater to shallow marine carbonate deposits and,

297   in the Eastern Sector, also with hypersaline marine dolostone, which are described below (Figs.

298   5-6).

299   The freshwater and the marine-influenced limestone FAs are both characterised by

300   black and fetid limestones and, less commonly, by marls, which are widespread in both sectors

301   (Figs. 5; 6A-D). Abundant biota is observed in both FAs, including charophytes (in the

302   freshwater FA; Fig. 6A-B), dasycladales (in the marine-influenced FA; Fig. 6C-D), ostracods,

303   gastropods and vertebrate remains. Microbialites (oncoids, skeletal stromatolites and

304   thrombolites) are also observed (Suarez-Gonzalez et al., 2019). Both freshwater and marine-

305   influenced limestone FAs are generally arranged in thickening-upwards sequences up to 4 m

306   thick, with abundant desiccation and edaphic features at their top (Figs. 5, 6A, C), and are

307   interpreted as deposited in shallow water-bodies with diverse salinities, from fresh to near-

308   marine, which underwent periods of desiccation and inundation, and were surrounded by

309   vegetated areas (Suarez-Gonzalez et al. 2015). Thus, both FAs are sedimentologically

310   equivalent, differing only in the influence of seawater and their palaeontological content.

311   Lithoclasts of Jurassic rocks may occur within these limestone beds, indicating lateral

312   association with the alluvial fan palaeoenvironments and suggesting that the source of

313   freshwater to the water bodies was related to the weathering and erosion of the Jurassic

314   substrate of the basin (Suarez-Gonzalez et al. 2013; 2015).

315   Regarding isotopic compositions, freshwater limestone yields $\delta^{18}O$ values of -7.9 to -

316   5.8‰ in the Eastern Sector and of -6.5 to -4.3 ‰ in the Western Sector; $\delta^{13}C$ values range

317   between -5.2 and -0.4‰ in the Eastern Sector and between -8.0 and -2.6‰ in the Western

318   Sector; $^{87}Sr/^{86}Sr$ ratios ranges between 0.708785 and 0.707988 in the Eastern Sector and

319   between 0.707373 and 0.707719 in the Western Sector (Figs. 5, 7; Table 1 of Supplementary

320   material).

321   Marine-influenced limestone yields $\delta^{18}O$ values of -5.4 to -5.6‰ in the Eastern Sector

322   and of -2.1 to -4.8‰ in the Western Sector; $\delta^{13}C$ values range between -1.7 and -5.9‰ in the

323   Eastern Sector and between -3.5 and –4.9‰ in the Western Sector; $^{87}Sr/^{86}Sr$ ratios in the

324   Western Sector range between 0.707597 and 0.707801 (Figs. 5, 7; Table 1 of Supplementary

325   material). It was not possible to obtain enough micritic carbonate powder for performing Sr

326   isotopes in thick sections of this FA in the Eastern Sector, because of the abundance of calcite

327   cement filling intra- and interparticle primary porosity, which could have altered the Sr isotopic

328   values of depositional (micritic) carbonate.

329   The marginal-marine carbonate FA (Fig. 6E-F) is characterised by grey limestone or

330   dolostone, which are slightly different in the Eastern and in the Western sectors. In the Eastern

331   Sector, these deposits are characterised by alternation of oolitic and micritic dolostone

332   containing abundant ostracods, miliolid foraminifers and agglutinated stromatolites (Suarez-

333   Gonzalez et al., 2014; 2016b; 2019), which displays flaser, wavy and lenticular bedding and

334   subaerial exposure features. In the Western Sector, this FA consists of grey limestone, either

335   bioclastic (containing ostracods, miliolid foraminifers and gastropods) or micritic, displaying

336   commonly fenestral porosity and desiccation features. Facies in both sectors are interpreted as

337   deposited in shallow marginal-marine areas affected by tides. This FA was dominated by

338   seawater, with salinities mostly higher than in the marine-influenced FA, but still probably

339   variable, temporarily decreasing due to freshwater influence (mainly in the Western Sector) or

340   increasing, due to evaporation (in the Eastern Sector, see next FA), which in turn, favored early

341   dolomite precipitation (Suarez-Gonzalez et al. 2014; 2015; 2016b; 2019), as observed in recent

342   coastal carbonate settings where syn-depositional dolomite commonly precipitates (e.g. Tucker

343   and Wright, 1990; Warren, 2016 and references therein).

344   In the Eastern Sector, marginal-marine dolostone of this FA yields $\delta^{18}O$ values of -1.3 to

345   +0.6‰, $\delta^{13}C$ values of -6.7 to -1.8‰ and $^{87}Sr/^{86}Sr$ ratios of 0.708302 to 0.708978. In the

346   Western Sector, marginal-marine limestone of this FA yields $\delta^{18}O$ values of -4.0 to -1.1‰, $\delta^{13}C$

347   values of -4.8 to -1.7‰ and $^{87}Sr/^{86}Sr$ ratios of 0.707679 to 0.707761 (Figs. 5, 7; Table 1 of

348   Supplementary material).

349   The hypersaline dolomite-evaporite FA (Fig. 6 G-H) is only observed in the Eastern

350   Sector, where it is laterally associated with deposits of the marginal-marine FA (Figs. 3; 5). This

351   FA is characterised by laminated dolomicritic deposits, containing rare ostracods and

352   foraminifers, abundant pseudomorphs after gypsum and anhydrite, desiccation features and,

353   locally, micritic-evaporitic stromatolites. The dolomite-evaporite FA is interpreted as deposited in

354   very shallow and restricted hypersaline marine areas, which reached high salinity through

355   evaporation (Suarez-Gonzalez et al. 2013; 2015; 2019).

