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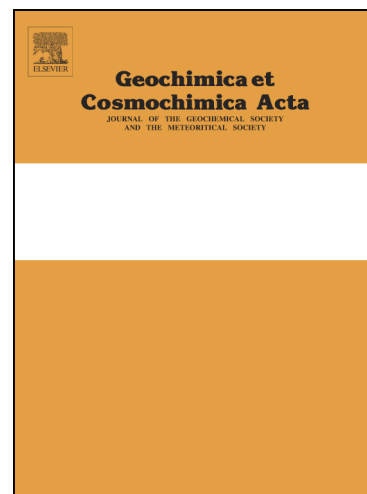
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Contribution of NAD 2D-NMR in liquid crystals to the determination of hydrogen isotope profile of methyl groups in miliacin

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Abstract

The hydrogen isotopic composition (δD or (D/H) value) of molecular biomarkers preserved in sedimentary archives is increasingly used to provide clues about the evolution of past climatic conditions. The rationale is that intact biomarkers retain isotopic information related to the climatic conditions that prevailed at the time of their synthesis. Some of these biomarkers may be degraded during diagenesis, however. The extent to which these degradations alter the original δD value of the source biomarker is presently debated and the capacity to resolve the debate by determinations of compound-specific δD values alone is limited. The “bulk” or “global” δD value of any molecule is in fact a composite of δD values at each site within this molecule ($(\delta D_i$ or (D/H)_{*i*} with *i*= number of hydrogen/deuterium atoms in the considered molecule). Determination of this site-specific δD_i value in biomarkers could not only yield outstanding paleoenvironmental information but also help forecast the impacts of diagenesis and define essential steps in biosynthetic pathways.

This task is analytically challenging. Here, we examined the capabilities of natural abundance deuterium 2D-NMR (NAD 2D-NMR) using homopolypeptide liquid crystals as an NMR solvent to: i) analyze the NAD spectra of biomarkers; ii) determine the site-specific distribution of hydrogen in the nine methyl groups (δD_{Mei} with *i*= 23 to 31) of miliacin, a pentacyclic triterpene of the amyrin family and key biomarker for broomcorn millet in sedimentary archives. Relative (D/H)_{Mei} values were established by anisotropic NAD 2D-NMR. Then absolute δD_{Mei} values were obtained by determining δD_{Mei} value of the methoxy group of miliacin using two independent approaches: isotropic NAD NMR (SNIF-NMRTM) and GC-irMS. The resulting isotope profile for miliacin shows, for the first time, large variations in δD_{Mei} values that can directly be explained by biosynthetic processes. This approach has also the potential to permit predicting fractionations during pentacyclic triterpene diagenesis.

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50 **1. INTRODUCTION**

51
52 Higher plant pentacyclic triterpenes are natural products that bear an oxygenated group at the C-3
53 position (**Fig. 1**). The large diversity of structures, isomerisms and functional groups resulting from
54 specific enzymatic processes have led to the use of compounds in this family for establishing precise
55 chemotaxonomic relationships (Das and Mahato, 1983; Mahato et al., 1992; Mahato and Sen, 1997).
56 Although β - and α -amyrins are very common structures in angiosperms, several classes of
57 compounds are more or less specific to given taxa. For example, pentacyclic triterpenes with an
58 acetate function at C-3 are largely restricted to Asteraceae species (Lavrioux et al., 2011) whereas
59 those bearing a methoxy group at the C-3 position are mostly synthesized by Poaceae (Ohmoto et al.,
60 1970; Jacob et al., 2005). After the death of their source organisms, these compounds may be
61 archived in geological deposits such as soils or sediments. If diagenesis does not strongly modify
62 their structure, these compounds can be analyzed for presence/absence and concentrations in
63 sedimentary records in order to reconstruct past vegetation dynamics (e.g., Cranwell et al., 1984;
64 Killops et al., 1995; van Aarsen et al., 2000; Regnery et al., 2013).

65 3β -methoxyolean-18-ene, usually denoted miliacin or germanicol methyl ether (**Fig. 1**), is such a
66 specific molecular biomarker. It is a pentacyclic triterpene bearing a methoxy group at position C-3
67 that is predominantly produced by Poaceae species. Furthermore, this compound is most abundant in
68 broomcorn millet (*Panicum miliaceum* L) (Itô et al., 1934; Ohmoto et al., 1970; Bossard, 2013).
69 Miliacin concentrations in lake sediments and soils have thus been used to reconstruct the history of
70 millet cultivation (Jacob et al., 2008, 2008b, 2009; Simonneau et al., 2013; Motuzaitė-Matuceviciute
71 et al., 2013).

72 In addition to these crucial information on past vegetation, the hydrogen isotopic compositions
73 (δD or D/H) of lipid compounds, such as miliacin, in geological deposits are providing superior
74 insights about paleoclimate (Sachse et al., 2012; Terwilliger et al., 2013; Terwilliger and Jacob,
75 2013). This is because meteoric water is the original source of hydrogen atoms in biochemicals
76 produced by autotrophs and the δD values of meteoric water are strongly influenced by climate
77 (Dansgaard et al., 1964; Gat et al., 1996). Further studies are needed in order to fully exploit the
78 paleoclimate potential of δD values of lipid compounds for providing clues about past climates, with
79 distinct levels of understanding on the processes occurring at different steps (Sachse et al., 2012).
80 The impacts of environmental factors such as soil evaporation and leaf transpiration are relatively
81 well identified. Leaf transpiration can alter the δD value of meteoric water along its path to the sites
82 of photosynthesis where its hydrogen atoms from leaf water will be used to produce organic
83 compounds via biosynthetic pathways (Sessions et al., 1999; Chikaraishi and Narakoa, 2003; Hou et
84 al., 2007b; McInerney et al., 2011). Additionally, it has been demonstrated that plant type can cause
85 differences in δD values of the most common lipid compounds such as *n*-alkyl lipids (Sachse et al.,

86 2006; Liu et al., 2006; Smith and Freeman, 2006; Hou et al., 2007; Feakins and Sessions, 2010;
87 Wang et al., 2013). Because it would not be affected by variations caused by differences in plant-
88 source taxa, the δD value of more specific compounds such as sedimentary miliacin is expected to
89 solve this issue and could provide even higher resolution information about climatic conditions at the
90 time of their synthesis (Bossard et al., 2011; Bossard, 2013; Terwilliger et al., 2013; Schwab et al.,
91 2015). A better understanding of the biosynthetic pathway that designs the δD values of a given
92 compound is also necessary since distinct NADPH sources and enzymatic processes can lead to
93 highly variable fractionations (i.e. Sauer et al., 2001; Chikaraishi et al., 2004, 2009). Although the
94 biosynthetic pathway of pentacyclic triterpenes such as miliacin is rather well known (Xu et al.,
95 2004), associated H isotopic fractionations are less understood.

96 Finally, it is crucial to determine whether diagenetic derivatives retain the original paleoclimate
97 information acquired by biochemicals during biosynthesis. For instance, pentacyclic triterpenes can
98 undergo several transformations during early diagenesis such as the loss of functional groups, the loss
99 of rings, double bond migration, aromatization, or epimerization of methyl groups (Corbet, 1980;
100 Trendel, 1985; Lohmann, 1988; Jacob et al., 2007). Only isotopic exchanges with water have been
101 addressed on polycyclic compounds (Wang et al., 2013) but the impact of diagenetic transformations
102 on δD values of diagenetic by-products compared to their precursors is yet unknown.

103
104 Our hypothesis is that a site-specific (or intramolecular) heterogeneous distribution of hydrogen
105 isotopes in a biochemical precursor would explain any isotopic difference with its derivatives caused
106 by the preferential loss of D-enriched or D-depleted groups during diagenesis. Identifying such
107 isotopic difference between biochemicals and their diagenetic derivatives will allow better climate
108 reconstructions from δD values of diagenetic derivatives. In addition, obtaining the site-specific
109 distribution of hydrogen isotopes could provide useful information on biosynthetic pathways. As
110 emphasized by Eglinton and Eglinton (2008), "*intramolecular compound-specific isotope*
111 *measurements (i.e., analyses of the distribution of isotopes within a molecular structure) are*
112 *analytically challenging and presently rarely attempted, but may ultimately prove of value*" and so
113 addressing this hypothesis requires the development of new tools.

114 The two main objectives of our study were to test the hypothesis that hydrogen isotopes are not
115 randomly distributed in molecular biomarkers and to identify the means of analyzing the site-specific
116 distribution of hydrogen isotopes necessary for this test. We use miliacin as a representative of
117 pentacyclic triterpenes. Specifically, we determined the (D/H) ratios (δD) of hydrogen located in the
118 methyl groups of miliacin by Natural Abundance Deuterium (NAD), two-dimensional Nuclear
119 Magnetic Resonance (2D-NMR) spectroscopy using aligning organic media (anisotropic systems) as
120 NMR solvents. This advanced technique modifies the well-known SNIF-NMRTM method pioneered

121 by Martin and co-workers in the 80's (Martin et al., 1980; 1986) by dissolving the analyte in a liquid
 122 crystal (LC) instead of a liquid solvent (isotropic system). The replacement of isotropic to oriented
 123 solvent is analytically highly valuable because we have access to ^2H residual quadrupolar couplings
 124 in solutes, leading to the presence on ^2H NMR spectra of quadrupolar doublets (QD) for each
 125 inequivalent deuteron instead of singlets. The range of splittings of each QD leads in turn to
 126 distribute the NAD signals on larger spectral windows, thus reducing the peak overlaps.
 127 Concomitantly the use of 2D-NMR experiments simplifies the analysis of entangled, overcrowded
 128 anisotropic NAD 1D-NMR spectra. As we will see, this approach makes it possible to distinguish
 129 several NAD signals from H in methyl groups of miliacin that resonated at the same (or very close)
 130 frequencies in isotropic solvents. This unusual strategy has been recently pioneered by Lesot and
 131 coworkers for analyzing the site-specific isotope ratios, $(\text{D}/\text{H})_i$, in fatty acids and then triglycerides
 132 (Lesot et al., 2008, 2009, 2011, 2012; Serhan et al., 2010). We report here its first application for
 133 investigating biomarkers of interest such as miliacin.

134

135 2. ANISOTROPIC ^2H NMR SPECTROSCOPY

136

137 When a molecule in the spectrometer's magnetic field does not tumble isotropically, all
 138 orientation-dependent NMR interactions become visible on spectra. Thus ^2H NMR spectra of solutes
 139 in a mesophase contains new informative NMR interactions such as the chemical shift anisotropy (^2H
 140 CSA); ii) the dipolar interactions (D); iii) and the quadrupolar interaction ($I \geq 1$) (Sarfati et al., 2000;
 141 Lesot et al., 2015) (isotopically normal or enriched).

