

Differentiation of Isomeric Camphane-2,3-diols by NMR Spectroscopy and Chemical Ionization Mass Spectrometry

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Four diastereoisomeric camphane-2,3-diols have been synthesized and their structures verified by ^1H and ^{13}C NMR spectroscopy. Mass spectrometric differentiation of these compounds was difficult by conventional methods: the electron ionization mass spectra were almost identical, stereochemical effects were weak when NH_3 and $i\text{-C}_4\text{H}_{10}$ were used as reagent gases in chemical ionization, and the differences apparent in the CH_4 chemical ionization spectra were not easily related to the stereochemistry. Stereochemical effects were clear, however, in the collision-induced dissociation spectra of the ammonium adduct $(M + \text{NH}_4)^+$ in which ions and isomers were easily differentiated. Under chemical ionization, oxidation and/or hydride-ion abstraction reactions took place, leading to products the structure of which strongly reflected the configuration of the original diol thereby offering a further means to isomeric identification.

Cyclic diols are useful model compounds in studies on the stereochemistry of structurally more complex natural products, and much effort has gone into the study of their stereochemistry, especially under chemical ionization (CI).¹⁻¹⁰ In most cases, the greater proton affinity of the *cis*- over the *trans*-diol allows easy differentiation of these isomers. The differentiation of 1,2-diols has proved more difficult, however, because sometimes the flexibility of the ring system and/or the proximity of two hydroxy groups allow the formation of a stabilized proton bridge or chelate structure even in the case of the *trans*-isomer.^{1,4} The rigid norbornane skeleton offers interesting possibilities for the examination of the stereochemical interactions between functional groups since the stereochemical position of the groups in the molecule are known exactly. However, there is only one paper¹¹ dealing with the mass spectrometry of diols having the bicyclo[2.2.1]heptane skeleton and that is an electron impact study.

rise to mixtures of isomers.^{13,14} Our goal was to develop a simple mass spectrometric method for their differentiation, even when present as a mixture. In view of the different configurations reported for camphane-2,3-diols prepared by different methods,¹⁵⁻¹⁷ we decided first to verify the configurations of our diols by ^1H and ^{13}C NMR spectroscopy. The complete establishment of the structures presented was based on two-dimensional COSY, NOESY, and C,H-correlated data.

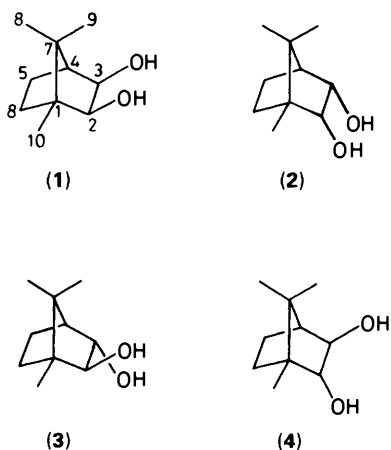
Results and Discussion

Although the configuration identification of camphane-2,3-diols by ^1H NMR spectroscopy has attracted considerable interest,¹⁵⁻¹⁷ assignment of the spectra has been far from complete. Only a few chemical shifts and coupling constants have been reported. In Table 1 we report all the important ^1H chemical shifts and some ^1H coupling constants for compounds (1), (2), and (4).

Our determination of the configurations of the diols was mostly based on the coupling constants for the protons at C-2 and C-3, since the spatial arrangement of these protons is unique for each compound. In accordance with the Karplus equation, only one coupling is possible for a 2-*exo*-3-*exo*-diol. This was the case for compound (1), for which only the single coupling $^3J_{2,3} = 7.0$ Hz was observed. For compound (2), in addition to the normal couplings ($^3J_{2,3} = 8.8$ Hz, $^3J_{3,4} = 4.6$ Hz), there were two *W* couplings, $^4J_{2,6} = 1.9$ Hz and $^4J_{3,5} = 1.5$ Hz, which confirm that the arrangement of the hydroxy groups is 2-*endo*-3-*endo*. In the case of compound (4), the NOESY spectrum of the proton at C-2 was in agreement with protons at C-9 and C-10, indicating the 2-*endo*-3-*exo* configuration. The earlier assignment of Anet¹⁵ for this diol is correct, and the coupling he predicts between the protons at C-2 and C-6 exists ($^2J_{2,3} = 2.5$ Hz, $^4J_{2,6} = 1.0$ Hz).

The signals due to the methyl protons were assigned exactly for each compound using 2D NOESY spectra. Resolution enhancement was required to observe the weak, though clear, coupling between protons at C-8 and C-9 (quartet 0.4–0.6 Hz).