356   Dolostone of this FA yields $\delta^{18}O$ values of -1.0 to +2.8‰, $\delta^{13}C$ values of -8.2 to -1.3‰

357   and $^{87}Sr/^{86}Sr$ ratios of 0.708304 to 0.709033 (Figs. 5, 7; Table 1 of Supplementary material).

5. Discussion: Constraints of applying strontium isotope stratigraphy in coastal and shallow marine carbonates

Isotopic data obtained from carbonates of the different FA of the Leza Fm in both studied sectors are apparently contradictory. As discussed below, the $\delta^{18}O$ values reflect the sedimentary palaeoenvironment and the nature of the waters from which they precipitated, however, the $^{87}Sr/^{86}Sr$ values reflect the strong influence of the riverine waters, which may have had a wide range of Sr isotope compositions, depending on the nature of rocks that were being weathered and eroded during deposition.

$\delta^{18}O$ values obtained from carbonates of the different FA, in both the Eastern and the Western sectors, are consistent with carbonate precipitation from fresh- to marine and even hypersaline waters. Freshwater limestone in both sectors shows the lowest $\delta^{18}O$ values. $\delta^{18}O$ values progressively increase in marine-influenced limestone, in marginal-marine limestone (in the Western Sector) and dolostone (in the Eastern Sector) and in hypersaline dolostone (Figs. 5, 7A-B). According to Prokoph et al. (2008), the oxygen isotopic composition of the Upper Barremian-Lower Aptian marine limestone and calcitic fossils deposited in low latitude (as that of the Iberian Plate for that time, e.g. Masse et al. 2000) ranged approximately between --2.8 and -0.4‰ (Figs. 5, 7A-B). In the case of the Leza Fm, $\delta^{18}O$ values of marginal-marine limestone of the Western Sector range between -4.0 and -1.1‰, which are close to or in the range of the published marine values by Prokoph et al. (2008) (Figs. 5, 7A-B). In the Eastern Sector, $\delta^{18}O$ values of marginal-marine dolostone range between -1.3 to +0.6‰, being heavier than those of the marginal-marine limestone of the Western Sector, but also mostly in the range of the published marine values (Fig. 7A-B). The heavier $\delta^{18}O$ values in dolostone (the mean $\delta^{18}O$ value of marginal marine dolostone is -0.31‰ whereas the mean $\delta^{18}O$ value of marginal marine limestone is -2.95‰; Table 1 of supplementary material) are consistent with the difference between the water-calcite and the water-dolomite fractionation factors for a given temperature, which results in dolomite $\delta^{18}O$ values of ~ 3‰ heavier than those of the calcite precipitating from the same water and at the same temperature (Fritz and Smith 1970; Friedmann and O'Neil 1977; McKenzie 1981; Tucker and Wright 1990; Arenas et al., 1997). Freshwater limestone, as expected, shows more negative $\delta^{18}O$ values, which are in the range of

387　carbonates precipitated from meteoric freshwater at low latitudes (e.g. Hudson 1977; Allan and

388　Matthews 1982; Lohmann 1987; James and Choquette 1990; Tucker and Wright 1990). Marine-

389　influenced limestone has $\delta^{18}O$ values ranging between the marine and freshwater limestones,

390　which would be derived from the mixing of sea- and freshwater at different proportions (e.g.

391　Frank and Lohmann 1995). Dolostone of hypersaline facies has the heaviest $\delta^{18}O$ values,

392　ranging from -1.0 to +2.8‰. These values are in the range of the $\delta^{18}O$ values obtained from

393　dolomites precipitated in Cenozoic and recent coastal sabkhas undergoing intense evaporation

394　(e.g. Tucker and Wright 1990; Arenas et al., 1997; Warren 2016, and references therein).

395　　　　　Regarding the C isotopic compositions, Prokoph et al. (2008) estimated $\delta^{13}C$ values

396　ranging approximately between +0.8 and +3.4‰ for marine limestone and calcitic fossils

397　deposited in low latitude during the Late Barremian-Early Aptian. $\delta^{13}C$ values of all analysed

398　carbonates of the Leza Fm, however, are largely variable and more negative than those

399　published for marine carbonates (Fig. 7A). This shift to lighter values would have been caused

400　by the incorporation of ^{12}C into calcite and dolomite, which could have derived from the

401　oxidation of organic matter, commonly soil-derived (Allan and Matthews 1977; 1982; Lohmann

402　1987; Tucker and Wright 1990; Leng and Marshall, 2004), and/or from bacterial sulphate

403　reduction, as observed in some modern coastal sabkhas (Tucker and Wright 1990; Warren

404　2016 and references therein). In fact, the combination of relatively invariant $\delta^{18}O$ values with

405　highly variable and negative $\delta^{13}C$ values is a common trend in meteoric or in transitional marine-

406　to-meteoric systems (Lohmann, 1987; James and Choquette, 1990).

407　　　　　$^{87}Sr/^{86}Sr$ ratios, as pointed out in the introduction, are commonly employed for dating

408　and correlating marine carbonates (strontium isotope stratigraphy, SIS; McArthur, 1994; Veizer

409　et al. 1997, 1999; Prokoph et al., 2008; McArthur et al., 2012, among many others) and,

410　according to published data (Jones et al., 1994; McArthur et al., 2001; 2012; Prokoph et al.,

411　2008), the $^{87}Sr/^{86}Sr$ values of Upper Barremian-Lower Aptian marine carbonates approximately

412　range between 0.7073 and 0.7075 (Figs. 5, 7C). However, and in contrast to what occurs with

413　the O isotopic compositions, $^{87}Sr/^{86}Sr$ data of the Leza Fm carbonates do not show the

414　expected trend according to their different depositional palaeoenvironments in none of the

415　studied sectors; moreover, the $^{87}Sr/^{86}Sr$ ratios obtained in the Eastern and Western sectors are

416   significantly different (Figs. 5, 7C). In the Eastern Sector, the $^{87}Sr/^{86}Sr$ ratios are higher (more

417   radiogenic) than those expected for Upper Barremian-Lower Aptian marine carbonates.