142 Assuming that ^2H CSA is generally negligible while the ^2H - ^1H couplings can be removed by
 143 ^1H decoupling, the ^2H signal of aligned monodeuterated molecule is a simple QD (two transitions)
 144 centered on the anisotropic ^2H chemical shift, $\delta(^2\text{H})^{\text{aniso}}$, (generally $\delta(^2\text{H})^{\text{aniso}} \approx \delta(^2\text{H})^{\text{iso}}$) (Lesot et al.,
 145 2009). The separation (in Hz) between components of doublet is referred to as ^2H quadrupolar
 146 splitting (or the residual quadrupolar coupling) and will be noted $\Delta\nu_{\text{Q}_i}(^2\text{H})$ therein (**Fig. S-4**,
 147 **Appendix A.II**). For a C-D internuclear directions oriented in a weakly-aligning LC, the electric
 148 field gradient ($V_{\text{C-D}}$) is usually assumed to be axially symmetric along the C-D vector and the value
 149 of $\Delta\nu_{\text{Q}_i}$ relative to the \mathbf{B}_0 can be expressed as (**Eq. 1**; Sarfati et al., 2000; Lesot et al., 2009):

150

$$151 \Delta\nu_{\text{Q}} = \frac{3}{2} C_{\text{Q}}^{\text{D}_i} \times S_{\text{C-D}_i} = \frac{3}{2} \left(\frac{eQ_{\text{D}_i} V_{\text{C-D}_i}}{h} \right) \times \left(\frac{1}{2} \langle 3\cos^2(\theta_{\text{C-D}_i}) - 1 \rangle \right) \quad (1)$$

152

153 where $C_{\text{Q}}^{\text{D}_i}$ is the quadrupolar coupling constant at deuterium atom i , $S_{\text{C-D}_i}$ is the order parameter of
 154 the C-D _{i} vector and $\theta_{\text{C-D}_i}$ is the angle between the \mathbf{B}_0 magnetic field axis and the C-D _{i} bond axis.

155 The $\langle \dots \rangle$ denotes an ensemble average. As the trigonometric function in brackets varies between 1

156 (when $\theta_{C-D_i} // \mathbf{B}_0$) and -0.5 (when $\theta_{C-D_i} \perp \mathbf{B}_0$), $\Delta\nu_{Q_i}$ can be positive or negative. When θ_{C-D_i} is
157 equal to 54.7° (the so-called ‘magic angle’), S_{C-D_i} becomes null, and so the doublet collapses to a
158 single line.

159 As the second stable isotope of hydrogen, deuterium atoms are naturally in all organic
160 compounds, and hence they can be used as nuclear probe to study the site-specific natural isotope
161 distribution of molecules. Even with low natural abundance of deuterons (around $1.55 \cdot 10^{-2} \%$ V-
162 SMOW value; De Laeter et al., 2003), routine NMR spectrometers can detect quite easily (with
163 reasonable experimental times) their NMR signals both in isotropic and anisotropic solvents,
164 successful results depending also on the concentration of the analyte and its molecular weight (Lesot
165 et al., 1998, 2009).

166 Proton-decoupled NAD NMR spectra of solutes dissolved in homogeneous mesophases
167 consist of a sum of resolved independent quadrupolar doublets instead of single lines as in liquids,
168 each of them corresponding to the various inequivalent ^2H sites in the molecule. For middle to large-
169 sized molecules, the distribution of positions and the splitting of ^2H doublets over the spectral
170 window can generate complex spectra (with possible overlaps of resonances), where the assignment
171 of QD can be ambiguous. Various two and three-dimensional (2D/3D) NMR sequences belonging to
172 NMR experiment class entitled “QUadropole Ordered SpectroscopY” (QUOSY) have been
173 specifically developed to achieve clearer analyses of overcrowded anisotropic NAD 1D spectra
174 (Merlet et al, 1999; Lesot and Lafon, 2008b). All of them allow the spectral information (δ , $\Delta\nu_Q$) to
175 be distributed on several (two or three) spectral dimensions (F_1 , F_2 and F_3), thus facilitating the
176 assignment of ^2H quadrupolar doublets.

177

178 3. ANALYTES, MATERIALS AND METHOD

179

180 3.1. Structure of miliacin and germanicol

181 Like other pentacyclic triterpenes, miliacin is formed from mevalonic acid *via* the mevalonate
182 pathway through the cyclisation of squalene epoxide by an oxidosqualene cyclase (Xu et al., 2004;
183 **see Section 6**). This scheme leads to the formation of germanicol, a triterpene alcohol constituted of
184 five six-membered rings (**Fig. 1**) that bear eight methyl groups (Me23 to Me30). The final conversion
185 of the alcohol function into a methyl ether function, which principally takes place in plants of the
186 family Poaceae (Jacob et al., 2005), transforms germanicol into miliacin, by the addition of a methyl
187 group (Me31) linked to the oxygen on the C-3 position. In miliacin, the nine methyl groups are
188 numbered from Me23 to Me31 (**Fig. 1**). For simplicity, the five 6-membered rings of miliacin have
189 been labeled A-E and contain two or three methyl groups each (ring A: Me23, Me24 and Me 25; ring
190 C: Me26 and Me27; ring E: Me28, Me29 and Me30).

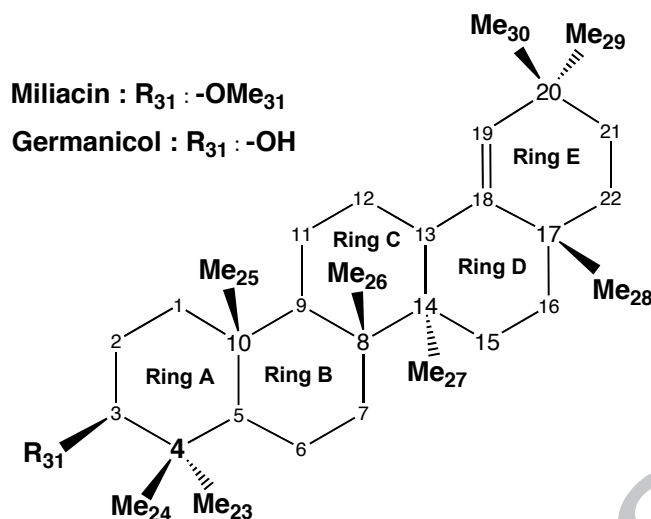


Figure 1: Structure of miliacin where $R_{31} = -OMe$ and germanicol where $R_{31} = -OH$, together with the atomic numbering used and notation of rings (A to E) and methyl groups (23 to 31).

3.2. Miliacin and germanicol extraction and purification

Miliacin and germanicol were recovered from millet oil (provided by HITEX, Vannes, France) of > 98% purity as determined by Gas Chromatography/Mass Spectrometry (GC/MS). 6 g of miliacin were directly recovered from 750 ml of oil by repeated precipitation in cold acetone (Itô, 1934). From these 6 g of analyte, only about 100 mg of miliacin was necessary to prepare NMR samples used for NAD NMR analyses described in this work. Germanicol, which is far less abundant than miliacin in the oil, was recovered from a longer process of separating the oil into neutral, acidic and polar fractions by Solid Phase Extraction using aminopropyl bonded silica (Jacob et al., 2005). The neutral fraction was recovered by elution with CH_2Cl_2 :isopropanol (9:1) and further separated on activated silica (120 °C during 24 h) deactivated with 5% weight water. After elution of aliphatic hydrocarbons, aromatics, esters and ether, and ketones, the alcohol fraction that contains germanicol was eluted with 2 ml of hexane:ethyl acetate (85:15) and then 2 ml of hexane:ethyl acetate (80:20) as described by Jacob et al. (2008b). To eliminate the large amounts of sitosterol that coelutes with germanicol, we then separated the alcohol fraction on activated silica by splitting the alcohol fraction into sub-fractions of 500 μ l of hexane:ethyl acetate (85:15). After GC/MS analysis of an acetylated aliquot of these sub-fractions, we combined fractions containing germanicol.

3.3. Miliacin and germanicol δD values by GC-irMS

Germanicol was acetylated into germanicol acetate with acetic anhydride and pyridine (1:1) during 1h at 80°C prior to its GC-irMS analysis. Acetic anhydride with an offline-determined δD value of -133 ± 2 ‰ was acquired from A. Schimmelmann (Indiana University, USA). After drying under nitrogen, the fraction was dissolved in isooctane prior to analysis by Gas Chromatography-isotope ratio Mass Spectrometry (GC-irMS) in order to determine its δD value. Miliacin from the 6 g

219 in-house stock was also dissolved in isooctane prior to GC-irMS analysis.

220 δD values were determined on a TraceGC chromatograph equipped with a Triplus
 221 Autosampler coupled to a DeltaV Advantage isotope ratio mass spectrometer through a GC-Isolink
 222 interface and a Conflo IV dilution system (all from Thermo Scientific, Bremen, Germany). The gas
 223 chromatograph was fitted with a TG5-MS capillary column (60 m, 0.25 mm i.d., 0.25 μm film
 224 thickness; ThermoScientific). The temperature of the column was held at 80°C for 1 min, and then
 225 increased from 80 to 300°C at 20°C.min⁻¹, with a final isothermal hold at 300°C for 30 min. Precision
 226 and accuracy were determined by using a mixture of 15 *n*-alkanes (*n*-C₁₆ to *n*-C₃₀) with δD values
 227 ranging from -9 to -254 ‰ determined off-line (A5 mixture, A. Schimmelmann, Indiana University,
 228 USA) and allowed us to normalize the δD values of miliacin ($\delta D_{\text{miliacin}}$) and of germanicol ($\delta D_{\text{germanicol}}$)
 229 to the V-SMOW isotopic scale. The measured δD values for the standard *n*-alkanes are in good
 230 agreement with those measured off-line ($r^2 = 0.987$). The overall precision for the *n*-alkanes standards
 231 was $\leq 4\%$. Samples were injected at least three times and were accurate to $\pm 5\%$ for miliacin and
 232 germanicol. The δD value of germanicol acetate was mathematically corrected from the contribution
 233 of acetic anhydride to obtain the $\delta D_{\text{germanicol}}$ value. Our results are shown as both (D/H) ratios in ppm
 234 and δD values in ‰, calculated using a (D/H) value of V-SMOW of 155.76 ± 0.05 ppm, and
 235 converting from ppm values to ‰ values using Equation 2:

$$236 \quad \delta D = \left(\frac{(D/H)_i}{(D/H)_{\text{V-SMOW}}} - 1 \right) \times 1000 \quad (2)$$

237 3.4. Isotropic ¹H and ¹³C NMR of miliacin

239 The full assignment of the proton and carbon-13 signals recorded in liquid solvents (CDCl₃)
 240 was achieved using homonuclear ¹H-¹H 2D COSY, heteronuclear ¹³C-¹H HMBC and HMQC 2D
 241 experiments combined with the analysis of ¹³C-¹³C ADEQUATE 2D spectrum. Several isotropic
 242 NMR spectra of miliacin are given in **Figs. S-1, S-2 and S-3** in **Appendix A.II**. All isotropic NMR
 243 data were recorded on a Bruker 9.4 T (400 MHz) Advance I spectrometer equipped with 5 mm o.d.
 244 BBI probe.