Using the proton chemical shifts, carbon signals were easily assigned by carbon-proton chemical shift correlation two-dimensional spectroscopy. ^{13}C Chemical shifts and coupling constants ($^1J_{\text{CH}}$) are presented in Table 2. Stereochemical effects in the ^{13}C NMR spectra of bicyclic compounds have been well



In this work we synthesized four diastereoisomeric camphane-2,3-diols, all with the same skeletal configuration as (+)-camphor. These compounds have long been known,¹²⁻¹⁴ but the assignment of their exact configuration has proved difficult, especially in the case of the *trans*-isomers.¹⁵⁻¹⁷ The main reason for this is that their synthesis almost always gives

Table 1. ^1H Chemical shifts (a) and some ^1H coupling constants (b) for camphane-2,3-diols.

(a)										
Comp.	δ_{H} (ppm relative to Me_4Si)									
	2	3	4	5- <i>exo</i>	5- <i>endo</i>	6- <i>exo</i>	6- <i>endo</i>	8	9	10
(1)	3.51 (d)	3.84 (d)	1.70 (d)	1.60 (m)	0.85 (m)	1.40 (m)	0.80 (m)	1.11 (s)	0.80 (s)	0.94 (s)
(2)	3.80 (dd)	4.21 (m)	1.85 (m)	1.44 (m)	1.71 (m)	1.16 (m)	1.71 (m)	0.91 (s)	0.87 (s)	0.86 (s)
(4)	3.96 (m)	3.54 (d)	1.66 (m)	1.72 (m)	1.17 (m)	1.19 (m)	1.72 (m)	0.85 (s)	1.07 (s)	0.88 (s)

(b)					
Comp.	$^3J_{\text{HH}}/\text{Hz}^a$			$^4J_{\text{HH}}/\text{Hz}^a$	
	2-H	3-H	4-H	2-H	3-H
(1)	7.0	7.0	4.7	—	—
(2)	8.8	8.8; 4.6	4.6; 4.6	1.9	1.5
(4)	2.5	2.5	4.7	1.0	—

^a Other multiplets were too complicated to solve without thorough computer simulation.

Table 2. The ^{13}C chemical shifts and $^1J_{\text{CH}}$ ^{13}C coupling constants for camphane-2,3-diols.

Comp.	1	2	3	4	5	6	7	8	9	10
δ_{C} (ppm; Me_4Si)										
(1)	46.43	79.93	76.19	51.47	24.05	33.13	48.75	21.01	21.81	11.09
(2)	44.37	73.71	67.93	50.30	17.84	25.50	49.40	19.93	18.26	14.28
(4)	47.17	86.10	84.58	52.46	25.06	25.41	50.28	20.98	19.31	12.85
$^1J_{\text{CH}}/\text{Hz}$										
(1)	—	151.3	151.5	140.4	134.2	130.9	—	124.9	124.4	124.8
(2)	—	148.1	149.0	137.1	131.3	128.1	—	125.8	124.3	124.5
(4)	—	147.7	147.6	141.1	131.2	131.1	—	124.9	124.4	124.2

Table 3. Ammonia CI mass spectra of compounds (1)–(4). (Intensities as $\% \Sigma_{60}$.)

<i>m/z</i>	(1)	(2)	(3)	(4)
95	1.6	2.1	1.9	2.4
109	—	0.5	0.6	0.9
123	—	0.5	0.6	0.7
152	0.6	1.0	1.1	1.8
153	5.0	1.8	7.5	1.8
154	0.6	—	1.0	—
170	0.8	0.3	1.1	2.1
186	12.4	8.7	7.3	10.3
187	1.6	1.1	1.0	1.5
188	67.2	72.6	67.2	68.4
189	8.6	9.3	8.5	8.4

documented in earlier articles.^{18,19} In addition to these observations, we found that the *exo*-OH group had a significant deshielding effect on C-9 giving rise to the chemical shifts at 21.81, 19.31, and 18.26 ppm in the spectra of compounds (1), (4), and (2), respectively. Also the shifts of C-5 and C-6 were sensitive to the stereochemistry (*exo/endo*) of the OH group at opposite positions C-3 and C-2, respectively, because a large downfield shift appeared in the case of the *exo*-OH group.

Eliel *et al.*²⁰ have shown that *endo*- and *exo*-norbornanols and related bornanols can be differentiated by means of ^{17}O NMR spectroscopy because the chemical shift of the *endo*-OH is upfield of the *exo*-OH. We tried to apply this technique to camphane-2,3-diols, but the extremely broad signals made any configurational assignment impossible.

The 70 eV mass spectra of camphane-2,3-diols (Figure 1) bear a close resemblance to the spectra of the related monoalcohols,

bornanol and isobornanol.²¹ The molecular ion peak is hardly visible because of favourable water elimination and subsequent ring rupture reactions. Typical of the bornane ring system, the base peak in the spectrum at *m/z* 95 corresponds to the $[\text{C}_7\text{H}_{11}]^+$ ion.^{21,22} Although small variations in peak intensities exist, they are not large enough for isomeric differentiation.