418   Additionally, it is also significative that all the analysed carbonates, regardless of their fresh-,

419   marine- or hypersaline-water origin, show similar range of $^{87}Sr/^{86}Sr$ values in each sector (more

420   radiogenic in the Eastern Sector and less radiogenic in the Western Sector), despite $\delta^{18}O$

421   values being different according to their depositional palaeoenvironments (Fig. 7B-C). It could

422   be argued that the Sr isotopic compositions, which are similar in all the carbonates of each

423   sector, but different in the Eastern and in the Western sectors (Figs. 5, 7C), could be derived

424   from diagenetic alteration. However, powder samples were carefully obtained from the areas of

425   thick sections of samples with no evidences of diagenetic alteration; furthermore, it is important

426   to note that, if the Sr isotopic ratios would have been altered by diagenetic fluids, changes in the

427   oxygen isotopic compositions would be also expected, because the $\delta^{18}O$ of carbonates depends

428   on the $\delta^{18}O$ of the waters from which they precipitate (a diagenetic fluid, if alteration had

429   occurred) and on temperature (e.g. Fritz and Smith 1970; Friedmann and O'Neil 1977; Banner

430   1995). However, the $\delta^{18}O$ values are in accordance with the different palaeoenvironmental

431   conditions where carbonates of the different FAs were formed, thus indicating the absence of

432   significant diagenetic modification of the original isotopic signature.

433   Therefore, it is interpreted that the Sr isotopic values of carbonates of the Leza Fm are

434   largely derived from $^{87}Sr/^{86}Sr$ compositions of the riverine freshwaters that discharged into the

435   coastal and shallow marine areas after weathering and eroding the faulted and exposed marine

436   Jurassic rocks of the substrate. In the Eastern Sector, the eroded Middle to Upper Jurassic

437   substrate, is mainly siliciclastic (e.g. Durántez et al. 1982; Hernández-Samaniego et al., 1990;

438   see Section 4 for detail). In this regard, riverine waters may have a wide range of $^{87}Sr/^{86}Sr$

439   values, but if they have weathered and eroded Rb-rich silicate rocks (such as granite, gneiss

440   and siliciclastic sedimentary rocks), their $^{87}Sr/^{86}Sr$ values are commonly higher than those

441   estimated for the Phanerozoic seawater (Faure 1977; Stueber et al. 1984; 1987; Banner 1995).

442   In that case, even small inputs of riverine waters into the sea may have significant effects on the

443    $^{87}Sr/^{86}Sr$ values of the resulting mixed water, which may increase significantly (Banner 1995,

444   Bryant et al. 1995; McArthur et al., 2012; Meknassi et al., 2018). Thus, in the Eastern Sector,

445   where essentially siliciclastic Jurassic rocks were being weathered and eroded, the more

446   radiogenic $^{87}Sr/^{86}Sr$ values of the riverine freshwater would have significantly contributed to

447   increase the marine $^{87}Sr/^{86}Sr$ values of carbonates of the Leza Fm, while the oxygen isotopic

448   compositions reflect their formation in the different freshwater to marine and hypersaline

449   depositional palaeoenvironments (Fig. 7B-C).

450   In the Western Sector, however, the $^{87}Sr/^{86}Sr$ values of freshwater to marginal-marine

451   limestone are lower and closer to the published data of the Upper Barremian-Lower Aptian

452   marine carbonates than those of the Eastern Sector, even though the overall marine influence

453   in the Western Sector was lower than in the Eastern Sector (Figs. 5, 7C). In fact, in the Western

454   Sector, the freshwater limestone shows $^{87}Sr/^{86}Sr$ values closer to the Upper Barremian-Lower

455   Aptian marine Sr isotopic values than those of the marginal-marine limestone, although the $\delta^{18}O$

456   values record the expected trend, consistent with their depositional environment (more negative

457   in freshwater than in marginal marine carbonates) (Figs. 5, 7B-C, see above). These

458   contradictory data may be explained if the following facts are considered: 1) in the Western

459   Sector, the substrate that was being eroded was mainly composed of Lower to Upper Jurassic

460   carbonates (e.g. Ramírez-Merino et al. 1990; Hernández-Samaniego et al. 1990; see section 4);

461   2) the $^{87}Sr/^{86}Sr$ ratios of the Jurassic marine carbonates range between ~ 0.7068 and ~0.7077

462   (Jones et al. 1994; MacArthur 2001; Prokoph et al. 2008; MacArthur et al. 2012); 3) the range of

463   the Jurassic Sr isotopic values, in turn, includes the range of $^{87}Sr/^{86}Sr$ values from the Late

464   Barremian to Early Aptian (Figs. 5, 7C). In this sense, and similarly to what occurs when

465   weathering Rb-rich silicate rocks, previous authors have interpreted that meteoric waters and

466   brines that interact with marine carbonates may inherit Sr isotope compositions that are

467   diagnostic of the age of the carbonates (e.g. Müller et al.1990; Müller and Mueller 1991; Banner

468   et al. 1994; Banner 1995). Thus, in the Western Sector, the riverine freshwater would have had

469   less radiogenic $^{87}Sr/^{86}Sr$ values compared to those in the Eastern Sector, because Jurassic

470   carbonates were being weathered and eroded, in contrast to the Eastern Sector, where the

471   Jurassic substrate was mainly siliciclastic. Thus, in the Western Sector, when riverine and

472   seawater mixed, both with similar Sr isotopic compositions, the resulting water would have

473   similar Sr isotope ratio than that of both end members, leading to freshwater and marine

474   carbonates having similar Sr isotopic ratios, but different $\delta^{18}O$ values, depending on their

475   depositional environment, and even leading to freshwater carbonates showing $^{87}Sr/^{86}Sr$ values

476   within the range of the Late Barremian-Early Aptian values (Figs. 5, 7B-C).