245 3.5. Preparation of polypeptide oriented samples

246 The ability to solubilize a given analyte but also to form a polypeptidic homogeneous liquid-
 247 crystalline phase is an important factor that depends on what organic co-solvent is chosen. We were
 248 best able to solubilize miliacin using 30 mg of miliacin, 80 mg of poly- γ -benzyl-*L*-glutamate (PBLG)
 249 with a degree of polymerization of 743 (MW (viscosity) = 162 900 g/mol) and 810 mg of
 250 chloroform, corresponding to 8.7% w/w (PBLG) and 3.2 % w/w (miliacin). Over this latter mass
 251 ratio, miliacin is not totally dissolved in the mesophase, and solid particles are visible, even at higher
 252 temperatures. Other polar and apolar organic solvents that we experimented and that proved less

253 satisfactory include CH_2Cl_2 , tetrachloroethane, THF, dioxane, pyridine. For all of them, the solubility
254 of miliacin was found to be extremely low. Note that even DMSO (incompatible with PBLG) is not
255 suitable.

256 As the polypeptide is chiral, oriented solutions of PBLG is able to discriminate between NMR
257 signals of enantiomers of wide range of organic molecules but also enantiotopic directions in
258 prochiral compounds (Lesot et al., 2000, 2009). Nevertheless, in this work, PBLG was selected not
259 for its enantiodiscriminating properties, which are useless for miliacin (enantiopure biocompound), but
260 for its ability to homogeneously orient a guest molecule with a rather low degree of alignment (Lesot
261 et al., 2000).

262 Due to the high molecular weight ($\text{MW} = 440.7 \text{ g/mol}$) and the small amount of miliacin that
263 can be solubilized in the PBLG/ CHCl_3 mesophase (only 30 mg), the molar amount in
264 monodeuterated isotopomers is equal to $3.17 \times 10^{-8} \text{ mol}$ for methyl groups and $1.06 \times 10^{-8} \text{ mol}$ for
265 methines, if $(\text{D/H}) = 1.55 \times 10^{-2}\%$. Assuming that density of the mixture is equal to 1, the
266 concentration of isotopomers in the sample at methyl and methine sites is evaluated at about 3.4
267 $\mu\text{mol/l}$ and 1.14 $\mu\text{mol/l}$, respectively. This isotopomeric concentration is weak (30 fold less)
268 compared to the value of chloroform. However recording anisotropic NAD spectra of solute with
269 rather short recycling delays ($T_R = 1 \text{ sec}$) allows to significantly reduce the intensity of ^2H signal of
270 CDCl_3 (and avoid a bad digitization of solute signals) whereas quantitative conditions ($T_R = 5T_1(^2\text{H})$)
271 were maintained to record the ^2H signals of miliacin (Lesot et al., 2008).

272 273 **3.6. Anisotropic NAD 2D-NMR in LC**

274 All anisotropic NAD 2D-NMR spectra were recorded with a 14.1 T Bruker Advance II
275 spectrometer (92.1 MHz for deuterium nuclei) equipped with a 5 mm o.d. selective ^2H cryogenic
276 probe. NAD Q -resolved Fz 2D experiments combined with proton Waltz-16 decoupling sequence
277 was chosen to analyze of NAD NMR spectra of miliacin dissolved in PBLG/ CHCl_3 (Lafon et al.,
278 2009). In this experiment, the ^2H chemical shifts are refocused in the F_1 dimension. After a double
279 FT, the 2D map can be tilted (see the principle on **Figure S-5** in **Appendix A.II**), and then
280 symmetrized, thereby spreading the ^2H chemical shifts, $\delta(^2\text{H})$, and quadrupolar splittings, $\Delta\nu_Q(^2\text{H})$
281 information in the F_2 (horizontal axis) and F_1 (vertical axis) dimensions, respectively. Thus a series
282 of ^2H singlets are displayed in F_2 whilst a series of independent ^2H doublets are observed in F_1 .

283 The anisotropic Q -resolved Fz 2D spectra were recorded using a 2D matrix of 2652 (t_1) \times 300
284 (t_2) data points, then zero-filled to 4096 (t_1) \times 1024 (t_2) data points *prior* the double FT. 256 scans
285 were added at each t_1 increment. A lorentzian filtering was applied in both dimensions ($\text{LB} = 1.5 \text{ Hz}$).
286 The recycling delay (T_R) of anisotropic NAD 2D experiments was set to 1 sec, leading to a total
287 acquisition time of 24 hours. Such a delay is large enough to record the anisotropic NAD spectrum

288 of miliacin with quantitative conditions and reliable evaluation of peak integrals (on 1D spectra) or
 289 2D volume on 2D spectra of miliacin is then possible (Lesot et al., 2008). “Integral of two
 290 components of NAD doublets measured on 1D traces extracted to 2D maps (see below and sup info)
 291 were determined by peak deconvolution (Top-spin 3.0 software)“. To improve the accuracy of the
 292 measure of (D/H) ratios and evaluate the standard deviation, six identical NAD 2D-NMR
 293 experiments on the same NMR sample of miliacin were recorded and analysed.

295 3.7. SNIF-NMR™ protocol and experimental details

296 According to the SNIF-NMR protocol, isotropic NAD 1D-NMR spectra of analytes are
 297 recorded under quantitative conditions ($T_R = 5T_1$) with internal isotopic reference whose D/H ratio is
 298 calibrated. If the mass of compounds (analyte and reference) is accurately weighted, the site-specific
 299 (D/H)_i ratios (expressed in ppm) can be calculated from evaluation of peaks surface on NMR spectra
 300 as follows (Eq. 3; Lesot et al., 2011; Martin et al., 1986):

$$(D/H)_i^{anal} = \left(\frac{A_i^{anal}}{A_i^{ref}} \right) \times \left(\frac{P_i^{ref} \times m^{ref} \times M^{anal}}{P_i^{anal} \times m^{anal} \times M^{ref}} \right) \times (D/H)_i^{ref} \quad (3)$$

301 In Eq. 3, A_i^{anal} and A_i^{ref} are the areas of the signals at site *i* for the analyte and the reference, P_i^{anal} and
 302 P_i^{ref} are their stoichiometric numbers of hydrogen at site *i*, M^{anal} , M^{ref} , m^{anal} and m^{ref} are the molecular
 303 weights and masses of the analyte and the reference, respectively. Finally, $(D/H)_i^{ref}$ is the isotope
 304 ratio of reference (at site *i*).

305 From the experimental conditions viewpoint, the SNIF-NMR 1D spectrum of miliacin was
 306 recorded in chloroform in the presence of isotopically calibrated tetramethyl urea (TMU) as internal
 307 chemical reference ((D/H)_{TMU} = 84.4 ± 2 ppm, Lot 0116XAC from Eurofins). The temperature of
 308 305 K used provided a good compromise between a reasonable experimental time for the NAD 1D
 309 experiments (< 15 h) and a full solubilization of miliacin. At 305 K, the $T_1(^2H)$ of TMU was
 310 measured at 1.17 sec (average of three NAD inversion-recovery 1D-NMR experiments), leading to a
 311 recycling delay, T_R , of 6 sec (with 3.5 sec of acquisition time) and in turns to a total acquisition time
 312 of 15 hours for 9000 scans added. Six experiments were recorded with 6k data points (zerofilled to
 313 16K), filtered by an exponential function (1 Hz) prior FT and peak integral for Me31 and TMU
 314 signal were quantified by peak deconvolution after a baseline correction.

315 The mixture was prepared in a small flask tube by adding 39.9 mg of miliacin and 18.6 mg of
 316 TMU (MW = 116.16 g.mol⁻¹) and 1.640 g of dry CHCl₃. The flask was then actively mixed (by
 317 strongly shaking) prior to a part of mixture (≈ 700 mg; this amount is optimized for the length of the
 318 coil in cryogenic probe) was transferred into the 5-mm NMR tube. The tube has been fire-sealed to
 319 avoid long-term solvent evaporation. Due to the low solubility of miliacin in CHCl₃, the sample was
 320

321 prepared with larger amounts of components in order to reduce the error on the weightings of small
 322 masses. Also, the mass of TMU used (twelve deuterium equivalent sites) was calculated to reach a
 323 ratio in peak intensity of TMU and Me31 (three deuterium equivalent sites) equal to about 4, thus
 324 optimizing the S/N ratio of TMU.