Ammonia chemical ionization (NH_3 CI) allows a clear distinction of diastereoisomeric borneol and isoborneol^{23,24} and one would expect the same for the related diols studied in this work. In addition to the adduct ion ($M + \text{NH}_4$)⁺ peak, however, there were very few peaks in the NH_3 CI spectra and in particular the ($M + \text{H}$)⁺ ion peak was very small for all the isomers (Table 3). The same has been found for the *cis*- and *trans*-cyclopentane-1,2-diols⁴ and follows from the possibility for formation by both isomers of a stable chelate structure with linear H-bonds. The favourable chelate formation almost completely prevented the nucleophilic substitution reaction, which is so important in differentiating borneol and isoborneol from each other in NH_3 CI.^{23,24}

Collision-induced dissociation (CID)²⁵ spectra of the ($M + \text{NH}_4$)⁺ ions, by contrast, showed clear stereochemical effects, making possible unambiguous differentiation of the isomers, as can be seen from Table 4. Both *cis*-diols (1) and (2) lost NH_3 from the adduct ion and then water (Scheme 1). The elimination sequence was verified by using ND_3 as the reagent gas. The loss of NH_3 gave rise to an ($M + \text{H}$)⁺ ion at *m/z* 171, the intensity of which was considerably larger for the 2-*endo*-3-*endo* isomer (2) than for the 2-*exo*-3-*exo* isomer (1) due to steric crowding caused by the methyl groups at C-1 and C-7 in the 2-*exo*-3-*exo* isomer (1). The fragmentation pattern for the 2-*endo*-3-*exo*-isomer (4) was quite different. The *m/z* 171 was of only low intensity which means that either the elimination of NH_3 did

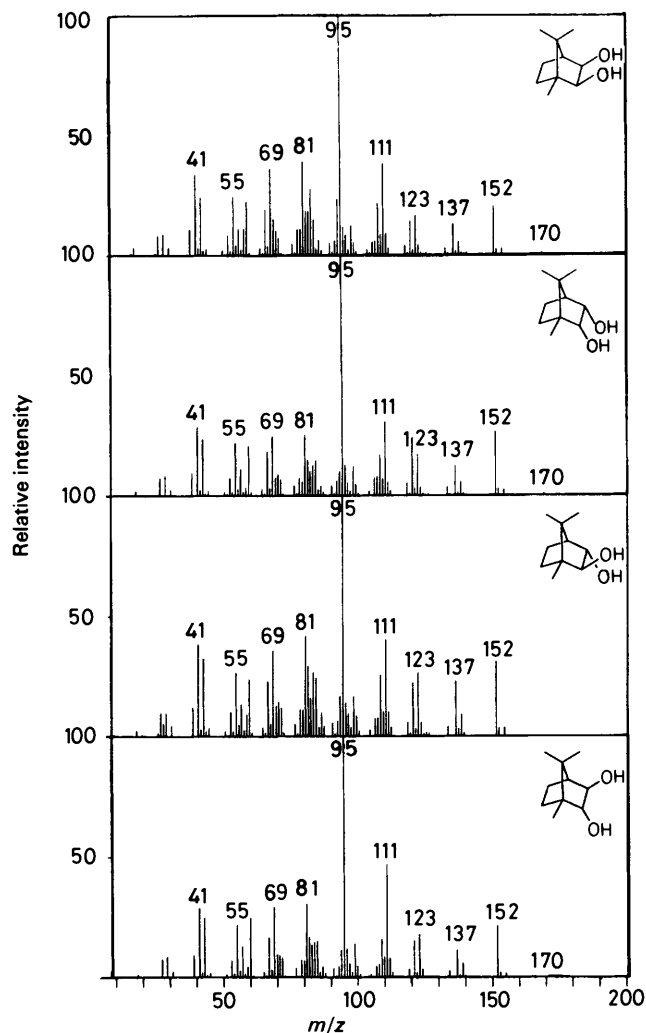


Figure 1. 70 eV electron ionization mass spectra of the isomeric camphane-2,3-diols.

Table 4. The CID spectra recorded from $(M + \text{NH}_4)^+$ ions of the studied camphane-2,3-diols. (5) represents the 2:1 mixture of compounds (3) and (4). Intensities are normalized to a total fragment-ion abundance of 100%. The data are not corrected for metastable peaks.

m/z	(1)	(2)	(4)	(5)
91	1.3	—	—	—
95	2.1	2.2	3.8	4.9
107	1.8	2.3	3.7	—
109	8.4	5.4	9.2	14.9
110	2.0	1.3	2.6	—
123	2.1	2.5	3.9	3.7
124	1.9	—	—	—
125	1.3	—	—	—
135	4.6	4.5	7.8	4.9
137	3.8	2.7	4.1	2.4
152	5.3	4.1	12.4	4.9
153	47.8	37.9	36.6	49.6
154	9.4	6.7	4.6	4.9
170	—	—	10.2	10.0
171	7.7	27.8	0.9	—
172	—	2.8	—	—