477   In this regard, Bryant et al. (1995) made a two-component mixing model to calculate the

478    $^{87}Sr/^{86}Sr$ of waters of different salinities and tested it with analyses performed in molluscs from

479   estuaries of the Mississippi Sound and coastal Florida. On the one hand, these authors found

480   out that both, their model results and analyses, suggested that even in the most marginal-

481   marine systems the freshwater flux did not have a measurable influence until the salinity was

482   very low (10 ppt or less), and these findings have been used for interpreting that "*when rivers*

483   *locally lower the salinity of seawater, marine $^{87}Sr/^{86}Sr$ is rarely altered at salinities above 20 psu*"

484   (McArthur et al. 2012; note that psu is equivalent to g/kg or $^{0}/_{00}$). Nevertheless, Bryant et al.

485   (1995) also pointed out that carbonates precipitating in estuarine settings not always record the

486   global marine $^{87}Sr/^{86}Sr$ value because, once the marine signature is affected by freshwater

487   input, $^{87}Sr/^{86}Sr$ seawater values change rapidly, leading McArthur et al. (2012) to highlight that

488   "*when dating coastal and shallow water faunas, it is wise to establish that the local riverine*

489   *inputs did not alter the $^{87}Sr/^{86}Sr$ of seawater in the depositional environment.*". More recently,

490   Meknassi et al. (2018) have analysed $^{87}Sr/^{86}Sr$ values from modern marine carbonate skeletons

491   (bivalves, gastropods, cephalopods, chitons, and calcifying algae) collected in coastal settings

492   worldwide and have found out that epibenthic and eurytopic organisms, such as bivalves and

493   gastropods, from coastal domains with water mass restriction, low salinity or strong continental

494   supplies, may display slight to considerable offsets compared to the $^{87}Sr/^{86}Sr$ values of modern

495   seawater. Based on their data, these authors calculated that "*only 10%, 33%, and 52% of the*

496   *published Phanerozoic $^{87}Sr/^{86}Sr$ curve can provide time calibration with respective accuracies of*

497   *±1, ±2 and ±3 m.y., hence obscuring most dating at the scale of the shorter Phanerozoic*

498   *stages*".

499   In the Leza Fm, our data strongly support that the $^{87}Sr/^{86}Sr$ ratios of all carbonates

500   (freshwater, marine-influenced, marginal-marine, and hypersaline) were, not only affected, but

501   mainly controlled by the Sr ratios of the riverine freshwater, which discharged into the coastal

502   and marine areas after weathering and eroding the carbonate or siliciclastic Jurassic substrate

503   of the basin. Interestingly, this strong influence of freshwater Sr isotopic values is observed

504   even without petrographic evidence of detrital input in the analysed carbonate samples, and

505 even though the $\delta^{18}O$ values of carbonates are coherent with their formation from fresh- to

506 marine and hypersaline waters. Nevertheless, it is important to highlight that it has been

507 possible to make this interpretation because the Jurassic substrate of both studied sectors is

508 different; if the Jurassic substrate were carbonate and similar in both sectors, as occurs in many

509 areas of the Iberian Basin (Gómez, et al. 2004; 2019), it would not have been possible to

510 accurately evaluate the influence of the riverine water in the $^{87}Sr/^{86}Sr$ of carbonates, considering

511 that the $^{87}Sr/^{86}Sr$ of Barremian-Aptian marine carbonates, as well as most of those of the

512 Cretaceous, are in the range of the Jurassic $^{87}Sr/^{86}Sr$ marine values, being even identical for

513 some periods of time (Jones et al. 1994; McArthur 2001; Prokoph et al. 2008; MacArthur et al.

514 2012). Thus, our data indicate that caution should be taken when interpreting Sr isotopic data

515 for performing SIS studies obtained from fossil shells and/or carbonates (even those well-

516 preserved and/or without direct evidence of detrital input) deposited in coastal and shallow

517 marine sedimentary environments. This is particularly important for coastal and shallow-marine

518 carbonates deposited in active tectonic settings. In these settings, the uplifted areas are

519 significantly prone to weathering and erosion, leading to the common development of alluvial

520 fan systems that eventually discharge into coastal and shallow marine settings, as occurred in

521 the Iberian Basin during the Late Jurassic-Early Cretaceous extensional phase.

522 **6. Conclusions**

523 The Lower Cretaceous Leza Fm (Cameros Basin, N Spain) is an essentially carbonate

524 unit, which was deposited in the context of the Mesozoic Iberian Extensional System, and

525 whose deposition and thickness were strongly controlled by faulting of the basin substrate

526 (mainly composed of Jurassic rocks). A coastal wetland system that included carbonates

527 deposited in freshwater, marine-influenced, marginal-marine and hypersaline water bodies,

528 formed at that time in the studied area. This system was laterally related with alluvial fans,

529 whose deposits (conglomerate, sandstone, sandy limestone and marl), sourced in the faulted

530 and exposed basin substrate, are interbedded with carbonates.