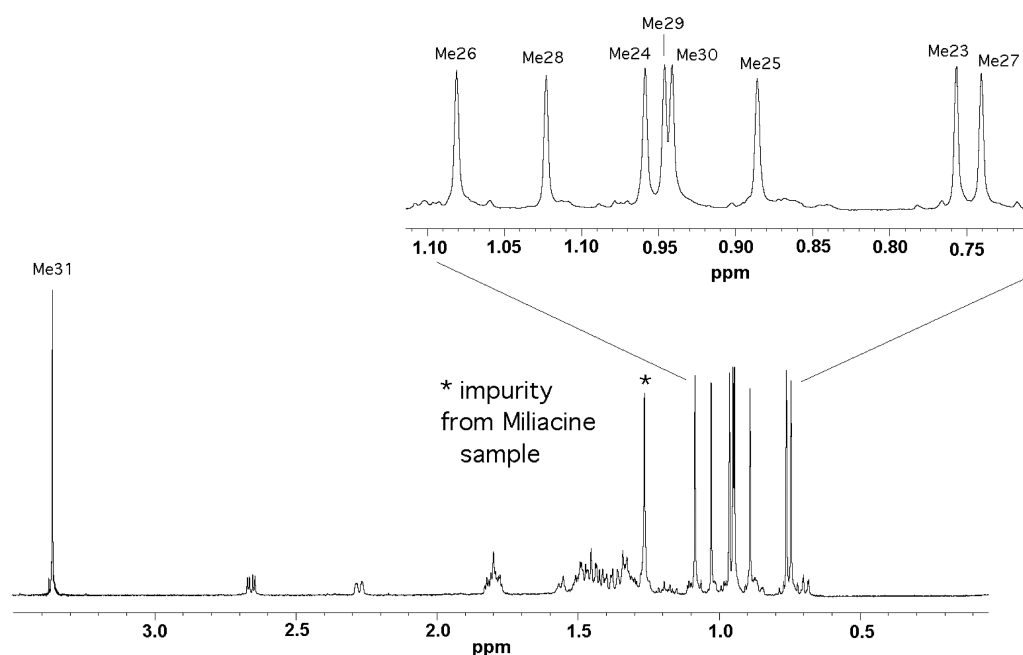
325

326 4. RESULTS

327

328 4.1. Spectral assignment of isotropic ^1H and ^{13}C resonances

329 In order to avoid any misinterpretation of the isotopic profile of methyl groups on miliacin,
 330 we re-examined the assignment of ^1H signals in combination with ^{13}C signals before analyzing NAD
 331 2D spectra in oriented solvent and then evaluating the site-specific isotope distribution. **Fig. 2** gives
 332 the 600 MHz ^1H spectrum of miliacin dissolved in chloroform at 295 K. Due to the presence of
 333 several stereogenic centers (asymmetric carbons), the geminal protons in CH_2 groups and the *gem*-
 334 dimethyl groups are diastereotopic, and hence yield distinct ^1H (and also ^2H) signals. The proton-
 335 decoupled carbon-13 1D spectrum ($^{13}\text{C}\{-^1\text{H}\}$) as well as $^{13}\text{C}/^1\text{H}$ heteronuclear HSQC and HMBC 2D
 336 spectra of miliacin dissolved in chloroform at 295 K and recorded at 9.4 T (100 MHz) (**Fig. S-1**)
 337 (**Figs. S-2 and S-3**) are presented in **Appendix A.II**. The combined analysis of all spectral data
 338 allows an unambiguous assignment of all ^{13}C and ^1H resonances. The full assignment of ^{13}C and ^1H
 339 signals is listed in **Tables S-1, S-2 and S-3** in **Appendix A.I**. Note here that our assignment agrees
 340 with Smetanina et al. (2001), but the two ambiguities pointed out by these authors have been
 341 eliminated (**Fig. S-5** in **Appendix A.II**).



342

343 **Figure 2:** 600.1 MHz proton 1D-NMR spectrum of miliacin in CDCl_3 (295 K). The assignment of
 344 resonances of methyl groups is given in **Table S-1, S-2 and S-3** in **Appendix A.I** of **Supp.**
 345 **Info.**). The peak marked by an asterisk ($\delta = 1.24$ ppm) is an unidentified impurity.

346

347 **4.2. Analysis of anisotropic NAD signals of methyl groups**

348 Miliacin is a very illustrative example of the analytical performance of anisotropic NAD 2D-
 349 NMR to determine the intramolecular site-specific isotope distribution. Indeed, on the isotropic NAD
 350 1D-NMR spectrum of miliacin, the resonances of methyl groups, Me₂₄, Me₂₉ and Me₃₀ as well as
 351 Me₂₃ and Me₂₇ are not spectrally resolved (even at 92.1 MHz) (see **Fig. S-4** in **Appendix A.I of**
 352 **Supp. Info.**). As a consequence, only two broad ²H resonances are observed, thus preventing a
 353 specific determination of their respective peak areas, and consequently the associated (D/H) ratios at
 354 each individual site.

355 **Fig. 3a** shows the shielded region of methyl groups (Me₂₃- Me₃₀) of the tilted *Q*-resolved Fz
 356 2D map of miliacin recorded in PBLG/CHCl₃ at 295 K (see **Fig. S-7, Appendix A.II of Supp. Info.**
 357 for the full map). As expected, all methyl signals are now separated on the basis of their $\delta(^2\text{H})$
 358 and $\Delta\nu_Q(^2\text{H})$. The sixteen ²H resonances (8 quadrupolar doublets) detected on the 2D map correspond
 359 to eight inequivalent methyl sites, Me₂₃-Me₃₀; each of them giving one integrated signal of three ²H
 360 equivalent sites. As expected, almost all QDs of methylene and methine ethylene groups of miliacin
 361 do not clearly emerge from the spectral noise (baseline) and cannot be used reliably for quantitative
 362 purposes. In contrast, the doublets of all methyl groups are detected on 2D map with S/N ratios
 363 varying between 8 (Me₃₀) and 25 (Me₂₆) whereas a value of 35 is found for the methyl of methoxy
 364 group (Me₃₁) (**Table 1**). Due to the small amount of miliacin solubilized in the mesophase and its
 365 high MW, the S/N ratios are unusually low. However a reliable (acceptable) evaluation of peak areas
 366 leading to reliable (D/H) ratios is still possible.

367
 368 **Table 1:** Spectral data associated to anisotropic NAD signals of methyl groups
 369 of miliacin at 295 K.

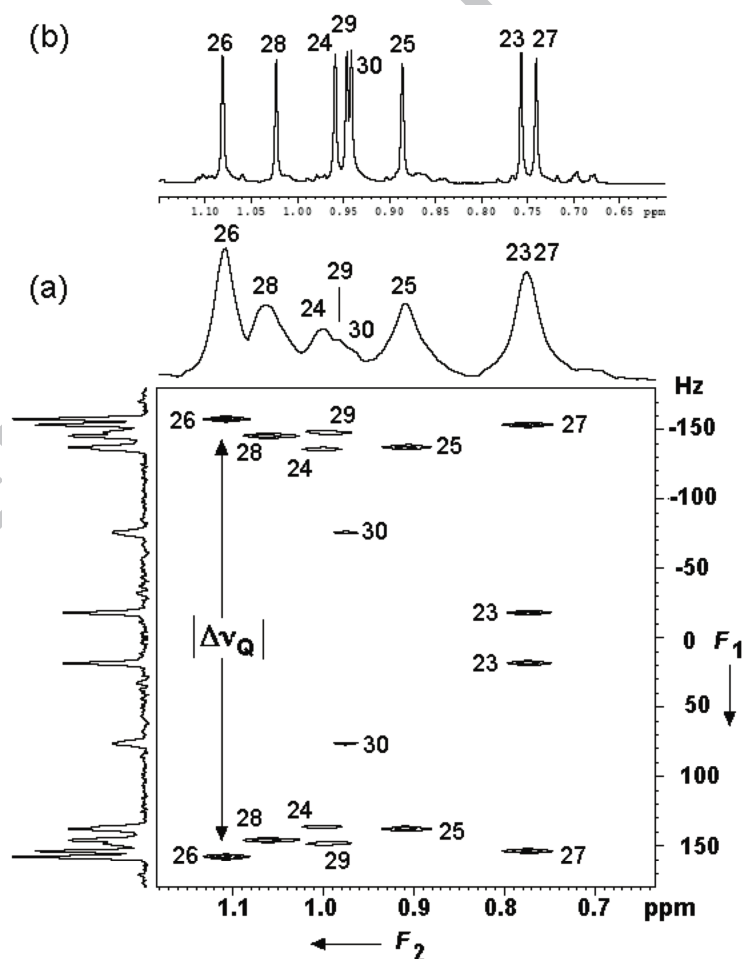
| Methyl group | Ring | $\delta(^2\text{H})^a$ (ppm) | $\Delta_{1/2}$ (Hz) | S/N | $ \Delta\nu_Q $ (Hz) |
|-------------------|------|---------------------------------|------------------------|---------------------|-------------------------|
| Me ₂₇ | C | 0.771 (0.746) | 2.4 | 24 | 309 |
| Me ₂₃ | A | 0.774 (0.763) | 2.8 | 22 | 36 |
| Me ₂₅ | A | 0.905 (0.891) | 3.3 | 12 | 275 |
| Me ₃₀ | E | 0.978 (0.948) | 3.6 | 8 | 272 |
| Me ₂₉ | E | 0.999 (0.952) | 5.6 | 9 | 152 |
| Me ₂₄ | A | 0.982 (0.965) | 3.3 | 9 | 296 |
| Me ₂₈ | E | 1.057 (1.029) | 3.3 | 17 | 292 |
| Me ₂₆ | C | 1.105 (1.086) | 2.3 | 25 | 314 |
| Me ₃₁ | A | 3.399 (3.368) | 2.1 | 35 | 193 |
| CHCl ₃ | — | 7.270 (7.270) | 1.8 | 3000 ^(b) | 273 |

370 ^(a) $\delta(^2\text{H})$ measured on the F_2 projection of anisotropic NAD 2D spectrum ($\delta_{\text{chloroform}} = 7.27$ ppm).

371 In parenthesis are reported the $\delta(^1\text{H})$ measured on the isotropic ¹H 1D-NMR spectrum ($\delta_{\text{chloroform}} = 7.27$ ppm).

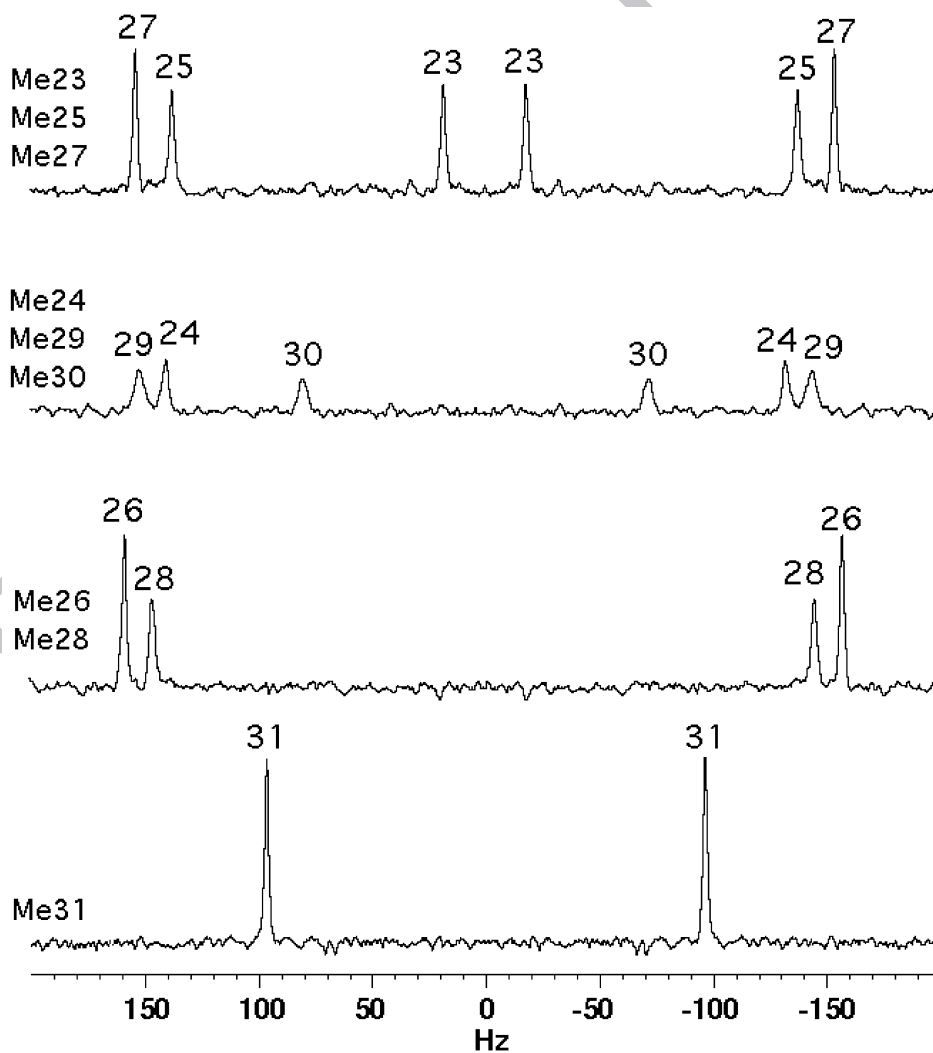
372 ^(b) The large difference between the S/N ratios of Me groups and CHCl₃ originates from the
 373 difference of deuterated isotopomer concentrations and the linewidths of ²H signals.