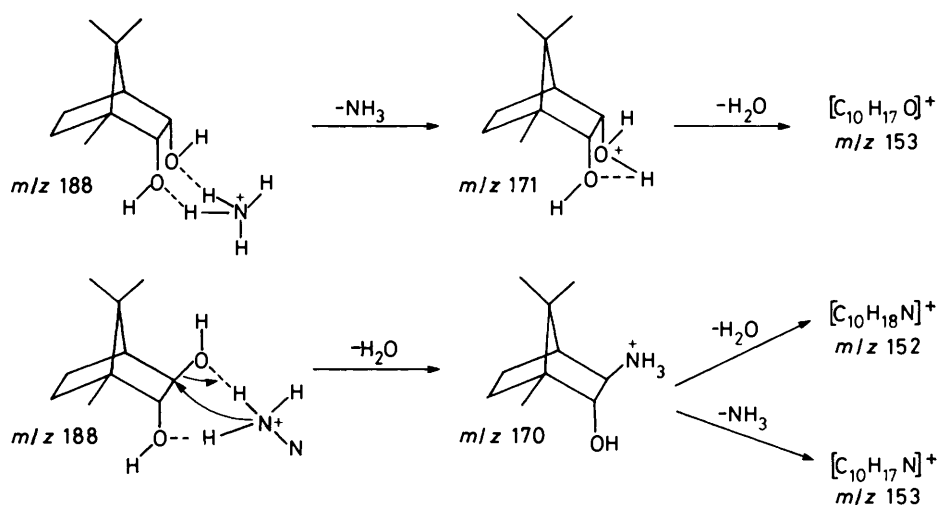
not take place or that the stability of the ion was low because the formation of a stabilizing hydrogen bridge is not possible for

Table 5. The CID spectra of $(M - \text{H}_2 + \text{NH}_4)^+$ ions generated from camphane-2,3-diols and related hydroxy ketones under NH_3 CI. (5) represents the 2:1 mixture of compounds (3) and (4). Intensities are normalized to a total fragment-ion abundance of 100%. The data are not corrected for metastable peaks.

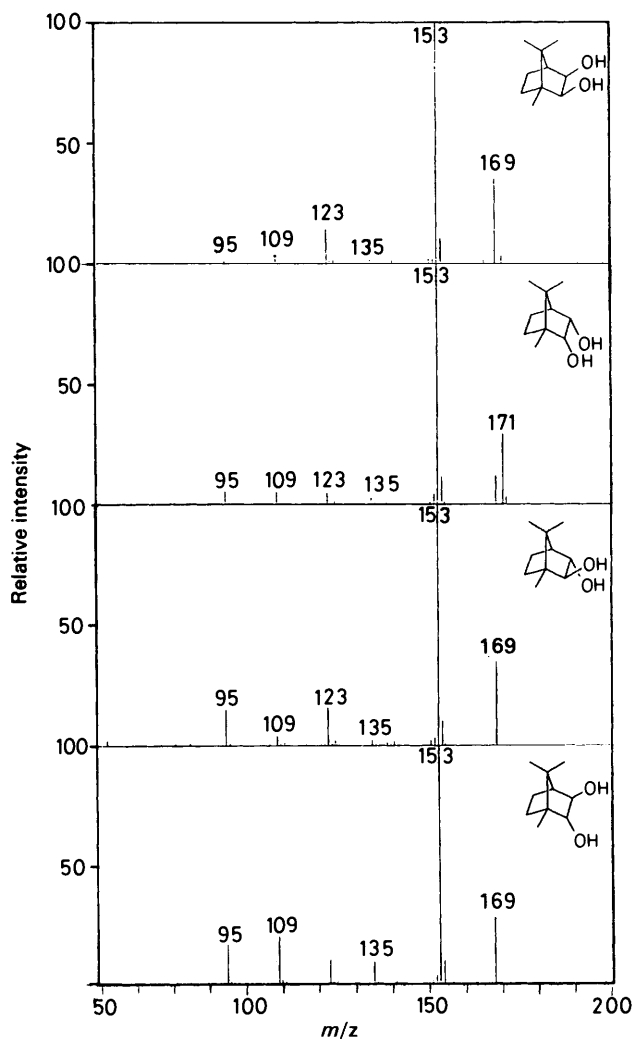
m/z	(1)	(2)	(4)	(5)		
55	1.4	—	—	—	—	—
67	1.8	1.8	—	—	—	—
69	3.3	3.6	4.1	3.5	—	—
77	1.6	1.7	—	—	—	—
79	2.1	2.1	2.0	1.7	—	—
81	3.0	3.0	3.9	3.4	—	—
83	4.0	4.6	4.2	5.1	—	—
84	2.1	3.9	3.9	3.1	—	—
91	2.2	2.1	2.1	2.6	—	—
93	3.0	3.3	4.6	3.5	—	—
94	1.7	2.0	10.8	2.4	—	—
95	7.6	10.0	—	8.8	—	—
96	—	1.5	—	—	—	—
97	3.3	5.3	3.9	3.3	—	—
99	—	—	—	—	—	1.6
107	3.2	3.0	3.5	3.2	1.0	1.6
108	1.7	—	—	—	—	—
109	17.3	13.1	17.0	16.7	3.3	2.3
110	1.9	1.6	1.0	—	—	—
111	2.0	1.8	2.1	2.6	3.5	1.8
123	2.6	3.4	5.7	3.8	7.1	4.7
125	2.6	1.5	—	—	—	1.9
135	4.6	4.4	5.7	4.5	—	—
137	2.1	2.0	—	1.7	—	—
140	—	—	—	—	—	1.6
151	—	—	—	—	4.2	2.9
152	1.8	1.5	2.0	2.5	—	—
153	19.3	13.8	8.4	15.8	—	1.6
154	—	—	—	—	—	1.5
168	—	—	—	—	11.6	7.3
169	3.9	5.7	15.3	8.6	61.9	67.4
170	—	—	—	2.8	2.1	3.7
171	—	3.2	—	—	—	—
185	—	—	—	—	5.4	—