531 Two sectors have been differentiated, Eastern and Western, based on the sedimentary

532 features of the Leza Fm deposits and those of the Jurassic substrate, which are slightly

533 different. In the Eastern Sector, the marine influence is higher with the detrital inputs being

534 lesser than in the Western Sector; additionally, the Middle and Upper Jurassic rocks of the

19

535   substrate are essentially siliciclastic in the Eastern Sector but essentially carbonate in the

536   Western Sector.

537   The δ^{18}O values in both sectors follow the expected trend, in accordance with the

538   different depositional palaeoenvironments: more negative values (down to -7.8‰) are recorded

539   in freshwater carbonates and more positive values (up to +2.8‰) in marine to hypersaline

540   marine facies. However, and independently of the marine or freshwater influence, the ^{87}Sr/^{86}Sr

541   ratios of the carbonates in the Western Sector (0.707373-0.707801) are significantly lower and

542   closer to the published Lower Cretaceous marine ^{87}Sr/^{86}Sr ratios, than those obtained in the

543   Eastern Sector (0.707988-0.709033) although, in this sector, the overall marine influence was

544   higher and the detrital alluvial input lower.

545   These data strongly support that the ^{87}Sr/^{86}Sr ratios of all carbonates studied herein

546   (freshwater, marine-influenced, marginal-marine, and hypersaline) were strongly controlled by

547   the Sr ratios of the riverine freshwater, which arrived to the coastal and marine areas after

548   weathering and eroding the carbonate or siliciclastic rocks of the Jurassic substrate of the basin

549   that was faulted and exposed, even if there is no petrographic evidence of detrital influence, and

550   even if the δ^{18}O values of carbonates are coherent with their formation in fresh- to marine and

551   hypersaline waters.

552   Thus, our data indicate that caution should be taken when interpreting Sr isotopic data

553   for performing SIS studies obtained from fossil shells and/or carbonates (even those well-

554   preserved) deposited in coastal and shallow marine sedimentary environments, particularly in

555   active tectonic settings, such as those occurring in the Iberian Basin during the Late Jurassic

556   and Early Cretaceous extensional system.

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1007

Figure captions

Fig. 1. Geological setting of the studied area. **A**. Map of the Iberian Peninsula, showing the pre-

Mesozoic Variscan Massif and the Mesozoic Iberian Extensional System (MIES). Red square

marks the location of the Cameros Basin. **B**. Geological map of the Cameros Basin showing the

location of the studied area. Red square marks the location of Figs. 2A and 3. **C**. Chrono- and

lithostratigraphic chart of the eight depositional sequences (DS) of the Cameros Basin

sedimentary infill, modified after Mas et al. (2011). The Leza Fm (highlighted in red) is part of

DS7, Late Barremian – Early Aptian in age.

Fig. 2. A. Detailed geological map of the northernmost margin of the Cameros Basin (modified

from Suarez-Gonzalez et al. 2015). Note the tectonic control and individualization of outcrops of

the Jubera and Leza Fms, deposited mostly on top of the Bathonian to Kimmeridgian marine

Jurassic substrate of the basin and, locally, over the pre-Bathonian marine Jurassic or over the

Triassic Keuper facies. Note that the Jubera plus Leza Fms lithotopes are limited by faults, and

that the colour code of this map is equivalent to that of the stratigraphic chart of Fig. 1C. **B**.

Correlation panel of the stratigraphic sections showing the thickness of the Jubera and Leza

Fms (the stratigraphic sections analysed in this study, the Leza River section (LZ), in the

Western Sector, and the Préjano section (PR), in the Eastern Sector, are highlighted with red

asterisks). On top, to the right, there is a simplified map showing the location of each section

and the correlation line (in blue). The top of the Leza Fm has been used as datum for

correlation. The thickness of the Jubera Fm has been obtained from Ochoa (2006), Hernández-

Samaniego et al. (1990) and our own measurements. Note the tectonic control of the Jubera

and Leza Fms and the lateral facies change between the Jubera and Leza Fms. Modified from

Suarez-Gonzalez et al. 2013.

Fig. 3. **A**. Palaeogeographic map of NE Iberian Peninsula during deposition of the Leza Fm.

(modified from Suarez-Gonzalez et al. 2013) **B**. Detailed palaeogeographical scheme showing a

general interpretation of the spatial distribution of depositional environments in NE Cameros

Basin during sedimentation of the Leza Fm coastal wetlands and the complex array of

sedimentary environments that characterizes these multifaceted depositional systems (see

location in A; modified from Suarez-Gonzalez et al., 2015). The map covers approximately the

same area as the map in Fig. 2A (see names of the main towns in both maps). White areas

1038 represent zones with no outcrops of Lower Cretaceous rocks. These areas may have been

1039 those where the Jurassic substrate of the Cameros Basin cropped out during sedimentation,

1040 being the source of the Leza Fm alluvial sediments.

1041 **Fig. 4**. **A.** Field photograph showing conglomerates of the Leza Fm at the Western Sector,

1042 where they are mainly composed of fragments of Jurassic carbonates. **B.** Transmitted light

1043 photomicrograph showing in detail the detrital facies of the Leza Fm at the Western Sector.

1044 Note that many clasts are composed of oolitic limestone (JL) and reworked single ooids (JO)

1045 and echinoderms fragments (blue arrow), which are identical to those of the Upper Jurassic

1046 limestone deposited in the studied area, and other carbonate extraclasts (red arrows) of

1047 unknown origin. Quartz grains (Q), are also present in variable amounts. **C-D**. Field

1048 photographs of the detrital alluvial sediments of the Leza Fm at the Eastern Sector. **C**. Very

1049 poorly sorted conglomerate made up of large marine sandstone clasts (yellow arrows), quartzite

1050 pebbles (white), and sandy matrix. Coin is 2.3 cm in diameter. **D.** Poorly-sorted conglomerate

1051 made up mainly of quartzite pebbles (white) in a carbonate matrix.