374 On the tilted 2D map, it becomes possible to extract a single or several columns (projection of
 375 columns) associated to a single or several ^2H site(s) (Lesot et al., 2008). Four NAD 1D sub-spectra
 376 (containing the signal associated to one to four ^2H sites) were selected (**Fig. 4**) in order to separate
 377 reliably all quadrupolar doublets (regions selected are shown in **Fig. S-8** in **Appendix A.II. of Supp.**
 378 **Info.**) **Table 1** lists the ^2H quadrupolar splittings in Hz (distance in Hz between two components of
 379 each ^2H doublet). As seen, the $\Delta\nu_Q$'s (in absolute value) varies from 36 to 314 Hz, but the majority of
 380 doublets (6 / 9) range from 272 to 314 Hz. As expected by using 2D NMR approach, the NAD
 381 signals associated to each methyl group of miliacin are spectrally distributed (on the 2D map) on the
 382 basis of their ^2H chemical shifts and quadrupolar splittings. Hence it becomes possible to evaluate the
 383 areas of each doublet by peak deconvolution. For the same molecule, these areas are proportional to
 384 the number of monodeuterated isotopomers contributing to the NAD signal (three for a methyl
 385 group) and the $(\text{D}/\text{H})_i^{\text{Mc}}$ ratio at methyl site i (results, discussion in **Section 4.4**).
 386



387
 388 **Figure 3:** (a) Methyl region (Me31 not shown) of the 92.1 MHz NAD tilted Q -resolved F_z 2D map
 389 of miliacin dissolved in PBLG/ CHCl_3 and recorded at 295 K. (b) 600 MHz proton 1D
 390 spectrum of miliacin in CHCl_3 plot at the horizontal same scale (in ppm). A lorentzian filtering
 391 (LB = 1.5 Hz) has been applied in both spectral dimensions. On the F_1 and F_2 axes are shown
 392 the spectral 2D projections. Note the significant variations of peak intensity of ^2H doublets in
 393 F_1 dimension illustrating the enrichment/depletion in deuterons.

394
 395 As far as possible, the assignment of ^2H resonances in F_2 dimension on the Q -resolved F_z map
 396 of miliacin can be derived from the position of ^1H lines of methyl groups observed the isotropic ^1H
 397 spectrum (see **Fig. 3**). However when ambiguities exist (as for sites 23 and 27), further arguments
 398 based on the orientation of the C- CH_3 axis (see **Fig. 5**) can help to assign the quadrupolar doublets on
 399 the basis of their magnitude. Indeed as the quadrupolar splittings are proportional to the order
 400 parameter, $S_{\text{C-D}}$, of the C-D bond (see **Eq. 1**), they can be related to the relative positions of
 401 associated C-D vectors in a (rigid) molecular structure (Aroulanda et al., 2001; Lesot et al., 2015).
 402 We can therefore correlate the magnitude of ^2H doublets to geometrical data, thus providing
 403 complementary information for their assignment. This approach was typically useful to assign the
 404 quadrupolar doublets associated to Me23 and Me27, for instance. Detailed explanations and further
 405 discussions on the assignment of doublets are given in **Appendix A.III** of **Supp. Info**.
 406



407
 408 **Figure 4:** Series of four NAD 1D sub-spectra extracted from the tilted Q -resolved F_z 2D map
 409 showing the nine methyl groups of miliacin along with their assignments (see also **Fig. S-9**).
 410 Each sub-spectrum is plotted with the same amplitude of noise. Note the variation of peak
 411 intensity of ^2H doublets. The variations observed reveal the differences of (D/H) for each site.
 412

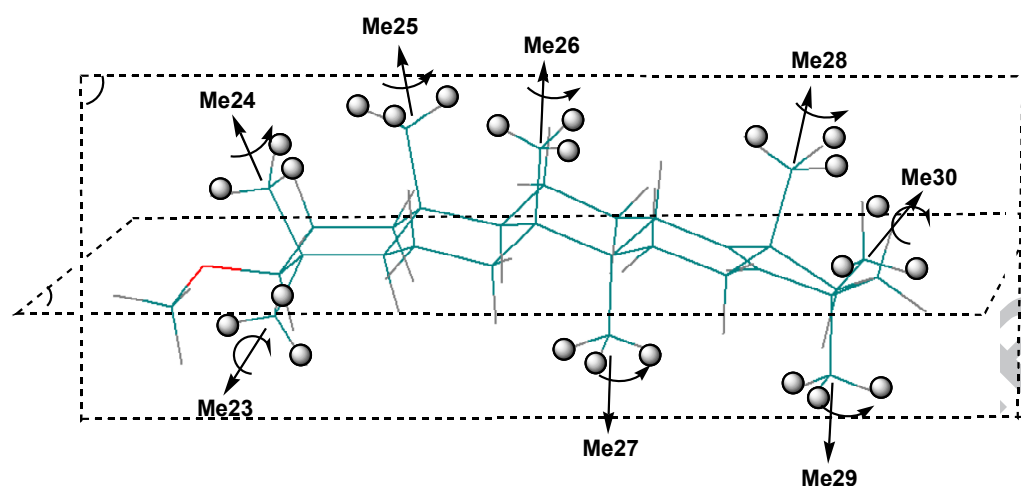


Figure 5: 3D view of the minimal energy conformation of miliacin calculated with Hyperchem 3.0 software. A semi-empirical quantum chemistry methods based on the Hartree–Fock formalism (Austin Model 1 or AM1) has been used for modeling the molecule. The minimal energy was found at -8177.99 kJ/mol. Except for ring E distorted by the double bond, all other cycles have adopted a chair conformation. Note the difference of orientation axes of C-CH₃ vectors for Me23 and Me30 (close to the median horizontal molecular plan) compared to Me24 to Me29 (see also **Fig. S-9** in **Appendix A.II** of **Supp. Info.**).

4.3. Absolute (D/H) and δD values of methyl groups

In contrast to their ¹H signals (**Fig. 2**), significant variations in the intensity of ²H doublets for the nine methyl groups are observed on the 2D map or the associated F_1 and F_2 projections (**Figs. 3** and **4**). As NAD 2D-NMR spectra have been recorded with quantitative experimental conditions, the peak areas on projections (or peak volume on the 2D map) are in principle proportional to the number of isotopomers contributing to the NAD signal (three for a methyl group) and the isotope ratio (D/H) at each methyl site.

4.3.1. Evaluation of relative ²H peak surface by anisotropic NAD 2D-NMR

When the direct quantification of peak surfaces on anisotropic 2D spectra (using an isotopically calibrated, internal chemical reference) is experimentally difficult as in case of miliacin (problem with mesophase, interference between the ²H solute and reference signals), other strategies must be proposed. Thus the use of an electronic reference signal (ERETIC method) is a possible alternative but required special equipment not implemented in the majority of spectrometers (Akoka et al., 1999). For the study of miliacin, we have adopted a two-step protocol for quantification of relative D concentrations in methyl groups (or any other sites) consisting into: i) evaluating the relative variation of ²H surfaces of each doublet using the NAD signal of methyl group of methoxy (Me31) as internal reference value; ii) determining the (D/H) and δD values of Me31 using either GC-irMS (see **Section 4.3.2**) or isotropic quantitative NAD NMR in presence of TMU (see **Section 4.3.3**). Note that the choice of the Me31 as internal reference is advantageous for both methods. From GC-irMS viewpoint, the (D/H)_{Me31} ratio can be easily quantified by comparing the global δD of miliacin and the one of germanicol. From an NMR viewpoint, the isotropic ²H signal of Me31 is

443 isolated from other signals of miliacin, reducing errors on the measure of peak surface by
 444 deconvolution, and does not interfere with the signal of TMU.

445 The measurement of relative surface of peaks can be either directly performed on the 2D map
 446 or using 1D projections of selected slices extracted from the map (Massou et al., 2007; Lesot et al.,
 447 2008). Adopting this second approach, the evaluation of relative surface of doublet of methyl groups
 448 was performed as following: i) selection of 10 columns centered on the NAD signal of each
 449 inequivalent ^2H site and calculation of their respective F_1 projection, ii) addition of NAD signal of
 450 Me31 (10 columns) to each NAD 1D sub-spectrum; iii) determination (by signal deconvolution) of
 451 the peak surface for each methyl group, iv) calculation of the average value obtained for the six
 452 different NAD 2D spectra recorded with the same experimental conditions (acquisition and
 453 processing), assuming a reference value for the Me31 signal. In order to determine the reliability of
 454 this approach, we have compared the peak area of Me31 for the six experiments. The variation
 455 between each experiment is below 2%. In column 3 of **Table 2** are listed the averaged surfaces
 456 measured for the six NMR experiments, when the value for the Me31 is arbitrary set at 100. Values
 457 for each experiment are given in **Table S-4** and plotted in **Fig. S-10** whereas **Fig. S-11** in **Appendix**
 458 **A.II of Supp. Info.** displays the associated average values together with the SD.

459

460 4.3.2. δD_{Me31} determined by GC-irMS and SNIF-NMRTM

461 δD_{Me31} was first estimated by comparing the GC-irMS δD values of miliacin ($\delta D_{\text{miliacin}}$) and
 462 of germanicol ($\delta D_{\text{germanicol}}$) extracted from millet oil according to the following rationale and
 463 equations. We assumed no other hydrogen isotopic difference between miliacin and germanicol (see
 464 **Fig. 1**) than the addition of three hydrogen atoms from the Me31.