trans-diols. Instead, the formation of the m/z 170 ion through nucleophilic substitution reaction was favourable. The position of the ammonium group in the chelate of the *trans*-diols is such that nitrogen can easily attach to one of the two hydroxy-bearing carbons as oxygen leaves ($\text{S}_{\text{N}}1$ reaction) (Scheme 1). The spatial arrangement of the atoms in the chelates of the *cis*-diols does not allow the same for them. Comparison of the CID spectra of compound (4) and of the mixture of compounds (3) and (4) shows that the *trans*-diols can also be identified by the CID method.

Besides the adduct ion, $(M + \text{NH}_4)^+$, the only important ion formed under NH_3 CI was the $(M - \text{H}_2 + \text{NH}_4)^+$ ion. Analogously, the two main peaks in the ND_3 CI spectra of the diols were due to the $(M + \text{ND}_4)^+$ and $(M - \text{D}_2 + \text{ND}_4)^+$ (m/z 190) ions. The deuteration experiment confirmed that the hydrogen atoms lost during the dehydrogenation process were mainly from the hydroxy groups. The related ketone structure has previously been proposed for the dehydrogenated ions of some monoalcohols.^{24,26} Madhusunan *et al.*²⁶ also verified their interpretation through ion structural studies and ND_3 CI measurements. Our results clearly point to a different main structure for the oxidation products of camphane-2,3-diols, although certain likenesses do exist between the CID spectra of our diols the related hydroxy ketones (Table 5). Nevertheless, the hydroxy ketone structures are not completely ruled out even



Scheme 1.

Figure 2. $i\text{-C}_4\text{H}_{10}$ CI mass spectra of camphane-2,3-diols.

in our case, as the ND_3 CI spectra of the diols contained a small m/z 191 ion peak.

The reason for the dehydrogenation reaction is not clear. The CID spectra showed that $(M - \text{H}_2 + \text{NH}_4)^+$ is not a fragment of the $(M + \text{NH}_4)^+$ ion. The intensity varied considerably with the experimental conditions, decreasing with

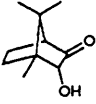
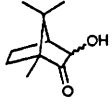
time and increasing with reagent-gas pressure and ionization current. Intensity variations have previously been attributed to a metal-catalysed process,²⁷ but this is improbable in our case because the electron ionization spectra were completely independent of related variations in measurement conditions.

In contrast with *cis*- and *trans*-cyclopentane-1,2-diols,^{1,4} camphane-2,3-diols exhibited only slight stereochemical effects in their isobutane chemical ionization spectra (Figure 2). The rigidity and compactness of the bornane ring system favoured the loss of water from the protonated molecular ions making them rather unstable. In this respect, the diols bear a close resemblance to the related monoalcohols, borneol, and isborneol.²⁸ Owing to the possibility of formation of a stabilizing proton bridge between the hydroxy groups, the *cis*-diols showed protonated molecular ion peaks but only with the less hindered 2-*endo*-3-*endo*-diol (2) was the peak of any considerable size.