1052 **Fig. 5**. Detailed stratigraphic sections used for isotopic analyses: the Leza River section, in the

1053 Western Sector, and the Préjano section, in the Eastern Sector (see Fig. 2 for location). In each

1054 section the $\delta^{18}O$ (pink) and the $^{87}/Sr/^{86}Sr$ (black) are shown. The range of published $\delta^{18}O$ and

1055 $^{87}Sr/^{86}Sr$ values for the Barremian-Aptian marine carbonates and, in the case of the Sr isotopes,

1056 for the Jurassic are also shown. Blue circles represent the depositional environment where the

1057 different carbonate facies were deposited.

1058 **Fig. 6**. Photographs showing the different studied carbonate facies, which were deposited in

1059 different sedimentary palaeoenvironments. **A-B.** Freshwater facies association. **A.** Field

1060 photograph showing tabular black limestone interbedded with thin beds of greenish marl. Note

1061 root traces at the top of the beds. Coin is 2.3 cm in diameter. **B.** Transmitted light

1062 photomicrograph showing a wackestone of charophyte thalli forming the nucleus of oncoids. **C-**

1063 **D**. Marine-influenced facies association. **C.** Field photograph showing tabular marine-influenced

1064 black limestone. Note the root traces at the top of the bed. Tip of hammer at the top-right corner

1065 for scale. **D.** Transmitted light photomicrograph showing a wackestone of dasycladales green

1066 algae. **E-F**. Marginal-marine facies association. **E.** Field photograph of dolostone displaying

1067 wavy bedding with alternation of grainy facies showing small-scale cross-bedding (red arrows)

1068 and muddy facies (blue arrows). Coin is 2.4 cm in diameter. **F**. Transmitted light

1069 photomicrograph showing a wackestone-packstone of benthic miliolid foraminifera and

1070 ostracods. **G-H**. Hypersaline facies association. **G**. Field photograph of hypersaline dolostone

1071 displaying abundant calcite pseudomorphs after gypsum (yellow arrows). **H**. Transmitted light

1072 photomicrograph showing a dolomudstone displaying calcite pseudomorphs after lenticular

1073 gypsum.

1074 **Fig. 7**. **A**. Carbon and oxygen isotope compositions of carbonates of the different facies

1075 associations in the Leza River section (Western Sector) and in the Préjano section (Eastern

1076 Sector). In both sectors, carbonates of each facies association have negative and variable δ^{13}C

1077 values and relatively invariant δ^{18}O values (more negative in freshwater limestone and

1078 progressively more positive in marginal-marine and hypersaline carbonates). **B-C**. δ^{18}O and

1079 ^{87}Sr/^{86}Sr values, respectively, *versus* the depositional environments where carbonate

1080 precipitated in both sectors. Note that in both sectors and, as expected, δ^{18}O values (B) are

1081 more negative in freshwater limestone, becoming progressively heavier in marine-influenced,

1082 marginal-marine and hypersaline carbonates. Note that most of the marine carbonates are in

1083 the range of or close to the published δ^{18}O values of the Barremian-Aptian marine carbonates

1084 (see text for explanation). However, ^{87}Sr/^{86}Sr ratios in each sector are very different, but δ^{18}O

1085 values of carbonates precipitated in the different palaeoenvironments in each sector are similar.

