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1 Seep deposits from northern Istria, Croatia: a first glimpse into the Eocene seep
2 fauna of the Tethys region

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14 Keywords: seep fauna, methane-derived carbonates, stable isotopes, biomarkers, Eocene,
15 Istria

17 **Abstract** – Three isolated limestone deposits and their fauna are described from a middle
18 Eocene Flysch succession in northwestern Istria, Croatia. The limestones are identified as
19 ancient methane-seep deposits based on fabrics and characteristic mineral phases, $\delta^{13}\text{C}_{\text{carbonate}}$
20 values as low as -42.2% , and ^{13}C -depleted lipid biomarkers indicative for methane-oxidising
21 archaea. The faint bedding of the largest seep deposit, the great dominance of authigenic
22 micrite over early diagenetic fibrous cement, as well as biomarker patterns indicate that
23 seepage was diffusive rather than advective. Apart from methanotrophic archaea, aerobic
24 methanotrophic bacteria were present at the Eocene seeps as revealed by ^{13}C -depleted
25 lanostanes and hopanoids. The observed corrosion surfaces in the limestones probably reflect

carbonate dissolution caused by aerobic methanotrophy. The macrofauna consists mainly of chemosymbiotic bivalves such as solemyids (*Acharax*), thyasirids (*Thyasira*), and lucinids (*Amanocina*). The middle Eocene marks the rise of the modern seep fauna, but so far the fossil record of seeps of this age is restricted to the North Pacific region. The taxa found at Buje originated during the Cretaceous, whereas taxa typical of the modern seep fauna such as bathymodiolin mussels and vesicomyid clams are absent. Although this is only a first palaeontological glimpse into the biogeography during the rise of the modern seep fauna, it agrees with biogeographic investigations based on the modern vent fauna indicating that the dominant taxa of the modern seep fauna first appeared in the Pacific Ocean.

1. Introduction

Authigenic carbonate rocks forming where methane or oil effuse from the sediments into the bottom waters act as an archive of life in chemosynthesis-based ecosystems at marine seeps (Peckmann & Thiel, 2004; Campbell 2006). The key biogeochemical process at seeps is the anaerobic oxidation of methane (Boetius *et al.* 2000). It results in carbonate precipitation forming seep limestones even way below the carbonate compensation depth (e.g. Ritger *et al.* 1997; Greinert, Bohrmann & Elvert, 2002) and the production of hydrogen sulphide that sustains benthic sulphide-oxidizing bacteria and thiotrophic bacteria in the tissues of chemosymbiotic metazoans (Sibuet & Olu, 1998). A growing number of Phanerozoic seep deposits has been described to date (Campbell, 2006; Teichert & van de Schootbrugge, 2013, and references therein). Their fossil inventory revealed a successive colonisation of seep environments by different groups of metazoans in the course of Earth history, commonly followed by the sooner or later disappearance of these groups of highly specialized taxa.

Methane-seep faunas were first discovered in the early 1980s in the Gulf of Mexico and are now recognized at most continental margins (Paull *et al.* 1984; Baker *et al.* 2010). Their highly specialized taxa are closely related to those at deep-sea hydrothermal vents and many

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52 rely on chemotrophic symbionts for nutrition (Paull *et al.* 1985). Although the rise of the
53 modern, mollusc-dominated vent and seep fauna began during the Cretaceous age, the main
54 players at present-day vents and seeps appeared in the early Cenozoic (Campbell & Bottjer,
55 1995; Kiel, 2010; Kiel & Little, 2006; Vrijenhoek, 2013). Biogeographically, however, the
56 Cenozoic fossil record of methane seeps is highly skewed toward the active continental
57 margins of the Pacific Ocean where uplift of deep-water sediments is frequent (Goedert &
58 Squires, 1990; Majima, Nobuhara & Kitazaki 2005; Campbell *et al.* 2008). In contrast, fossil
59 occurrences in the Atlantic realm are restricted to the Caribbean region (Gill *et al.* 2005; Kiel
60 & Peckmann, 2007) and the Mediterranean basin (Taviani, 1994).

61 Here we evaluate the fauna of middle Eocene seep deposits from the northern
62 Mediterranean basin (Istria, Croatia; Venturini *et al.* 1998) in the light of the early evolution
63 of the modern vent and seep fauna, establish the biogeochemical processes that lead to the
64 formation of the seep deposits, describe processes that imprinted their lithology, and
65 reconstruct the composition of fluids and the mode of seepage.

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67 **2. Geological setting and material**

68 The Istria peninsula, shared by Croatia, Slovenia, and Italy, is bordered to the northeastern
69 Adriatic Sea. During the Eocene, Istria was a part of the Dinaric foreland zone that
70 experienced a strong subsidence in response to the formation of an orogenic wedge (e.g.
71 Živkovic & Babić, 2003). The study area (Fig. 1a, b), located in the Croatian part of
72 northwestern Istria, is characterised by a regional WNW-ESE-oriented anticlinal structure,
73 commonly referred to as the Buje anticline or Buje Karst, whose origin is related to the
74 formation of the Dinarides (Matičec, 1994). At the southern margin of the Buje anticline the
75 foreland sequence is composed by more than 150 m of Lutetian lacustrine to shallow-marine
76 foraminiferal limestones (Drobne & Pavlovec, 1991) and by at least 350 m of Lutetian to
77 Priabonian turbidite deposits (referred to as Flysch Units; Marinčić *et al.* 1996; Pavšić &

Peckmann, 1996; Živković & Babić, 2003) that transgressively overlie an Aptian to Cenomanian sequence of shallow marine carbonates (Venturini *et al.* 1998). The Flysch deposits, in which the studied limestones are enclosed, consist of interbedded siliciclastic sandstones and marlstones as well as rare carbonate megabeds with basal breccias, representing calciturbidites (Venturini *et al.* 1998). The occurrence of turbidites indicates deposition by gravity flows in a deep-sea environment. The majority of the fine-grained marlstones, on the other hand, represents hemipelagic background sedimentation in a basinal setting (Pavšič & Peckmann, 1996). The occurrence of ichnogenera including *Paleodictyon*, as well as foraminifers and ostracods suggests deposition between 700 and 1200 m water depth (Gohrbandt *et al.* 1960; Pavšič & Peckmann, 1996).