Hydride-ion abstraction²⁹ or dehydrogenation of the $(M + \text{H})^+$ ions took place under $i\text{-C}_4\text{H}_{10}$ CI, resulting in $(M - \text{H})^+$ ions of equal intensity for compounds (1), (3), and (4). The intensity of the ion was somewhat weaker for compound (2), perhaps because the $(M + \text{H})^+$ ion is more stabilized than those of the other isomers. At least for compound (2), the $(M - \text{H})^+$ ion was the fragment of the protonated molecular ion, but this could not be proved for the other isomers because the $(M + \text{H})^+$ ion peaks were either too small or totally absent. Further experiments investigating the structure of the $(M - \text{H})^+$ ions are in progress, but certainly they do not have purely the hydroxy ketone structure as can be seen from Table 6. Even though the real structures of the m/z 169 ions are not known, their CID spectra allow differentiation of the isomeric camphane-2,3-diols. As under NH_3 CI, here too the spectrum of the *trans*-diol (4) differed considerably from the spectra of the *cis*-diols (1) and (2) and bore a closer resemblance to the spectra of the hydroxy ketones.

The methane chemical ionization spectra of the camphane-2,3-diols were different enough (Figure 3) to make direct isomeric identifications possible. These procedures, however, required model compounds to be available, because the ionization was such an exothermic process that the $(M - \text{H})^+$ and $(M + \text{H})^+$ ion peaks were either very small or totally absent. In addition, most of the fragment ions were products of ring cleavage reactions and as such their intensity ratios were hard to relate to the stereochemistry of the molecule. The main fragmentation pathways for compound (1) under CH_4 CI are presented in Scheme 2. The decomposition routes starting from protonated molecular ions were more important for the *cis*-

Table 6. The CID spectra of the m/z 169 ions generated from camphane-2,3-diols and related hydroxy ketones under $i\text{-C}_4\text{H}_{10}\text{Cl}$. Intensities are normalized to a total fragment-ion abundance of 100%. The data are not corrected for metastable peaks.

m/z	(1)	(2)	(4)		
55	1.1	1.2	—	—	—
67	1.4	1.4	—	—	—
69	2.2	2.3	—	—	—
77	1.5	1.3	—	—	—
79	1.6	1.4	—	—	—
81	2.5	1.9	3.5	2.8	—
83	2.2	3.2	0.6	2.8	—
84	—	1.5	—	—	—
85	—	1.0	—	2.7	3.5
91	1.8	1.5	0.6	2.8	3.5
93	2.0	2.2	—	—	—
95	4.6	7.0	4.1	3.7	4.1
97	2.0	4.0	1.9	2.7	—
98	—	—	—	2.7	3.8
107	2.8	1.8	3.9	4.4	4.0
108	0.7	—	—	2.9	—
109	9.9	9.9	7.2	6.0	10.6
110	1.4	1.1	—	—	—
111	3.0	1.1	3.9	11.4	13.8
113	—	—	—	3.0	—
123	16.4	5.7	43.9	22.7	23.6
124	2.6	1.1	6.2	3.0	4.0
125	2.8	2.0	3.6	4.4	6.2
135	2.8	4.8	—	—	—
141	—	—	3.3	2.7	3.5
151	4.5	1.5	10.5	14.6	15.4
152	3.0	1.9	3.4	—	—
153	27.2	37.0	2.4	4.7	3.9

than for the *trans*-diols. This was followed by their greater proton affinity, which allowed the proton-transfer reaction to compete better with hydride ion abstraction. The metastable transition and CID spectrum of the m/z 171 ion of compound (2) showed that the m/z 169 ion could not be a fragment of the m/z 171 ion and verified the importance of hydride abstraction. The different results under CH_4 than under $i\text{-C}_4\text{H}_{10}\text{Cl}$ are understandable in view of the greater hydride-ion affinity of methane than of isobutane reagent ions.²⁹ The structure of the m/z 169 ions was not determined but, here again, it was most probably not a hydroxy ketone structure, because, according to Scheme 2, the ion m/z 95 was also formed from the m/z 151 ion as well as from the m/z 153 ion, which was not the case for the related hydroxy ketones.

Experimental

Synthesis.—2-*exo*-3-*exo*-camphane-2,3-diol was prepared by LiAlH_4 reduction directly from camphorquinone and isolated from the crude product as its acetonide.^{13,14} For the synthesis of the other three diastereoisomeric diols, camphorquinone was converted into a mixture of hydroxy ketones according to Bredt and Ahren.³⁰ Pure 2-*endo*-hydroxyepicamphor was separated through its dimolecular methyl ether.³⁰ Its reduction with LiAlH_4 gave a mixture of 2-*endo*-3-*endo*- and 2-*endo*-3-*exo*-camphanediols, which were separated as described by Takeshita and Kitajima.¹⁴ The remaining 3-hydroxycamphor turned out to be a mixture of *endo*- and *exo*-isomers which yielded all four isomeric diols in LiAlH_4 reduction. The *cis*-diols were isolated as their acetonides but we were unable to separate the two *trans*-diols from each other as pure compounds.