1086 Also note that ^{87}Sr/^{86}Sr ratios in the Western Sector are similar or in the range of the published

1087 Barremian-Aptian marine carbonates, even those obtained from freshwater carbonates.

1088

1089 **Table 1 (Supplementary material)**. Isotopic data of the analysed samples
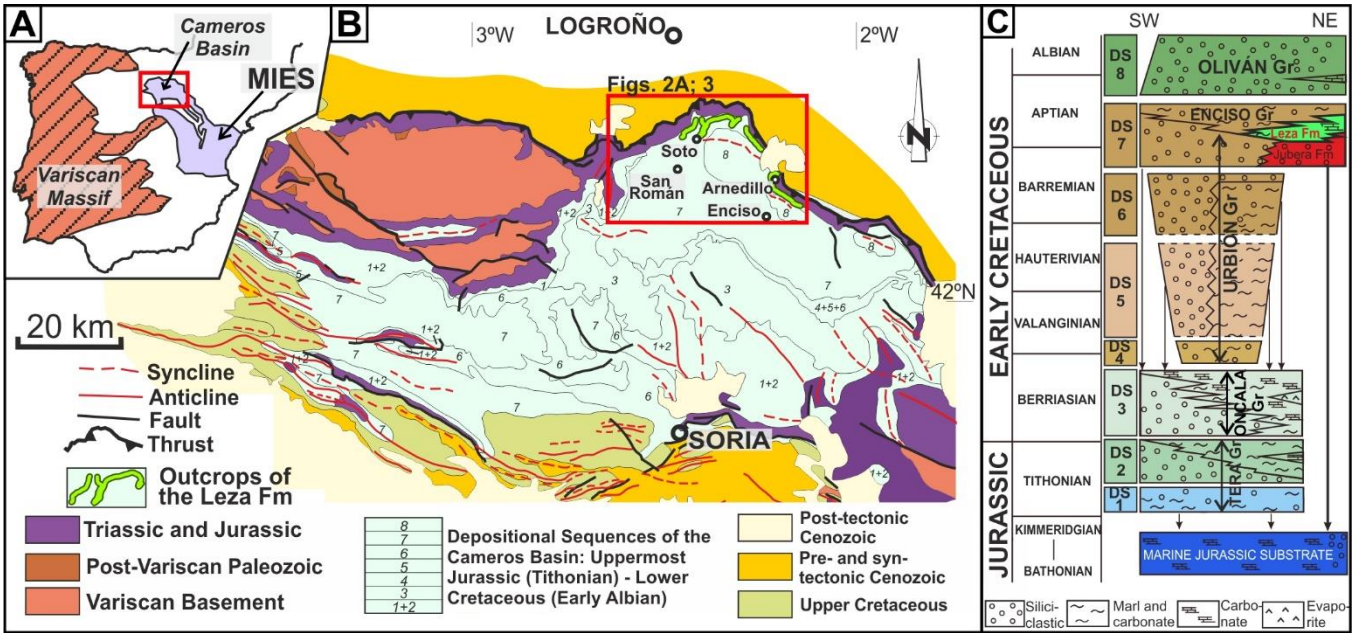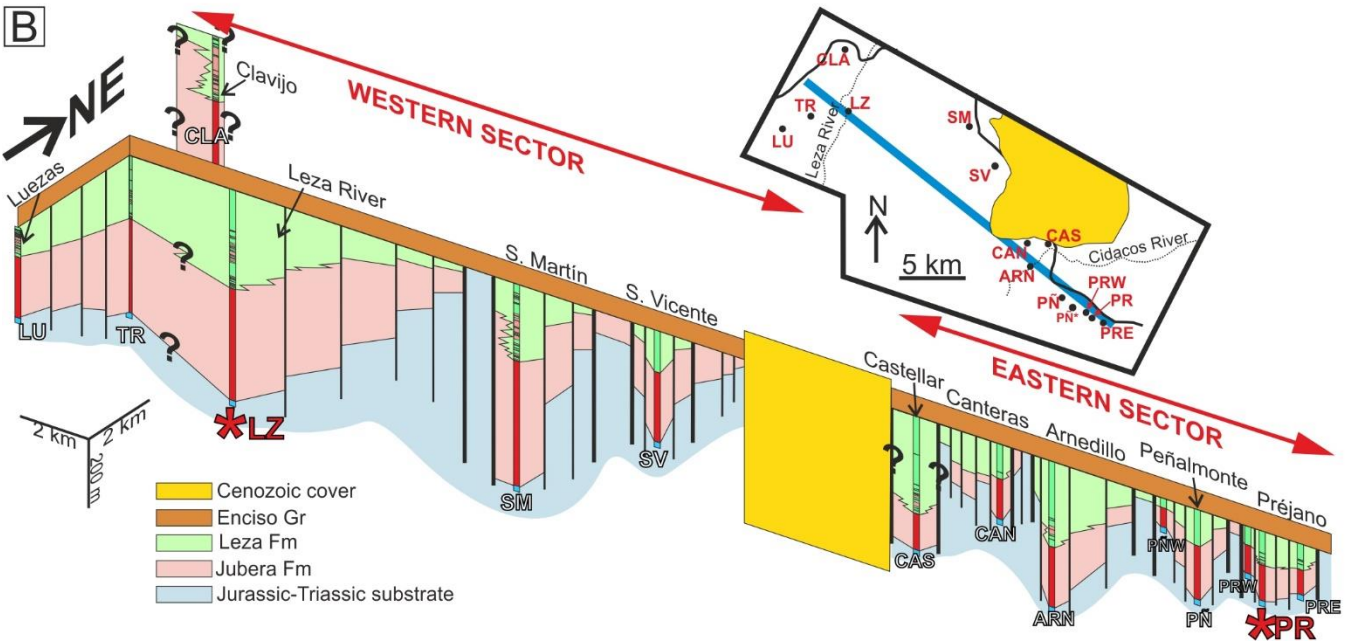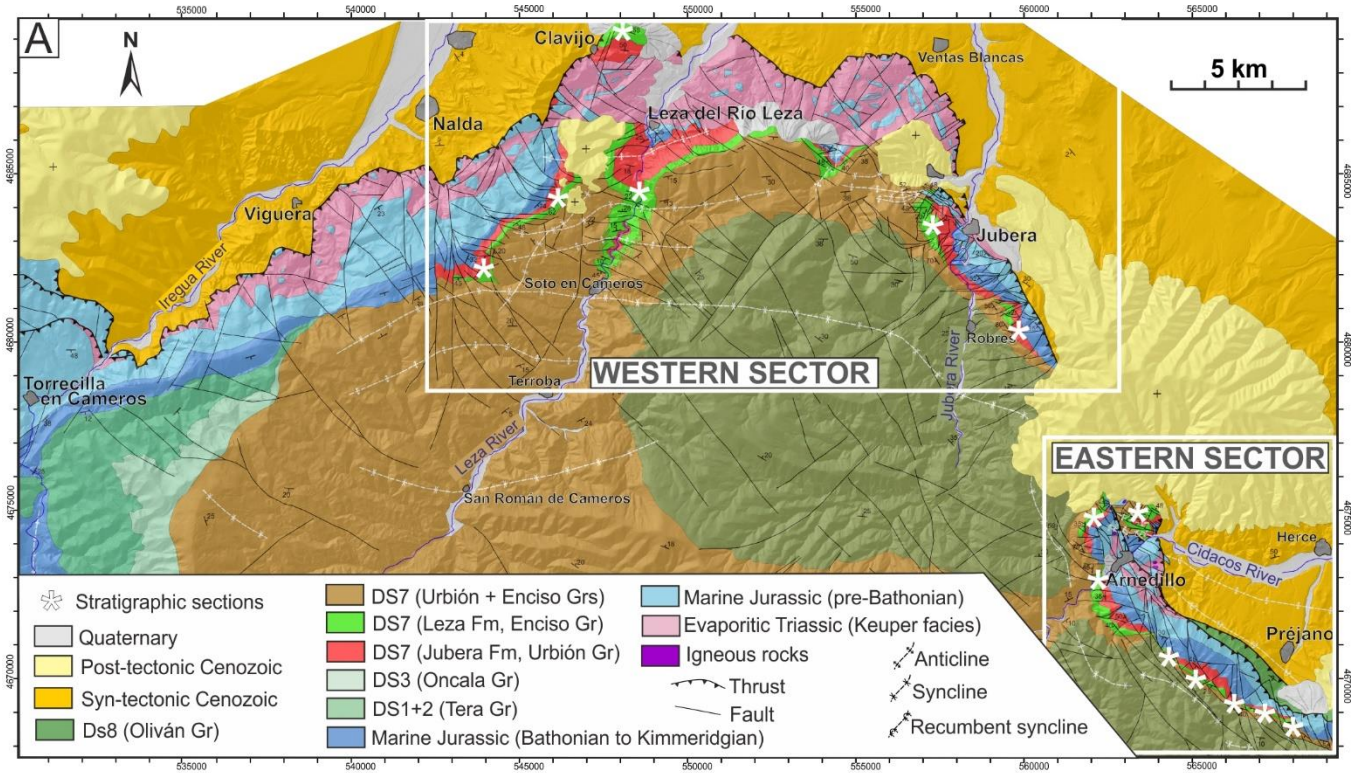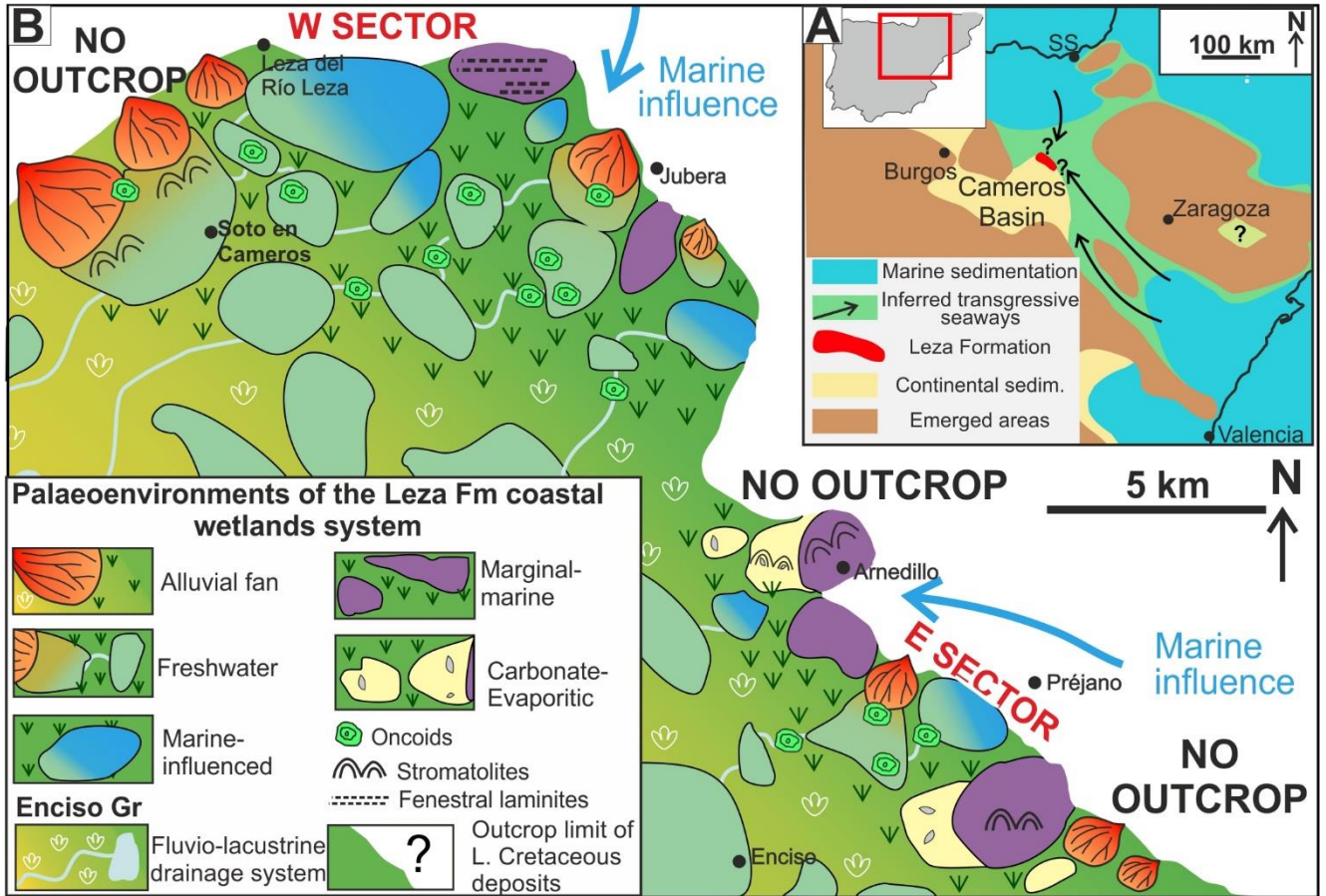
1090

Fig. 1

Fig. 2

Fig. 3

W SECTOR

B NO OUTCROP

Leza del Río Leza

Marine influence

Soto en Cameros

•Jubera

A

N
100 km ↑

SS

Burgos

Cameros Basin

Zaragoza
?

Valencia

Marine sedimentation
Inferred transgressive seaways
Leza Formation
Continental sedim.
Emerged areas

NO OUTCROP   5 km   **N** ↑

Arnedillo

Marine influence

•Préjano

E SECTOR

NO OUTCROP

Palaeoenvironments of the Leza Fm coastal wetlands system

Alluvial fan

Freshwater

Marine-influenced

Enciso Gr

Fluvio-lacustrine drainage system

Marginal-marine

Carbonate-Evaporitic

Oncoids

Stromatolites

Fenestral laminites

? Outcrop limit of L. Cretaceous deposits

•Enciso

Fig. 4

A

B

JL
JO
JO
Q
JL
Q
0.5 mm

C

D

Fig. 5

LEGEND OF STRATIGRAPHIC SECTIONS

Fig. 6

Fig. 7