The exotic blocks of limestone occurring in the vicinity of the town of Buje (Fig. 1b; 45°24'31''N, 13°40'01''E) have first been described by Venturini *et al.* (1998). The deposits studied here correspond to the “nearby Buje petrol station” section of Venturini *et al.* (1998; their Figures 4 and 5). In the captions of their Figures 10, 11, 13, and 14 as well as Table 1 Venturini *et al.* (1998) refer to this locality as “Buje”. The other two outcrops described by Venturini *et al.* (1998) were no longer accessible during field work in 2011. In the “nearby Buje petrol station” outcrop three limestone bodies are exposed in a road section in the eastern outskirts of Buje (Fig. 2, 3). These deposits are enclosed in a sequence of fine-grained marls intercalated with few decimetre-thick sandstone beds. The lowermost deposit (Buje 1) is about 4 m thick and laterally extends for approximately 20 metres in outcrop, the Buje 2 and 3 deposits are approximately 5 m and 2 m in width and 2 m and 1 m in height, respectively.

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100 3. Methods

101 Sampling of the carbonate deposits (Buje 1, 2, and 3) has been carried out in spring 2011.
102 Selected samples were prepared for palaeontologic, petrographic, and geochemical
103 investigations. All fossil specimens are deposited in the Geowissenschaftliches Museum,

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Georg-August-University Göttingen, Germany (GZG). Thin sections (15 x 10 cm and 10 x 7.5 cm) were studied with transmitted light and cathodoluminescence microscopy using a CITL 8200MK3, operating at about 17 kV and 400 mA. Thin sections were further analysed for their UV-fluorescence on a Nikon microscope with a UV-2A filter block, using ultraviolet light (illumination source 450-490 nm). Scanning electron microscopy and qualitative element recognition were performed with a Cambridge Instruments Stereoscan 360 scanning electron microscope equipped with an energy-dispersive Link System Oxford Instruments microprobe.

For stable isotope analyses mineral phases were drilled from the surface of slabs with a hand-held micro drill. Measurements of carbon and oxygen isotopes were performed with a Finnigan MAT 251 mass spectrometer using the “Kiel” carbonate device type “Bremen“ against natural carbon dioxide from Burgbohl (Rheinland, Germany). A Solnhofen limestone was used as standard, which was calibrated against the international standard NBS 19. Values are reported in the δ -notation relative to Vienna Pee Dee Belemnite (VPDB) standard. Long time standard deviation (1σ) for this measurement was 0.05‰ for $\delta^{13}\text{C}$ and 0.07‰ for $\delta^{18}\text{O}$ values.

Lipid biomarkers were extracted from two carbonate blocks (Buje 1 and 2 deposits), yielding almost identical patterns. Samples were prepared and decalcified as described in Birgel *et al.* (2006a). After saponification with 6% KOH in methanol, the samples were extracted with a microwave extraction system (CEM Discovery) at 80°C and up to 250 W with dichloromethane/methanol (3:1) three times. The resulting extracts were separated into four fractions by column chromatography (500 mg DSC-NH₂ cartridges, Supelco) as described in Birgel *et al.* (2008). Carboxylic acids were measured as their methyl ester (ME) derivatives. All fractions were measured using an Agilent 7890 A GC system coupled to an Agilent 5975 C inert MSD spectrometer. The GC-MS system was equipped with a 30 m HP-5 MS UI fused silica capillary column (0.25 mm i.d., 0.25 μm film thickness). The carrier gas was He. The gas chromatography (GC) temperature program used for both fractions was as

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3 130 follows: 60 °C (1 min); from 60 to 150°C at 10°C/min then to 320°C at 4°/min; 25 min
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5 131 isothermal. Identification of compounds was based on GC retention times and comparison
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7 132 with published mass spectra. No separation of crocetane and phytane was achieved with the
8
9 133 used column. The relative abundance of these compounds was assessed by the different
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11 134 fragmentation patterns, especially by the change of relative abundances of the masses 169
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13 135 (characteristic for crocetane) and 183 (characteristic for phytane) within the mixed
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15 136 crocetane/phytane peak. Compound-specific carbon isotope analyses were carried out with a
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17 137 Thermo Fisher Trace GC Ultra connected via a thermo Fisher GC Isolink interface to a
18
19 138 Thermo Fisher Delta V Advantage spectrometer. GC conditions were identical to those
20
21 139 described above. Carbon isotopes are expressed as $\delta^{13}\text{C}$ values relative to the VPDB standard.
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23 140 The carbon isotope measurements were corrected for the addition of ME-derivatives. Several
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25 141 pulses of carbon dioxide with known $\delta^{13}\text{C}$ values at the beginning and the end of the runs
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27 142 were used for calibration. Instrument precision was checked using a mixture of *n*-alkanes (C_{14}
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29 143 to C_{40}) with known isotopic composition. The analytical standard deviation was <0.7‰.
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145 4. Results

146 4.a. Fauna

147 Microfossils are abundant in the studied carbonate rocks, for the most part being represented
148 by benthic (*Bolivina* sp., *Stilostomella* spp., *Uvigerina* spp., and *Heterolepa* spp.) and planktic
149 (*Turborotalia* sp., *Acarinina* sp. and *Hantkenina* sp.) foraminifera. The occurrence of
150 *Hantkenina* sp. agrees with an Upper Lutetian-Bartonian age (cf. Pavšič & Peckmann, 1996).