The purity of the compounds was checked with a Carlo Erba

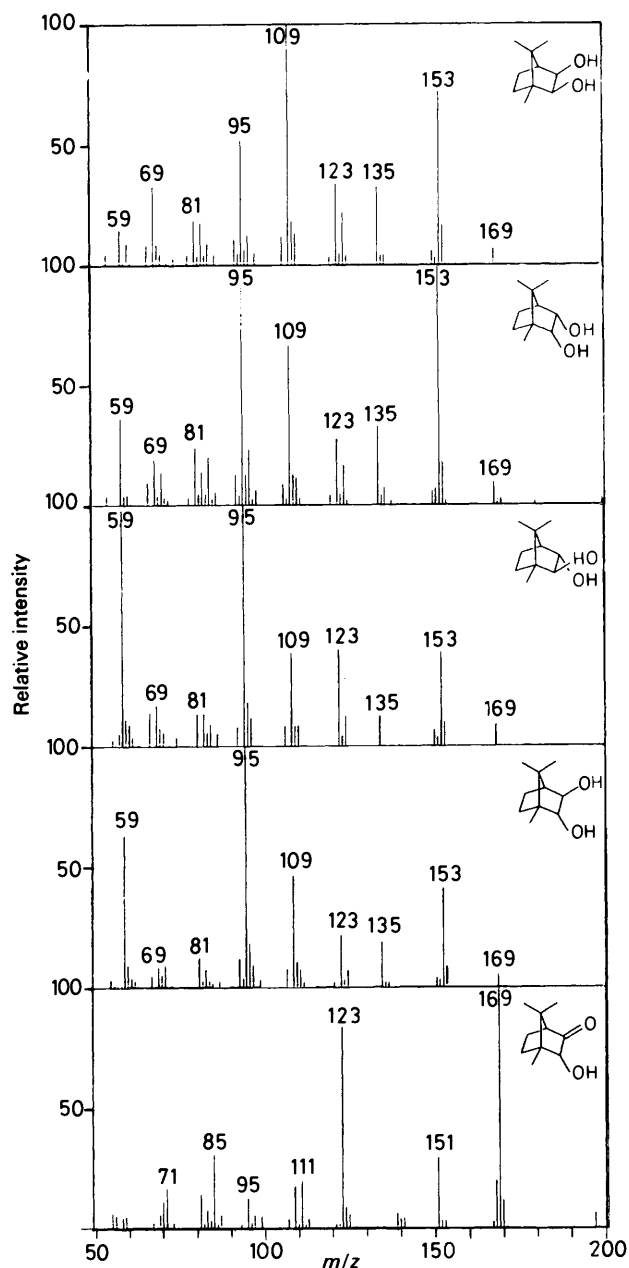
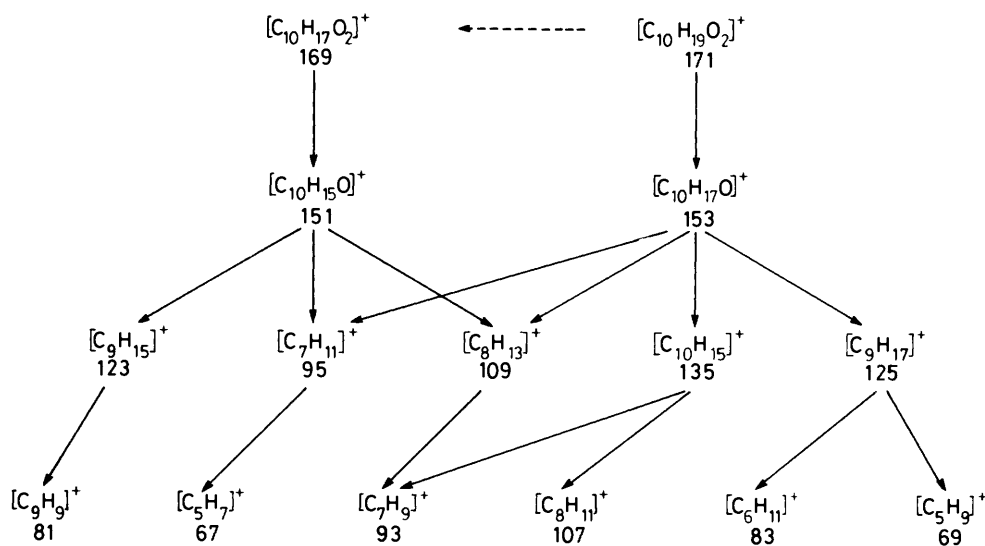


Figure 3. CH_4 CI mass spectra of camphane-2,3-diols and 2-hydroxyepicamphor.

Fractovap 4160 gas chromatograph (GLC) using a chemically bonded fused silica Carbowax 20 M column. The isomers were well separated and the order of elution was (1), (2), (3), then (4).