465 Experimentally, we obtained $\delta D_{\text{miliacin}} = -100 \pm 5 \text{ ‰}$ and $\delta D_{\text{germanicolacetate}} = -110 \pm 5 \text{ ‰}$, which
 466 gives $\delta D_{\text{germanicol}} = -108.6 \pm 5 \text{ ‰}$, after mathematically removing the contribution from acetic
 467 anhydride ($\delta D_{\text{acanh}} = -133 \pm 2 \text{ ‰}$) according to **Eq. 4**:

468

$$469 \quad \delta D_{\text{germanicol}} = \left(\frac{52 \times \delta D_{\text{germanicolacetate}} - 3 \times \delta D_{\text{acanh}}}{49} \right). \quad (4)$$

470 The error on $\delta D_{\text{germanicol}}$ was classically calculated as $\sqrt{(52/49)^2 \times (\delta D_{\text{germanicolacetate}})^2 + (3/49)^2 \times (\delta D_{\text{acanh}})^2}$, thus
 471 taking into account the multiplicative factors of **Eq. 4** and assuming that the correlative term is null
 472 (independent variables). Note here that this $\delta D_{\text{germanicol}}$ value does not take into account the H atom of
 473 the alcohol function that is highly exchangeable and was lost during acetylation. Hence, when
 474 calculating δD_{Me31} in mass balance equations **Eq. 4** and **Eq. 5**, we consider 49 H atoms in germanicol
 475 (instead of 50) and 52 H atoms in miliacin.

476

$$\delta D_{Me31} = \left(\frac{52 \times \delta D_{miliacin} - 49 \times \delta D_{germanicol}}{3} \right). \quad (5)$$

477
478
479 The calculation in **Eq. 5** gives δD_{Me31} equal to $+41 \text{ ‰} \pm 119 \text{ ‰}$. Propagation of uncertainties on the
480 δD_{Me31} was calculated as for **Eq. 4** (see **Table 2**, footnote i). Using **Eq. 2**, this corresponds to a
481 $(D/H)_{Me31}^{GC-irMS}$ value of 162 ± 19 ppm. Details for the conversion from δD to (D/H) are given in footnote g
482 of **Table 2**.

483 A possible experimental alternative to GC-irMS consists to determine δD_{Me31} value applying
484 the so-called SNIF-NMRTM protocol using NAD NMR in isotropic solvent in presence of calibrated
485 TMU (see **Section 3.7**). The analysis of experiments recorded indicates that standard deviation on the
486 area ratio ($R = A_{Me31}/A_{TMU}$) was found to be equal to 0.28 (e.g. $R = 25.2 \pm 0.6$), thus indicating a very
487 good repeatability of isotropic NAD 1D NMR experiments (see Table S-5). Knowing the $(D/H)_{TMU}$
488 and the masses of TMU and miliacin (purity of 98%) used, the $(D/H)_{Me31}$ was obtained using **Eq. 3**;
489 the average value was found to be equal to 154 ppm. The uncertainty value on $(D/H)_{Me31}$ was
490 classically calculated as $\Delta X = X \times \sqrt{\sum_i (\Delta g_i / g_i)^2}$ where g_i are the key variables of **Eq. 3** (see **Table 2**
491 and **S-5**) and found to be equal to ± 10 ppm. Expressed in δD_{Me31} (from the **Eq. 2**), the value is equal
492 to $-11 \pm 64 \text{ ‰}$ (see **Table 2**, footnote e).

493 Conclusively, it is worthwhile noting that, although they were determined by two very distinct
494 analytical methods, the $(D/H)_{Me31} / (\delta D_{Me31})$ values are consistent within the uncertainty range ($162 \pm$
495 19 ppm *versus* 154 ± 10 ppm ($+41 \pm 119 \text{ ‰}$ *versus* $-11 \pm 64 \text{ ‰}$). The difference on the nominal
496 $(D/H)_{Me31}$ value (relative discrepancy of 5%) could be explained by the lower sensitivity of NAD
497 NMR spectroscopy (compared to GC-irMS) in particular when samples cannot be enough
498 concentrated in analyte.

499 4.3.3. Absolute (D/H) and δD values of methyl groups 23 to 30

500 From $(D/H)_{Me31}$ value determined by the SNIF-NMRTM protocol or GC-irMS, it becomes
501 possible to evaluate the (D/H) value for each methyl group $(D/H)_{Mei}$ and corresponding δD_{Mei} with $i =$
502 23 to 30) in miliacin, using relative (D/H) values previously determined using the anisotropic NAD
503 NMR experiment (**Section 4.3.1**). All data and details of the calculation are given in **Table 2** and
504 footnotes. A graphical comparison of the $(D/H)_{Mei}$ and δD_{Mei} variations *versus* the methyl groups is
505 proposed in **Figs 6a** and **6b**. Large variations of $(D/H)_{Mei}$ values (up to a factor ≈ 2) exist from one
506 site to another one. Except for Me31, the $(D/H)_{Mei}$ values are significantly below the V-SMOW value.
507 This deuterium depletion in lipids produced by autotrophs is expected from biosynthetic fractionation
508 (Sessions et al., 1999). Besides for Me31, Me26 and Me27 appear to be the less depleted methyl
509

511 **Table 2:** Values of $(D/H)_{Me_i}$ (in ppm) and δD_{Me_i} (in ‰) of the methyl groups of miliacin.

| Ring | Methyl ^a group | Peak area ^b no unit | Anisotropic NMR / SNIF-NMR TM | | Anisotropic NMR / GC-irMS | |
|------|------------------------------|-----------------------------------|--|-------------------------------------|------------------------------------|-------------------------------------|
| | | | $(D/H)_{Me_i}$ ^c ppm | δD_{Me_i} ^e ‰ | $(D/H)_{Me_i}$ ^f ppm | δD_{Me_i} ^h ‰ |
| A | Me ₃₁ | 100 (0.0) | 154 ± 10 ^d | -11 ± 64 | 162 ± 19 ^g | +41 ± 119 ⁱ |
| A | Me ₂₃ | 74.1 ± 13.8 (6.9) | 114 ± 23 | -268 ± 148 | 120 ± 25 | -229 ± 162 |
| | Me ₂₄ | 54.6 ± 17.6 (8.8) | 84 ± 28 | -461 ± 180 | 88 ± 30 | -432 ± 193 |
| | Me ₂₅ | 73.5 ± 14.8 (7.4) | 113 ± 24 | -274 ± 154 | 119 ± 28 | -235 ± 177 |
| C | Me ₂₆ | 90.3 ± 10.2 (5.1) | 139 ± 18 | -107 ± 122 | 146 ± 23 | -60 ± 151 |
| | Me ₂₇ | 82.4 ± 9.6 (4.8) | 127 ± 17 | -186 ± 116 | 133 ± 22 | -143 ± 139 |
| E | Me ₂₈ | 76.8 ± 14.2 (7.1) | 118 ± 23 | -242 ± 154 | 124 ± 27 | -201 ± 173 |
| | Me ₂₉ | 66.8 ± 12.0 (6.0) | 103 ± 20 | -340 ± 128 | 108 ± 23 | -305 ± 148 |
| | Me ₃₀ | 41.5 ± 10.4 (5.4) | 64 ± 17 | -590 ± 109 | 67 ± 18 | -568 ± 116 |

512 a) The methyl group Me₃₁ is used as internal reference.

513 b) Average value of peak areas of NAD signals of methyl groups measured on anisotropic NAD 2D spectra (six NMR
514 experiments) when the methoxy group is arbitrary calibrated at 100. In parenthesis is given the value of the simple
515 standard deviation (σ_n) on peak areas calculated as: $\sigma_n = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2}$ where n = 6. The uncertainty, noted ΔX , on value X (such

516 as $X = x \pm \Delta X$) is calculated (in ppm) as $\Delta X = k \times \sigma_n$ where k = 2, namely leading to a confidence interval of 95% [$x -$
517 1.96σ ; $x + 1.96\sigma$].

519 c) The $(D/H)_{Me_{23-30}}$ values in ppm (methyl groups 23 to 30) are calculated as $(D/H)_{Me_{23-30}} = (\%A_{Me_{23-30}}^{Aniso\ NMR}) \times (D/H)_{Me_{31}}^{SNIF-NMR}$,
520 where $(D/H)_{Me_{31}}^{NAD\ NMR}$ is determined by isotropic NAD 1D-NMR (i.e. $(D/H)_{Me_{31}}^{SNIF-NMR} = 154 \pm 10$ ppm, see Table S-4). The
521 uncertainty on $(D/H)_{Me_{23-30}}$ values is evaluated (in ppm) as: $\Delta(D/H) = (D/H) \times \sqrt{\left(\frac{\Delta(Area)}{Area}\right)^2 + \left(\frac{\Delta(D/H)_{Me_{31}}^{SNIF-NMR}}{(D/H)_{Me_{31}}^{SNIF-NMR}}\right)^2}$.

522 d) The $(D/H)_{Me_{31}}^{SNIF-NMR}$ value in ‰ (methyl group 31) is experimentally determined by SNIF-NMRTM protocol in isotropic
523 solvent. See Table S-5 for the calculation of uncertainty on $(D/H)_{Me_{31}}^{NAD\ NMR}$.

524 e) The $\delta D_{Me_{23-30}}$ values in ‰ are calculated using Eq. 2. Considering that the $(D/H)_{V-SMOW}$ value is a constant
525 (international standard value) and not a variable, the uncertainty on $\delta D_{Me_{23-30}}$ values is simply evaluated as
526 $\Delta\delta_{Me_i} = \sqrt{\left(1000 \times \frac{\Delta(D/H)_{Me_i}}{(D/H)_{V-SMOW}}\right)^2}$, assuming that correlation term is null.

527 f) The $(D/H)_{Me_{23-30}}$ values in ppm are calculated as $(D/H)_{Me_{23-30}} = (\%A_{Me_{23-30}}^{Aniso\ NMR}) \times (D/H)_{Me_{31}}^{GC-irMS}$, namely from the relative peak
528 surfaces (%) measured on anisotropic NMR spectra (see Table S-4) and using the $(D/H)_{Me_{31}}^{GC-irMS}$ value (ppm) as reference.
529 The uncertainty on $(D/H)_{Me_{23-30}}$ is evaluated (in ppm) as: $\Delta(D/H) = (D/H) \times \sqrt{\left(\frac{\Delta(Area)}{Area}\right)^2 + \left(\frac{\Delta(D/H)_{Me_{31}}^{GC-irMS}}{(D/H)_{Me_{31}}^{GC-irMS}}\right)^2}$.

530 g) The $(D/H)_{Me_{31}}^{GC-irMS}$ value in ppm is calculated as $(D/H)_{Me_{31}} = \frac{\delta D_{Me_{31}}^{GC-irMS} \times (D/H)_{V-SMOW}}{1000} + (D/H)_{V-SMOW}$. From the same reason evoked in
531 footnote e, the uncertainty on $(D/H)_{Me_{31}}^{GC-irMS}$ is evaluated as $\Delta(D/H)_{Me_i} = \sqrt{\left(\frac{(D/H)_{V-SMOW} \times \Delta\delta_{Me_i}}{1000}\right)^2}$, leading to a value of ± 19 ppm.