151 Macrofossils were found only sporadically in the Buje 1 deposit and were almost absent
152 in the Buje 2 and Buje 3 deposits. Most common is a lucinid bivalve that includes also the
153 largest shell, followed by a thyasirid, and a solemyid bivalve. In addition to these bivalves, a
154 few callianassid claws and other crustacean fragments were found. The bivalves include: (1)
155 two specimens of a solemyid, the larger one 32 mm long and 10 mm high with the anterior

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end missing. It shows an elongate S-shaped band extending from the posteroventral corner of the anterior adductor muscle scar to the dorsal shell margin, had an external ligament, and is therefore referred to as *Acharax* (Fig. 4a-c). (2) Two specimens of a *Nucula*; the larger one is 20 mm long and 15 mm high, and although the taxodont hinge is missing in these specimens, they have the general shape of a *Nucula* and show the radial striation and crenulate ventral margin common to this genus (Fig. 4d). (3) Four specimens belong to *Thyasira* due to their general shape and strong posterior sulcus (Fig. 4e); the largest is 40 mm long. The “undetermined Veneroida (?Kelliidae)” figured by Venturini *et al.* (1998, p. 225, Fig. 11) may also belong to this *Thyasira* species. (4) Seven specimens and fragments of an oval lucinid bivalve with an edentulous, narrow hinge without triangular excavation below the umbo, and a maximum length of 52 mm (Fig. 4f-j) belong to the genus *Amanocina*. The lucinid is most likely the same species as the “*Lucina*” figured by Venturini *et al.* (1998, p. 225, Fig. 10).

4.b. Petrography and stable isotopes

The lithology of the three Buje carbonate deposits (Buje 1 to 3) is quite similar. The limestones consist of fossiliferous and bioturbated mudstone and wackestone (Fig. 5). The matrix is made up of dark brown micrite, revealing a bright autofluorescence (Fig. 6a, b). Terrigenous particles are angular, including abundant quartz and rare feldspar grains as well as lithic clasts. Apart from detrital grains, the micritic matrix contains abundant biogenic detritus, mostly tests of foraminifera (Fig. 6c). Some mm to cm wide, irregular cavities occur; the cavities are interpreted to result from bioturbation, representing successively filled burrows. Some cavities show geopetal infill (Fig. 6d). The cavities are filled by sediment and authigenic phases including peloids, homogenous micrite, laminated micrite, a phase referred to as cauliflower micrite, and different generations of carbonate cements (Fig. 6d-f). Peloidal fabrics are particular abundant (Fig. 6e). They consist of ovoidal peloids, showing an intense fluorescence, surrounded by a non-fluorescent calcite microspar. On the basis of shape and

182 composition, peloids are interpreted to represent faecal pellets. Banding in the authigenic,
 183 laminated micrites is sub-parallel to cavity walls (Fig. 6e). In places the laminated micrite is
 184 broken to pieces, forming fragments surrounded by calcite cement.

185 The cauliflower micrite is an obviously authigenic variety of micrite found in some of the
 186 cavities. It is represented by aggregates of mottled, microcrystalline calcite (Fig. 7a, b). Its
 187 aggregates exhibit a domal, grooved shape, resembling cauliflower. Micron-sized irregular
 188 pores, filled by calcite microspar, are present within these domes, generating a sponge-like
 189 texture (Fig. 7c). The fluorescent cauliflower micrite (Fig. 7d) is commonly covered by a
 190 circumgranular calcite cement (Fig. 7b, c). Remaining porosity in the cavities was
 191 subsequently filled by two main generations of cement, (1) banded and botryoidal aggregates
 192 of fibrous aragonite cement, mostly recrystallized to calcite, and (2) a drusy mosaic of equant
 193 calcite cement (Fig. 6c-f). Carbonate cements are overall not abundant, being restricted to the
 194 cavities believed to result from bioturbation.

195 The micritic matrix of the Buje deposits records episodes of carbonate corrosion. The
 196 surfaces of the affected aggregates of micrite are highly irregular, and commonly covered by a
 197 black rim of an opaque mineral up to a few tens of μm in thickness (Fig. 8a, b). Backscatter
 198 and EDS observations revealed that these rims consist of scattered bright grains (Fig. 8c)
 199 characterized by high contents of iron and manganese.

200 The volumetrically dominant micrite of the Buje carbonates has been analysed for its
 201 stable carbon and oxygen isotope composition; the amount of banded and botryoidal cement
 202 was not sufficient to allow for isotope analysis. The $\delta^{13}\text{C}$ values of micrite range from -42.2
 203 to -22.7‰ , the corresponding $\delta^{18}\text{O}$ values range from -3.9 to 0.0‰ (Fig. 9). The Buje 1
 204 deposit revealed the most negative $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values, as low as -42.2 and -3.9‰ ,
 205 respectively, with most $\delta^{13}\text{C}$ values falling between -35.2 and -30.2‰ . Buje 2 and Buje 3
 206 deposits show overall similar isotope values with less ^{13}C and ^{18}O depletion compared to the
 207 Buje 1 deposit.

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209 4.c. Biomarkers

210 Hydrocarbons, carboxylic acids, and alcohols were analysed. However, lipid biomarkers in
211 the alcohol fraction are only poorly preserved, and are thus not useful for the interpretation of
212 the depositional environment. The major group of compounds in the hydrocarbon fraction are
213 isoprenoid hydrocarbons (Fig. 10a). Among them are the head-to-tail linked isoprenoid
214 phytane (approximately 60% of the combined peak) and the tail-to-tail linked isoprenoid
215 crocetane (approximately 40%); their combined peak is the highest peak in this fraction. The
216 next abundant isoprenoids are the tail-to-tail linked isoprenoid pentamethylicosane (PMI) and
217 the head-to-head linked isoprenoid biphytane (bp-0). Other, minor constituents are
218 monocyclic biphytane (bp-1) with one cyclopentane ring and the tail-to-tail linked isoprenoid
219 squalane, as well as the head-to-tail linked isoprenoid pristane. Other than isoprenoids, few
220 straight-chain *n*-alkanes are present. Their overall distribution is patchy with the exception of
221 *n*-C₂₃, resembling the inventory of modern and ancient, non-oil stained seep carbonates and
222 sediments (e.g. Thiel *et al.* 2001; Peckmann *et al.* 2007; Chevalier *et al.* 2013). Apart from
223 aliphatic lipid biomarkers, few cyclic compounds, mainly steranes and one hopanoid were
224 found. Among steroids, most abundant are C₂₈ and C₂₉ steranes. Other detected steroids are
225 lanostanes, which have been described in some seep carbonates (Birgel & Peckmann, 2008).
226 The most abundant cyclic terpenoid found is the hopanoid hop-17(21)-ene.

227 The isoprenoids have the most negative $\delta^{13}\text{C}$ values with -111‰ and -109‰ for PMI
228 and bp-0, respectively. The head-to-tail linked isoprenoid pristane (-60‰) and the *n*-alkane
229 *n*-C₂₃ (-66‰) revealed intermediate values (Fig. 9), whereas other short-chain *n*-alkanes are
230 significantly less ^{13}C -depleted (-34‰). The $\delta^{13}\text{C}$ values of steranes fall in the same range as
231 short-chain and long-chain *n*-alkanes. Lanostanes are more ^{13}C -depleted with an average
232 value of -47‰ . Hop-17(21)-ene is more ^{13}C -depleted (-64‰) than the lanostanes.

233 The carboxylic acid fraction is predominated by *n*-fatty acids ranging from C₁₄ to C₂₈
 234 (Fig. 10b). The fatty acids are characterized by an overall even-over-odd predominance.
 235 Highest contents were found for short-chain *n*-C₁₆ fatty acid. Other abundant compounds are
 236 *n*-C₁₆ and C₁₈ fatty acids with one double bond. Apart from *n*-fatty acids, terminally-branched
 237 fatty acids are abundant, especially those comprising 15 carbons. Other compounds in the
 238 carboxylic acid fraction are phytanoic acid and PMI acid. Phytanoic acid co-elutes with a
 239 C_{18:1} fatty acid. Only one hopanoic acid, 17β(H),21β(H)-bishomohopanoic acid, was
 240 identified.

241 The strongest ¹³C depletions in the carboxylic acids were found for the isoprenoid PMI
 242 acid (−107‰). Although combined with the isotopic signature of the co-eluting *n*-C_{18:1} fatty
 243 acid, phytanoic acid is still considerably ¹³C-depleted (−75‰). Other compounds with
 244 significant depletion in ¹³C are the terminally-branched *iso*- and *anteiso*-C₁₅ fatty acids with
 245 δ¹³C values of −68‰ and −82‰, respectively, as well as 17β(H),21β(H)-bishomohopanoic
 246 acid (−70‰). Short-chain *n*-fatty acids yielded values of around −50‰, whereas the long-
 247 chain fatty acids revealed higher values (average −31‰).

249 5. Discussion

250 5.a. Biogeographic and evolutionary aspects

251 Methane seepage and associated faunal communities in the Mediterranean realm are known
 252 from the late Mesozoic when large lucinid bivalves and rhynchonellide brachiopods inhabited
 253 cold seeps along the northern shore of the Tethys Ocean (Gaillard, Rio & Rolin, 1992;
 254 Campbell & Bottjer, 1995; Peckmann *et al.* 1999; Kiel, 2013) and from the Miocene onward,
 255 largely along the Apennine chain in Italy (Ricci Lucchi & Vai, 1994; Taviani, 2011). These
 256 Neogene seep deposits are generally referred to as ‘Calcarei a *Lucina*’ (Clari *et al.* 1988;
 257 Taviani, 1994). Among them, the Miocene deposits contain essentially a modern seep fauna

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consisting of large bathymodiolin, vesicomysid, and lucinid bivalves, while the few Pliocene examples appear to have a reduced character of the modern Mediterranean Sea seep fauna (Table 1; Taviani, 2014). Many of the taxa that inhabit vents and seeps today originated in the early Cenozoic (Kiel & Little, 2006; Amano & Kiel, 2007; Kiel & Amano, 2013; Vrijenhoek, 2013). The middle Eocene Buje deposits can thus provide insights into the early evolution of the seep fauna and its biogeography.

The only seep deposits coeval with the Buje seeps are those of the middle Eocene Humptulips Formation in western Washington State, USA, and thus from the Pacific realm (Goedert & Squires, 1990). They share the common solemyids, the large thysirids, and the edentulous lucinids, although the latter are represented by different genera in the two regions (cf. Goedert & Squires, 1990; Saul, Squires & Goedert, 1996; Kiel, 2013). The Humptulips seep deposits differ, however, by the presence of large, high spired gastropods (Goedert & Kaler, 1996; Kiel, 2008) and vesicomysid bivalves (Squires & Goedert, 1991; Amano & Kiel, 2007), which appear to be absent from the Buje deposits. The Humptulips limestones also include the earliest bathymodiolin mussels discovered so far (Kiel & Amano, 2013). From one of the seep deposits at Buje, Venturini *et al.* (1998) reported several specimens of the mytilid ‘*Modiolus*’ that could potentially represent an as-yet unidentified bathymodiolin mussel; unfortunately that particular deposit was no longer accessible during our field work and the identity of this mussel remains elusive. The fauna of the Buje seep deposits is only a first glimpse into the Eocene seep fauna of the central Tethys Ocean and is unlikely to represent the full diversity of the regional pool of seep-inhabiting taxa. However, if taken at face value, the absence of the main modern taxa (bathymodiolins and vesicomysids) from Buje at a time when these taxa were present at Pacific seeps is in agreement with molecular phylogenetic analyses (Lorion *et al.* 2013; Roterman *et al.* 2013; Stiller *et al.* 2013) and quantitative biogeographic analyses (Bachraty *et al.* 2009; Moalic *et al.* 2012), which indicate a Pacific origin of the modern vent and seep fauna.