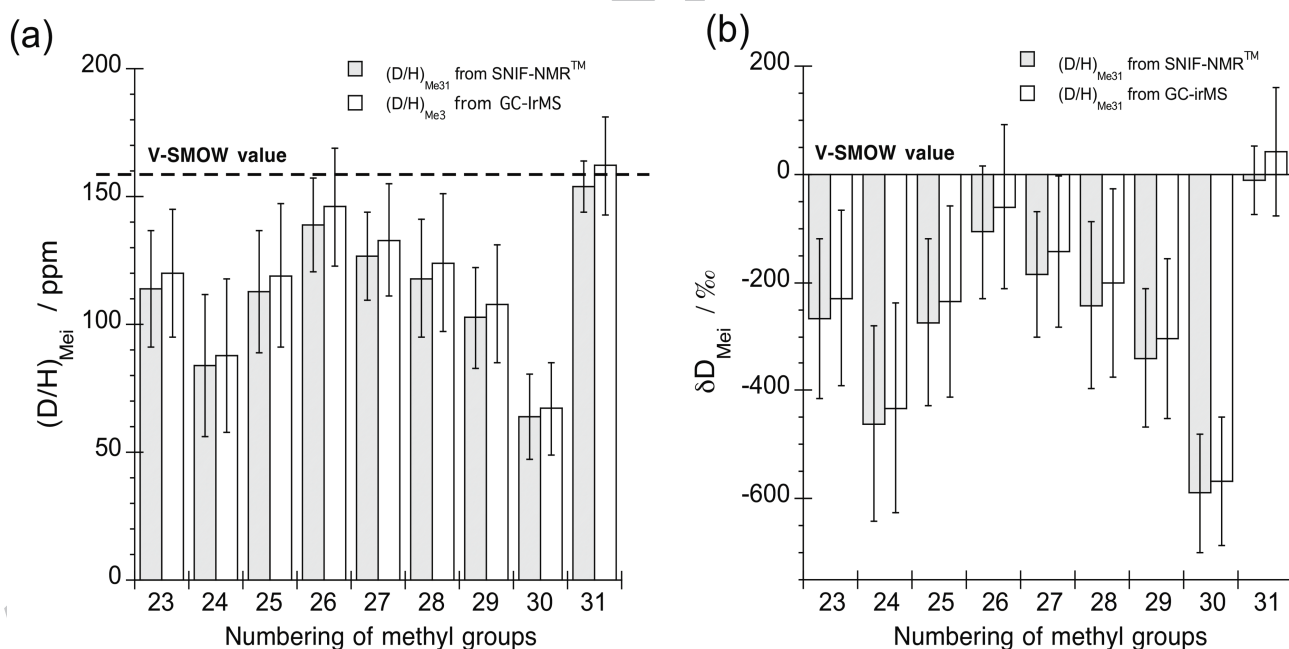
532 h) The $\delta D_{\text{Me23-Me30}}$ values in ‰ are calculated as $\delta D_{\text{Me23-Me30}} = (\%A_{\text{Me23-30}}^{\text{Aniso NMR}}) \times \frac{(D/H)_{\text{Me23-Me30}}^{\text{Aniso NMR}}}{(D/H)_{\text{V-SMOW}}}$. Note that these values cannot
 533 directly be obtained from $\%A_{\text{Me23-30}}^{\text{Aniso NMR}}$ and $\delta D_{\text{Me31}}^{\text{GC-irMS}}$ values due to the non-linearity of **Eq. 2**. For the same reason evoked
 534 in footnote e, the uncertainty on δD_{Mei} is simply evaluated as $\Delta \delta_{\text{Mei}} = 1000 \times \frac{\Delta(D/H)_{\text{Mei}}}{(D/H)_{\text{V-SMOW}}}$.

535 i) The $\delta D_{\text{Me31}}^{\text{GC-irMS}}$ value in ‰ was experimentally determined by GC-irMS. The calculation of uncertainty on $\delta D_{\text{Me31}}^{\text{GC-irMS}}$ is
 536 evaluated as $\Delta \delta D_{\text{Me31}}^{\text{GC-irMS}} = \sqrt{(52/3)^2 \times (\delta D_{\text{germanicolacetate}})^2 + (49/3)^2 \times (\delta D_{\text{acanh}})^2}$ and gives ± 119 ‰ (see main text).

537
 538 groups ($\delta D_{\text{Mei}} \sim -100$ ‰), followed by Me23, Me25, Me28 and Me29 ($\delta D_{\text{Mei}} \sim -250$ ‰), whereas
 539 Me30 and Me24 are strongly depleted ($\delta D_{\text{Mei}} \sim -500$ ‰).

540 More interesting is actually the global variation of $(D/H)_{\text{Me23-Me30}}$ values (the exogenous methyl
 541 31 group is disregarded), that can be modeled as a quasi symmetrical, bell curve, the biosynthetic
 542 implication of which is discussed below. Note also that these conclusions may still hold based on the
 543 relative variation of peak areas measured on anisotropic NAD 2D map of miliacin (see **Table S-4** and
 544 **Figure S-12**.)”

545



546

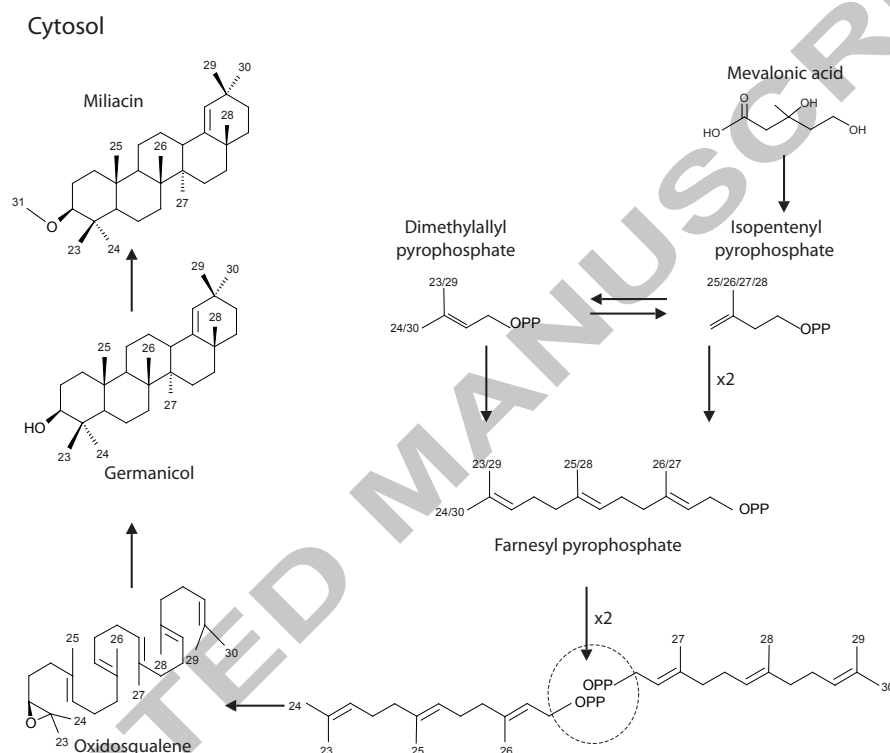
547 **Figure 6:** Variation of (a) (D/H) ratios in ppm and (b) δD in ‰ for each methyl group of miliacin
 548 when $(D/H)_{\text{Me31}}$ is evaluated by the SNIF-NMRTM (154 ± 10 ppm or -11 ± 64 ‰) and by GC-
 549 irMS (162 ± 19 ppm or 41 ± 119 ‰). Excluding the exogenous methyl group 31, note the
 550 (inverted) quasi-symmetrical bell shape of both plots.
 551

542 5. DISCUSSION

543 5.1. Implications for biosynthesis

544 The heterogeneous distribution of δD_{Mei} values in miliacin can be explained by the different
 545 steps involved in the biosynthesis of this molecule, by tracking back the origin of methyl groups (**Fig.**

556 7). As for any C-3 oxygenated pentacyclic triterpenes in other vascular plants, miliacin is produced in
 557 the cytosol from mevalonic acid, through the mevalonate pathway (i.e. Sachse et al., 2012).
 558 Mevalonic acid is converted into isopentenyl pyrophosphate that can be isomerized into dimethylallyl
 559 pyrophosphate. Then, farnesyl pyrophosphate is synthesized by the addition of two isopentenyl
 560 pyrophosphate units and a dimethylallyl pyrophosphate unit. Oxidosqualene is synthesized by the
 561 tail-to-tail combination of two farnesyl pyrophosphate units and is then cyclized by an oxidosqualene
 562 cyclase.



563
 564 **Figure 7:** Synthetic pathway of miliacin in the cytosol. Modified from Sachse et al. (2012).
 565

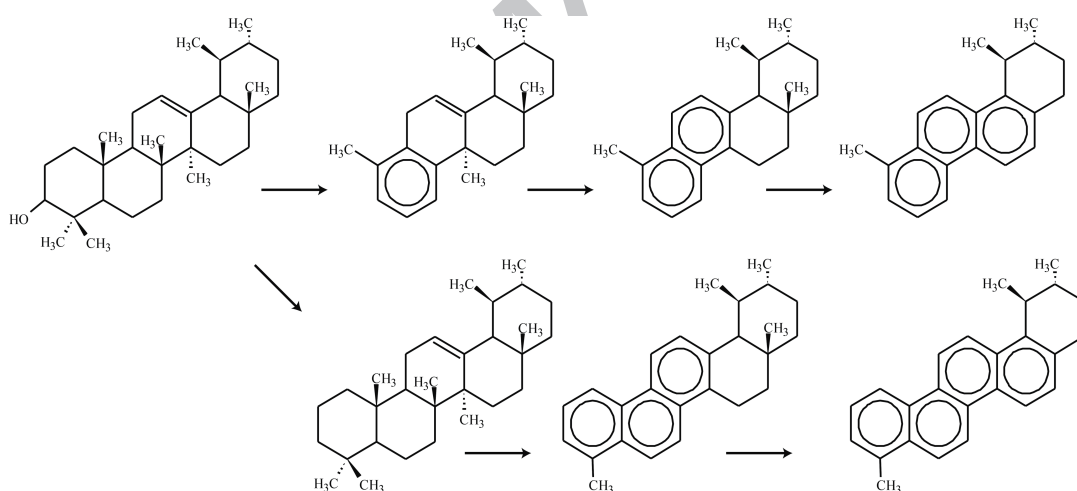
566 Hence, from a biosynthetic point of view, Me₂₄-Me₃₀, Me₂₃-Me₂₉, Me₂₅-Me₂₈ and Me₂₆-Me₂₇
 567 are isotopically equivalent because they derive from the same methyl groups in the farnesyl
 568 pyrophosphate unit. This biosynthetic equivalence explains reasonably the symmetry and the “bell-
 569 curve” variation of $(D/H)_{Me_i} / (\delta D_{Me_i})$ values of Me₂₃ to Me₃₀ as observed in **Fig. 6**. Farnesyl
 570 pyrophosphate is produced by head-to-tail combination of two isopentenyl pyrophosphate and a
 571 dimethylallyl unit. Thus, Me₂₅, Me₂₆, Me₂₇ and Me₂₈ in miliacin originate from the same methyl
 572 groups in isopentenyl pyrophosphate, whereas Me₂₃, Me₂₉, Me₂₄ and Me₃₀ originate from the
 573 dimethylallyl pyrophosphate. The dimethylallyl pyrophosphate itself results from the isomerization
 574 of isopentenyl pyrophosphate by an isopentenyl diphosphate isomerase (Sachse et al., 2012).