284 Compared to the ‘Calcarei a *Lucina*’ seep deposits in the Italian Miocene (Fig.1a; Clari *et*
 285 *al.* 1994; Taviani, 1994) and the modern Mediterranean seep fauna (Olu-Le Roy *et al.* 2004;
 286 Ritt *et al.* 2010; Taviani *et al.* 2013), the middle Eocene seep fauna at Buje shows clear
 287 differences (Table 1). Solemyids are rare in the Neogene to modern seeps in the
 288 Mediterranean Sea (Taviani *et al.* 2011; Rodrigues, Duperron & Gaudron 2011) in contrast to
 289 Buje, where they are common. Also the large *Thyasira* is a distinctive feature of the Buje
 290 seeps, while thyasirids are absent from the ‘Calcarei a *Lucina*’ deposits (Taviani, 2011; S. Kiel,
 291 own observation), and in the modern Mediterranean seep fauna they are represented only by a
 292 small (~10 mm) species (Olu-Le Roy *et al.* 2004). The lucinids at the Miocene to modern
 293 Mediterranean seeps clearly belong to different genera than the lucinid at Buje (Olu-Le Roy *et*
 294 *al.* 2004; Taviani, 2011; Kiel & Taviani, unpub. data), which belongs to the widespread Early
 295 Cretaceous to Oligocene genus *Amanocina*.

297 **5.b. Microbial activity steering carbonate formation and destruction**

298 The Buje carbonate deposits show several petrographical and geochemical lines of evidence
 299 that agree with a microbial origin sustained by hydrocarbon seepage. Not only the negative
 300 $\delta^{13}\text{C}$ values as low as -42‰ agree with methane seeping (cf. Paull *et al.* 1992; Peckmann &
 301 Thiel, 2004), but also microfabrics, such as peloidal and clotted micrite, laminated micrite,
 302 and banded and botryoidal cement filling cavities are typical of seep carbonates (e.g.
 303 Peckmann & Thiel, 2004). Finally, lipid biomarkers characteristic for methane seepage are
 304 found in the Buje deposits, confirming their microbial origin resulting from methane
 305 oxidation. Among the observed compounds, the most ^{13}C -depleted acyclic isoprenoids such as
 306 mixed phytane/croctane (-98‰), PMI (-111‰), and acyclic biphytane (-109‰) are
 307 molecular fossils of methanotrophic archaea (e.g. Elvert, Suess & Whiticar, 1999; Peckmann
 308 & Thiel, 2004; Birgel *et al.* 2006a; Peckmann, Birgel & Kiel, 2009). These biomarkers are
 309 accompanied by molecular fossils of sulphate-reducing bacteria, such as *iso*- and *anteiso*- C_{15}

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fatty acids (Elvert *et al.* 2003; Birgel *et al.* 2006b). As commonly observed in seep deposits, the lipids of the sulphate-reducing bacteria involved in anaerobic oxidation of methane are less ¹³C-depleted (−82‰ for *anteiso*-C₁₅ FA) than the lipids of methanotrophic archaea (e.g. Peckmann & Thiel, 2004).

At first glance, the petrographical characteristics and stable isotope and lipid biomarker patterns of the Buje deposits are not much different from other ancient Mediterranean seep deposits (e.g. Peckmann *et al.* 2004; Clari *et al.* 2009; Natalicchio *et al.* 2013). However, the Buje seep deposits show some peculiarities, as for example the occurrence of cauliflower micrite. These dome-shaped precipitates are made up of fluorescent clotted micrite and formed *in-situ* within cavities, properties that typify the products of organomineralisation (cf. Reitner *et al.* 1995; Dupraz *et al.* 2009). Two possible modes of formation are envisaged, (1) mineralised microbial mats or (2) sponges. (1) Mineralized biofilms have already been documented in Eocene seep deposits from western Washington State (Peckmann *et al.* 2003) and in Miocene seep deposits from the Italian Apennine (Peckmann *et al.* 1999). The cauliflower shape, representing a domal, accretionary mode of growth on a mm to cm scale in a cryptic environment is different from previous reports of much thinner mineralised biofilms within cracks of preexisting seep carbonate. Based on the larger size of the Buje cauliflower micrite and its domal growth habit along with its intense autofluorescence it seems feasible that this micrite resulted from the mineralisation of microbial mats that performed anaerobic oxidation of methane. The validity of this scenario is enforced by the presence of subsurface microbial mats of anaerobic oxidation of methane-performing prokaryotes at active seeps in the Black Sea (Treude *et al.* 2005). (2) Alternatively, the domal growth, clotted microfabric, and reticulate porosity of the cauliflower micrite resembles the outcome of sponge taphonomy (e.g. Delecat *et al.* 2001). Because no spicules have been observed, it is unlikely that cauliflower micrite represents fossils of spicular sponges. Even in case of siliceous spicules, the spicules would have been probably preserved in the authigenic seep carbonate. Where

sponges have been reported in ancient seep deposits, their overall preservation including spicules was good in case of Mesozoic examples (Peckmann *et al.* 1999) and excellent in case of Cenozoic examples (Goedert & Squires, 1990; Rigby & Goedert, 1996). If the sponge interpretation is correct, the sponges were probably non-spicular, belonging to a group informally referred to as keratose demosponges (J. Reitner, pers. comm.). Despite of lacking spicules, the taphonomy of keratose sponges results in micritic carbonate fabrics that can still be recognized in Phanerozoic rocks (Luo & Reitner, 2014). Seep-dwelling sponges have been reported from a number of modern sites (Olu-Le Roy *et al.* 2004, and references therein). Some demosponges have even been shown to contain endosymbiotic methanotrophic bacteria (Vacelet *et al.* 1996; Olu-Le Roy *et al.* 2004; Baco *et al.* 2010).

The abundant irregular corrosion surfaces partially covered by iron and manganese precipitates indicate dissolution of carbonate. Such dissolution features coupled with iron and manganese enrichment have commonly been interpreted as the product of microbially-driven corrosion, as for example reported for reef carbonates (Reitner *et al.* 2000; Tribollet *et al.* 2011). Analogous features have also been observed in ancient (Campbell *et al.* 2002; Peckmann *et al.* 2003; Birgel *et al.* 2006b) and modern (Matsumoto, 1990; Himmler *et al.* 2011) seep carbonates and were interpreted as biologically-induced corrosion features as well. Matsumoto (1990) was the first to suggest that carbonate corrosion at seeps is driven by bacterial aerobic methane oxidation and sulphide oxidation. Both processes have the potential to lower the pH and may thus promote carbonate dissolution (Himmler *et al.* 2011; Tribollet *et al.* 2011). Molecular fossils of sulphide-oxidizing bacteria cannot be easily identified in ancient rocks, since these lipids are of low specificity and prone to degradation (cf. Arning *et al.* 2008). In contrast, the former presence of aerobic methanotrophs at seeps can be constrained by lipid biomarkers including lanostanes and some hopanoids (Peckmann *et al.* 1999; 2004; Birgel & Peckmann, 2008; Sandy *et al.* 2012). The low $\delta^{13}\text{C}$ values of lanostanes and hopanoids in the Buje limestones agree with aerobic methanotrophs as source organisms,

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although other sources cannot be excluded in case of the ¹³C-depleted hopanoids (cf. Blumenberg *et al.* 2006; Eickhoff *et al.* 2013). The potential of aerobic methanotrophs to cause carbonate dissolution has recently been proven in laboratory experiments (Krause *et al.* 2014). Based on the confirmation that this mechanism is indeed capable of inducing carbonate dissolution and the detection of molecular fossils of aerobic methanotrophs, carbonate corrosion archived in the Buje seep limestones is best explained by aerobic methanotrophy.

5.c. Constraints on fluid flow

The occurrence of both anaerobic oxidation of methane – as revealed by ¹³C-depleted biomarkers and ¹³C-depleted authigenic carbonates – and aerobic oxidation of methane – as revealed by ¹³C-depleted biomarkers and carbonate corrosion – indicates discontinuous oxygenation conditions in the subsurface close to the seafloor at the Buje seep sites. The precipitation of the ¹³C-depleted micrite driven by anaerobic oxidation of methane occurred in anoxic environments within the pore space of the detrital background sediment, leading to the occlusion of the sedimentary matrix. After the pore space was successively filled by micrite, carbonate precipitation was largely restricted to some cavities resulting from preceding bioturbation, and allowing for the formation of fibrous, banded and botryoidal aragonite cement and clotted micrite. Based on the evidence for carbonate corrosion and the preservation of diagnostic biomarkers, at least some of the aerobic methanotrophic bacteria most probably lived in oxic sediments, rendering unlikely that these biomarkers were exclusively sourced from bacteria dwelling in the water column above the seeps.

A set of observations indicates that the mode of seepage was diffusive rather than advective. The Buje seep limestones largely consist of authigenic micrite cementing background sediments. Such a pattern with the dominance of micrite over early diagenetic aragonite cements is typical for diffusive seepage (e.g. Peckmann, Birgel & Kiel, 2009; Haas *et al.* 2010). Similarly, the faint stratification apparent in the Buje 1 deposit is an additional

argument in favour of this interpretation. Similarly, the circumstance that biphytane occurs in much higher contents than crocetane agrees with the dominance of archaea of the so-called ANME-1 group (Blumenberg *et al.* 2004; Niemann & Elvert, 2008; Rossell *et al.* 2011), another observation in favour of diffusive seepage (Nauhaus *et al.* 2005; Peckmann, Birgel & Kiel, 2009). ANME-1 archaea, like ANME-2 archaea, are commonly associated with sulphate-reducing bacteria of the *Desulfosarcina/Desulfococcus* branch of the Deltaproteobacteria (Knittel & Boetius, 2009). The bacterial partners of the ANME-1 archaea can be discerned from those of ANME-2 archaea by a much higher proportion of *ai*-C₁₅ fatty acid (Blumenberg *et al.* 2004; Niemann & Elvert, 2008), a compound that is particularly abundant in the Buje limestones (see Fig. 10b). All these observations argue in favour of diffusive seepage. It should, however, be kept in mind that other factors than just seepage activity can influence the distribution of ANME-1 versus ANME-2 archaea and the abundance of aerobic methanotrophs as well. An obvious factor for example is temperature, whereby higher temperatures are known for favour ANME-1 over ANME-2 archaea (Nauhaus *et al.* 2005).

It is interesting to note that some Cretaceous seep deposits for which diffusive seepage has been envisaged contain biomarkers of aerobic methanotrophs as well (Peckmann, Birgel & Kiel, 2009; Sandy *et al.* 2012), although the majority of seep deposits lacks these compounds (e.g. Peckmann & Thiel, 2004). Because the sulphate-methane transition zone (SMTZ) tends to be situated deeper within the sediments at sites of diffusive seepage than at sites of advective seepage (e.g. Sahling *et al.* 2002; Luff & Wallmann, 2003), we suggest that the preservation of lipids of aerobic methanotrophs is favoured in limestones forming at seeps typified by diffusive seepage – this is not meant to say that aerobic methanotrophs are necessarily more abundant at diffusive seeps. With aerobic methanotrophy being able to extend to greater sediment depth at diffusive seeps, the likelihood probably increases that the lipids of aerobic methanotrophs become engulfed in authigenic seep carbonates at a later stage

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upon dilatation of the zone of anaerobic oxidation of methane. If seepage continues for extended periods of time – as envisaged for the thick Buje 1 deposit – the prolonged formation of methane-derived carbonates, thus, assures the preservation of process markers of those biogeochemical processes that occurred in close proximity of the strata affected by anaerobic oxidation of methane. This effect will be intensified upon variations of seepage intensity that allow for vertical displacement of the SMTZ (cf. Feng, Chen & Peckmann, 2009). An upward movement of the SMTZ caused by an increase of seepage intensity and accompanied by a shift of carbonate formation to shallower depth will particularly favour the preservation of the lipids of aerobic methanotrophs.