575 During this process, the formation of a carbocation affects hydrogen atoms of Me₂₄/Me₃₀.
 576 This could explain their D depletion when compared to other methyl groups. As already noted, Me₃₁
 577 is highly enriched when compared to other methyl groups. We have currently no information on the

578 origin of this methyl group that would explain such a relative D enrichment. These results for
 579 miliacin can be directly extrapolated to any compound with an oleanane, and potentially an ursane or
 580 lupane structure. For compounds that originate from oleanane after successive migrations of methyl
 581 groups (friedo rearrangements leading to structures such as taraxerane, glutinane, multiflorane and
 582 friedelane; i.e Xu et al., 2004), additional fractionations of hydrogen can be expected.

583 5.2. Implications for diagenesis

584 Diagenesis of vascular plant C-3 oxygenated pentacyclic triterpenes can potentially consist of
 585 several structural modifications that comprise loss of functional groups, ring-A degradation,
 586 epimerisations, double bond migrations, loss or migration of methyl groups (Rullkötter et al., 1994)
 587 and aromatization (i.e. **Fig. 8** and Wolff et al., 1989). No discernible difference in $\delta^{13}\text{C}$ values has
 588 been found during aromatization between biochemical precursors and diagenetic byproducts
 589 (Freeman et al., 1994). Preliminary results in organic archaeological layers showed significant D
 590 depletion of diagenetic derivatives compared to their potential biochemical precursors whereas no
 591 carbon isotopic shift was recorded (Jacob et al., 2011).



593
 594
 595 **Figure 8:** Potential diagenetic pathways of pentacyclic triterpenes (here starting from α -amyrin)
 596 illustrating the loss of hydrogen atoms related to methyl groups, methylene/methine.
 597 Modified from Wolff et al. (1989).

598
 599 Our results have shown significant variations in $\delta\text{D}_{\text{Mei}}$ values of methyl groups in miliacin
 600 with a range > 500 ‰. Thus, removing of methyl groups during diagenesis could significantly enrich
 601 diagenetic by-products compared to their biochemical precursor. But, as depicted in **Fig. 8**, the loss
 602 of methyl groups during diagenesis is always associated with the loss of hydrogen atoms in
 603 methylene and methine groups associated to rings. Thus, in order to fully understand any isotopic
 604 shift during diagenesis, it is necessary to take into account δD values of methylene and methine
 605 ($\delta\text{D}_{\text{meth}}$). Miliacin is composed by 52 hydrogen atoms of which 25 are in methine or methylene
 606 groups and $3 \times 9 = 27$ compose methyl groups. The average $\delta\text{D}_{\text{meth}}$ value can thus be accessed by mass

607 balance according to equation **Eq. 5**.

$$608 \quad \delta D_{\text{Meth}} = \left(\frac{52 \times \delta D_{\text{miliacin}} - 3 \times \sum \delta D_{\text{Mei}}}{25} \right). \quad (6)$$

609
610 Using δD_{Mei} values of methyl groups from anisotropic NMR / SNIF-NMRTM combined
611 approach (**Table 2, column 5**) and the $\delta D_{\text{miliacin}} = -100 \text{ ‰}$ in Eq. 6, we obtain an average $\delta D_{\text{meth}} =$
612 89 ‰ . Using δD_{Mei} values of methyl groups from GC-irMS, we obtain $\delta D_{\text{meth}} = 48 \text{ ‰}$. From these
613 results it appears that methylene and methine are, on average, largely enriched in D compared to
614 methyl groups. One could thus expect that, during diagenesis, any D-enrichment of the diagenetic
615 byproduct compared to its precursor due to the loss of depleted methyl groups could be
616 counterbalanced by D-depletion due to the associated loss of D-enriched methylene and methine.
617 Nevertheless, in the absence of information on the heterogeneous distribution of D in methylene and
618 methine, it is yet impossible to fully forecast the impacts of pentacyclic triterpenes degradation on the
619 hydrogen isotopic composition of their by-products. In addition, only removal of hydrogen atoms is
620 here considered but fractionation processes can be expected from the preferential biotic or abiotic
621 degradation of biochemical precursors.

622 623 **6. CONCLUSION**

624
625 Obtaining the site-specific H isotope distribution in biomarkers by a reliable method is crucial
626 but has been analytically challenging. GC-irMS allows δD values determination at a molecular scale
627 but does not inform on any preferential position of H isotopes on molecular sites. In contrast,
628 anisotropic NAD 2D-NMR spectroscopy provides more detailed information on isotope location
629 within molecules. This study explains how and why NAD 2D-NMR using weakly aligning LC is a
630 fruitful analytical tool able to overcome difficulties associated to isotropic NAD 1D-NMR (SNIF-
631 NMR), with the final aim of studying the site-specific distribution of hydrogen isotopes. By coupling
632 anisotropic and isotropic NAD NMR techniques or anisotropic NAD NMR and GC-irMS
633 measurements, we were, for the first time, able not only to establish the relative distribution of
634 hydrogen isotopes in methyl groups of miliacin, but also to afford quantitative (D/H) and δD values
635 for each methyl group.

636
637 The resulting distribution of (D/H) values of methyl groups in miliacin provides detailed
638 information that is consistent with its biosynthetic pathways; i.e. miliacin results from the addition of
639 a methyl group on germanicol that is synthesized through the cyclisation of oxidosqualene. This later
640 is produced by the condensation of two farnesyl pyrophosphate units, themselves built from two
641 isopentenyl pyrophosphate units and a dimethylallyl pyrophosphate unit. The heterogeneous
642 distribution of site-specific δD values revealed in this study could have major consequences on the

642 δD values of diagenetic derivatives of pentacyclic triterpenes since removal of methyl groups is often
643 observed in diagenetic pathways. Although this work paves the way to exciting prospects in the
644 frame of a better understanding of hydrogen isotopic changes during pentacyclic triterpene diagenesis,
645 thus improving any climate reconstruction based on these derivatives, the next challenge will consist
646 of experimentally evaluating the δD values of all hydrogen sites in biomarkers in order to have a
647 complete picture of their heterogeneous distribution. By achieving this task, we expect being able to
648 forecast δD values of diagenetic derivatives from their precursors or to calculate the δD values of
649 biochemical precursors through δD values of their diagenetic derivatives.

650 Various analytical difficulties (assignment of the anisotropic NAD signals, low S/N ratios, ...)
651 met and discussed in this study are both related to the structure and the low solubility of miliacin.
652 They are therefore highly specific to this structurally-complex geological biomarker, and will not
653 necessarily come up gain when other (simpler) organosoluble biomakers will be studied. As seen
654 here, possible protocols/strategies/solutions were proposed to overcome them, thus showing that
655 NAD 2D-NMR in LC remains an adaptable method able to face the majority of problems associated
656 to given analyte. In all cases, the possibility to significantly increase the concentration of deuterio-
657 isotopomers in NMR samples and/or record the NAD experiments by using very high-field NMR
658 spectrometers ($B_0 > 14$ T) still equipped by a 2H cryoprobe are the most direct way to overcome the
659 sensitivity problem, rendering the accuracy of measurements higher.

660

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662

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671

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- 845

846 **FIGURE CAPTIONS**

847

848 **Figure 1:** Structure of miliacin where $R_{31} = -\text{OMe}$ and gemanicol where $R_{31} = -\text{OH}$, together with the
 849 atomic numbering used and notation of rings (A to E) and methyl groups (23 to 31).

850

851 **Figure 2:** 600.1 MHz proton 1D-NMR spectrum of miliacin in CDCl_3 (295 K). The assignment of
 852 resonances of methyl groups is given in **Table S-1, S-2** and **S-3** in **Appendix A.I of Supp.**
 853 **Info.**). The peak marked by an asterisk ($\delta = 1.24$ ppm) is an unidentified impurity.

854

855 **Figure 3:** (a) Methyl region (Me31 not shown) of the 92.1 MHz NAD tilted Q -resolved Fz 2D map
 856 of miliacin dissolved in PBLG/ CHCl_3 and recorded at 295 K. (b) 600 MHz proton 1D
 857 spectrum of miliacin in CHCl_3 plot at the horizontal same scale (in ppm). A lorentzian filtering
 858 ($\text{LB} = 1.5$ Hz) has been applied in both spectral dimensions. On the F_1 and F_2 axes are shown
 859 the spectral 2D projections. Note the significant variations of peak intensity of ^2H doublets in
 860 F_1 dimension illustrating the enrichment/depletion in deuterons.

861

862 **Figure 4:** Series of four NAD 1D sub-spectra extracted from the tilted Q -resolved Fz 2D map
 863 showing the nine methyl groups of miliacin along with their assignments (see also **Fig. S-9**).
 864 Each sub-spectrum is plotted with the same amplitude of noise. Note the variation of peak
 865 intensity of ^2H doublets. The variations observed reveal the differences of (D/H) for each site.

866

867 **Figure 5:** 3D view of the minimal energy conformation of miliacin calculated with Hyperchem 3.0
 868 software. A semi-empirical quantum chemistry methods based on the Hartree-Fock
 869 formalism (Austin Model 1 or AM1) has been used for modeling the molecule. The minimal
 870 energy was found at -8177.99 kJ/mol. Except for ring E distorted by the double bond, all other
 871 cycles have adopted a chair conformation. Note the difference of orientation axes of C-CH_3
 872 vectors for Me23 and Me30 (close to the median horizontal molecular plan) compared to
 873 Me24 to Me29 (see also **Fig. S-9** in **Appendix A.II of Supp. Info.**).

874

875 **Figure 6:** Variation of (a) (D/H) ratios in ppm and (b) δD in ‰ for each methyl group of miliacin
 876 when $(\text{D/H})_{\text{Me31}}$ is evaluated by the two-step NAD NMR approach. Excluding the exogenous
 877 methyl group 31, note the (inverted) quasi-symmetrical bell shape of both plots.

878

879 **Figure 7:** Synthetic pathway leading to miliacin. Modified from Sachse et al. (2012).

880

881 **Figure 8:** Potential diagenetic pathways of pentacyclic triterpenes (here starting from α -amyrin)
 882 illustrating the loss of hydrogen atoms related to methyl groups, methylene/methine. Modified
 883 from Wolff et al. (1989).

884