6. Conclusions

The fossil record and molecular age estimates indicate that the dominant taxa of the modern vent and seep fauna appeared during the Eocene. The fossil record of seep communities of this age, however, is highly skewed toward the Pacific region and thus macrofauna of the Buje seep deposits provides a first glimpse into the seep fauna of the Tethyan region. The absence of the main modern taxa (bathymodiolin mussels and vesicomysid clams) from the Buje seeps agrees with other lines of evidence suggesting that the modern vent and seep fauna originated in the Pacific Ocean. The Buje seep fauna also indicates a dynamic evolution of seep faunas in the Tethyan/Mediterranean basin: it resembles Cretaceous to early Palaeogene seep faunas from other parts of the world, whereas the late Miocene ‘*Calcar* a *Lucina*’ fauna in Italy resembles other Miocene to modern seep faunas worldwide, and the Pliocene seep faunas from northern Italy have the somewhat restricted character of Mediterranean seep fauna today that probably resulted from the extinction of the more ‘oceanic’ Miocene seep faunas during the Messinian salinity crisis.

The Buje seep deposits formed as a consequence of anaerobic oxidation of methane as revealed by the presence of ¹³C-depleted biomarkers of methanotrophic archaea and

associated sulphate-reducing bacteria. Apart from these anaerobic prokaryotes, aerobic methanotrophic bacteria lived at the middle Eocene seeps. Their metabolism apparently led to a local decrease of pore water pH values, which resulted in the dissolution of carbonate minerals. The large size of the Buje 1 deposit suggests that seepage activity was long-lasting. (1) Its faint stratification, (2) the dominance of authigenic micrite over early diagenetic fibrous cement, (3) biomarker patterns of the prokaryotes performing anaerobic oxidation of methane, and (4) possibly the preservation of the lipids of aerobic methanotrophs indicate that seepage activity was mostly diffusive rather than advective.

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3 761 **Figure and table captions:**

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7 763 Mediterranean area. (b) Geological sketch of the Istria region and location of the Buje seep
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9 764 deposits (45°24'31''N, 13°40'01''E).

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14 766 Figure 2. Composite image of studied Buje 1 to 3 seep deposits assembled from three
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35 776 (GZG.INV.82758). (d) The protobranch *Nucula* (GZG.INV.82759). (e) Large specimen of
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37 777 *Thyasira* showing the posterior sulcus (GZG.INV.82760). (f-j) The lucinid *Amanocina*; (f)
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41 779 narrow escutcheon (GZG.INV.82762); (i,j) large specimen (GZG.INV.82763) in dorsal view
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43 780 (i) and view on the edentulous hinge (j).

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49 782 Figure 5. Scanned thin sections of the three Buje seep deposits: (a) Buje 1, (b) Buje 2 (c) Buje
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51 783 3. The limestones represent bioturbated mudstone and wackestone; arrows indicate geopetal
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53 784 cavities (a) and black corrosion rims (c).

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Figure 6. Petrography of Buje seep deposits. m – matrix micrite; pm – peloidal micrite; ccc – circumgranular calcite cement; bbc – banded and botryoidal cement; s – sediment; ec – equant calcite cement. (a) Angular clasts cemented by matrix micrite, plane-polarized light. (b) Same detail as (a) showing the brightly fluorescent micrite; fluorescence image. (c) Fossiliferous wackestone containing planktic (white arrows) and benthic (black arrows) foraminifera; plane-polarized light. (d-f) Irregular cavities filled with peloidal micrite, sediment, and different generations of carbonate cements; plane-polarized light.

Figure 7. Petrography of cauliflower micrite. m – matrix micrite; pm – peloidal micrite; ccc – circumgranular calcite cement; cm – cauliflower micrite; ec – equant calcite cement. (a) Domal and grooved cauliflower micrite that grew on peloidal micrite and was postdated by circumgranular calcite and equant calcite cement, plane-polarized light. (b) Detail of (a). (c) Close up view of the cauliflower micrite with internal reticulate porosity filled by microspar (arrows); crossed-polarized light. (d) The cauliflower micrite exhibits an intense autofluorescence; fluorescence image.

Figure 8. Corrosion patterns. m – matrix micrite; bbc – banded and botryoidal cement; s – sediment. (a) Highly irregular cavity surface covered by a black rim (arrows); plane-polarized light. (b) Close up view of the dark irregular rim (arrow); plane-polarized light. (c) Bright spots on corrosion surfaces reveal an enrichment in iron (Fe) and manganese (Mn); see inserted EDS spectrum; SEM micrograph of thin section, backscatter view.

Figure 9. Cross plot of the carbon and oxygen stable isotope compositions in per mil versus VPDB standard of micrite forming the Buje seep deposits.

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Figure 10. Lipid biomarker patterns of the Buje 1 seep deposit; numbers in italics indicate compound-specific $\delta^{13}\text{C}$ values in per mil versus VPDB standard. Gas chromatograms (total ion current) of hydrocarbon (a) and carboxylic acid (b) fractions. (a) Circles – *n*-alkanes; white triangles – regular, head-to-tail linked isoprenoids; black triangles – irregular, tail-to-tail linked isoprenoids; grey triangles – irregular, head-to-head linked isoprenoids (biphytanes); Cr – crocetane; Ph – phytane; PMI – pentamethylicosane; Sq – squalane; black squares – steranes; istd – internal standard. (b) Circles – *n*-fatty acids; *i* – *iso*-fatty acids; *ai* – *anteiso*-fatty acids; M – monoenoic fatty acids; white triangles – regular, head-to-tail linked isoprenoidal acids; PMI – pentamethylicosanoic acid; $\beta\beta$ -32-HA – *17 β (H),21 β (H)-bishomohopanoic acid*; istd – internal standard.

822 Table 1. Schematic overview of the Palaeogene and Neogene seep deposits across the Mediterranean

Locality	Age	Type of seep	Fossil assemblage	$\delta^{13}\text{C}$ [‰VPDB]	$\delta^{18}\text{O}$ [‰VPDB]	References
Emilian Apennine (Italy)	Early Pliocene	Fossiliferous limestones, conduits	Solemyids and lucinids	-25 to -17	-3 to +3	Taviani <i>et al.</i> 1997; Barbieri and Cavalazzi, 2005
Tortona Apennine (Piedmont, Italy)	Late Miocene	<i>Lucina</i> and brecciated limestones, carbonate beds with veins, conduits	Lucinids, tubeworms, bacterial biofilms	-56 to +6	-6 to +7	Dela Pierre <i>et al.</i> 2010; Martire <i>et al.</i> 2010; Natalicchio <i>et al.</i> 2012, 2013
Maiella, central Apennine (Italy)	Late Miocene	Brecciated limestones	absent	-40 to +4	-9 to +4	Iadanza <i>et al.</i> 2013
Monferrato (Piedmont, Italy)	Middle and Late Miocene	<i>Lucina</i> and brecciated limestones, macroconcretions with veins, conduits	Lucinids, tubeworms, bacterial biofilms	-45 to -9	-1 to 8	Clari <i>et al.</i> 1988, 1994, 2009; Peckmann <i>et al.</i> 1999
Sicily (Italy)	Middle and Late Miocene	<i>Lucina</i> and brecciated limestones	Lucinids (?)	-49 to -29	+3 to +9	Ricci Lucchi and Vai, 1994
Tuscan-Romagna Apennine (Italy)	Early and Late Miocene	Fossiliferous and brecciated limestones	Solemyids, lucinids, bathymodiolins, and vesicomys	-58 to -16	-5 to +5	Taviani <i>et al.</i> 1997; Conti and Fontana, 1999, 2005; Lucente and Taviani, 2005
Buje (Croatia)	Middle Eocene	Fossiliferous limestones	Solemyids (<i>Acharax</i>), thysirids (<i>Thyasira</i>), lucinids (<i>Amanocina</i>), nukulids, <i>Callianassa</i>	-42 to -23	-4 to 0	Venturini <i>et al.</i> 1998; this study

Figure 1. Working area. (a) Distribution of the main domains of Cenozoic seep deposits in the Mediterranean area. (b) Geological sketch of the Istria region and location of the Buje seep deposits (45°24'31"N, 13°40'01"E).
129x208mm (600 x 600 DPI)

Figure 2. Composite image of studied Buje 1 to 3 seep deposits assembled from three photographs.
48x14mm (300 x 300 DPI)

Figure 3. Outcrop photographs of the studied seep carbonates. (a) Buje 1 and 2 seep deposits; person for scale. Note that the Buje 1 seep deposit is faintly stratified. (b) The lenticular Buje 3 seep deposit; hammer for scale.
121x185mm (300 x 300 DPI)

Figure 4. Bivalves from the Buje 1 seep deposit. (a-c) The solemyid *Acharax*; (a) large specimen (GZG.INV.82757), (b) detail showing the S-shaped band on the anterodorsal shell margin (arrow), and (c) small fragment showing radial ribs on the anterior part of the shell (GZG.INV.82758). (d) The protobranch *Nucula* (GZG.INV.82759). (e) Large specimen of *Thyasira* showing the posterior sulcus (GZG.INV.82760). (f-j) The lucinid *Amanocina*; (f) specimen with naticid drill hole (arrow; GZG.INV.82761); (g,h) specimen showing the narrow escutcheon (GZG.INV.82762); (i,j) large specimen (GZG.INV.82763) in dorsal view (i) and view on the edentulous hinge (j).
168x178mm (300 x 300 DPI)

Figure 5. Scanned thin sections of the three Buje seep deposits: (a) Buje 1, (b) Buje 2 (c) Buje 3. The limestones represent bioturbated mudstone and wackestone; arrows indicate geopetal cavities (a) and black corrosion rims (c).
165x341mm (300 x 300 DPI)

Figure 6. Petrography of Buje seep deposits. m – matrix micrite; pm – peloidal micrite; ccc – circumgranular calcite cement; bbc – banded and botryoidal cement; s – sediment; ec – equant calcite cement. (a) Angular clasts cemented by matrix micrite, plane-polarized light. (b) Same detail as (a) showing the brightly fluorescent micrite; fluorescence image. (c) Fossiliferous wackestone containing planktic (white arrows) and benthic (black arrows) foraminifera; plane-polarized light. (d-f) Irregular cavities filled with peloidal micrite, sediment, and different generations of carbonate cements; plane-polarized light.

191x215mm (300 x 300 DPI)

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127x96mm (300 x 300 DPI)

Figure 8. Corrosion patterns. m – matrix micrite; bbc – banded and botryoidal cement; s – sediment. (a) Highly irregular cavity surface covered by a black rim (arrows); plane-polarized light. (b) Close up view of the dark irregular rim (arrow); plane-polarized light. (c) Bright spots on corrosion surfaces reveal an enrichment in iron (Fe) and manganese (Mn); see inserted EDS spectrum; SEM micrograph of thin section, backscatter view.
182x416mm (300 x 300 DPI)

Figure 9. Cross plot of the carbon and oxygen stable isotope compositions in per mil versus VPDB standard of micrite forming the Buje seep deposits.
146x267mm (600 x 600 DPI)

Figure 10. Lipid biomarker patterns of the Buje 1 seep deposit; numbers in italics indicate compound-specific $\delta^{13}C$ values in per mil versus VPDB standard. Gas chromatograms (total ion current) of hydrocarbon (a) and carboxylic acid (b) fractions. (a) Circles – n-alkanes; white triangles – regular, head-to-tail linked isoprenoids; black triangles – irregular, tail-to-tail linked isoprenoids; grey triangles – irregular, head-to-head linked isoprenoids (biphytanes); Cr – crocetane; Ph – phytane; PMI – pentamethylcosane; Sq – squalane; black squares – steranes; istd – internal standard. (b) Circles – n-fatty acids; i – iso-fatty acids; ai – anteiso-fatty acids; M – monoenoic fatty acids; white triangles – regular, head-to-tail linked isoprenoidal acids; PMI – pentamethylcosanoic acid; $\beta\beta$ -32-HA – 17 β (H),21 β (H)-bishomohopanoic acid; istd – internal standard.

202x241mm (600 x 600 DPI)