NMR Spectroscopy.—The spectra were recorded with a Bruker AC-250 ASPECT 3000 system using a 5 mm $^1\text{H}/^{13}\text{C}$ dual probe. All experimental observations were made in CDCl_3 (a few drops of CD_3OD were added to ensure solubility). For ^1H measurements, 20 mg of diol and for ^{13}C measurements, 70 mg of diol was added to 0.5 ml of deuteriated solvent with Me_4Si as an internal reference. The number of data points in the ^1H experiment was 32 KW, and in the ^{13}C experiment 64 KW. Decoupled ^{13}C NMR spectra were measured using composite pulse sequence (Waltz decoupling). From coupled spectra the tops of broad peaks were measured using the line-fitting routine with a Gaussian function. The COSY and NOESY spectra were acquired as 256*512 matrices with zero filling to 512*512



Scheme 2.

points. Proton-carbon chemical shift correlated spectra were acquired using a 256*4K matrix with zero filling.

Mass Spectrometry.—The mass spectra were recorded on a Jeol JMS-D300 mass spectrometer equipped with a combined electron impact/chemical ionization source and connected to a Jeol JMA-2000H data system. The reagent gas flow was adjusted by monitoring the source housing pressure (8×10^{-6} Torr*). The other source conditions were: temperature 170 °C, electron energy 200 eV, accelerating voltage 3 kV, and ionization current 300 μ A if not stated otherwise. The CI spectra were usually obtained from one GLC run. For CID measurement, samples were introduced through a direct inlet system without heating. Because pure compounds were required, no data could be obtained for compound (3). The CID spectra were measured with linked scans at constant B/E , with helium led into the first field-free region so that transmission of the main beam was 33%. To ensure identical experimental conditions, spectra of all ions with the same mass value but generated from different compounds were recorded one after another without adjustment of the instrumental parameters.

* 1 Torr = 133.322 Pa.

References

- J. Winkler and F. W. McLafferty, *Tetrahedron*, 1974, **30**, 2971.
- R. Wolfschütz, H. Schwarz, W. Blum, and W. J. Richter, *Org. Mass Spectrom.*, 1978, **13**, 697.
- W. J. Richter and H. Schwarz, *Angew. Chem., Int. Ed. Engl.*, 1978, **17**, 424.
- F. J. Winkler and D. Stahl, *J. Am. Chem. Soc.*, 1979, **101**, 3685.
- B. Munson, B. L. Jelus, F. Hatch, K. Morgan Jr., and R. K. Murray Jr., *Org. Mass Spectrom.*, 1980, **15**, 161.
- J. Bastard, D. Do Khac Manh, M. Fetizon, and J. C. Tabet, *J. Chem. Soc., Perkin Trans. 2*, 1981, 1591.
- J. C. Tabet, I. Hanna, and M. Fetizon, *Org. Mass Spectrom.*, 1985, **20**, 61.
- P. Ashkenazi, W. Blum, B. Domon, A. L. Gutman, A. Mandelbaum,

- D. Müller, W. J. Richter, and D. Ginsburg, *J. Am. Chem. Soc.*, 1987, **109**, 7325.
- Y. Klopstock, P. Ashkenazi, A. Mandelbaum, D. Müller, W. J. Richter, and D. Ginsburg, *Tetrahedron*, 1988, **44**, 5893.
- W. J. Meyerhoffer and M. M. Bursey, *Org. Mass Spectrom.*, 1989, **24**, 169.
- H. F. Grützmaier and K. H. Fechner, *Tetrahedron*, 1971, **27**, 5011.
- H. Rupe and W. Thommen, *Helv. Chim. Acta*, 1947, **30**, 933.
- S. J. Angyal and R. J. Young, *J. Am. Chem. Soc.*, 1959, **81**, 5467.
- T. Takeshita and M. Kitajima, *Bull. Soc. Chem. Jpn.*, 1959, **32**, 985.
- F. A. L. Anet, *Can. J. Chem.*, 1961, **39**, 789.
- M. A. Johnson and M. P. Fleming, *Can. J. Chem.*, 1979, **57**, 318.
- M. S. Allen, J. H. Hutchinson, and T. Money, *Can. J. Chem.*, 1984, **62**, 2707.
- E. Lippmaa, T. Pehk, N. A. Belikova, A. A. Bobyleva, A. N. Kalinichenko, M. D. Ordubadi, and A. F. Platé, *Org. Magn. Reson.*, 1976, **8**, 74.
- J. B. Stothers, C. T. Tan, and K. C. Teo, *Can. J. Chem.*, 1976, **54**, 1211.
- M. Manoharan and E. L. Eliel, *Magn. Reson. Chem.*, 1985, **23**, 225.
- A. Daniel and A. A. Pavia, *Org. Mass Spectrom.*, 1971, **5**, 1237.
- A. F. Thomas and B. Willhalm, *Helv. Chim. Acta*, 1964, **47**, 475.
- F. J. Winkler, O. F. Gülacar, and A. Buchs, in 'Recent Developments in Mass Spectrometry in Biochemistry, Medicine and Environmental Research,' ed. A. Frigerio, Elsevier, Amsterdam, 1983, vol. 8, p. 307.
- F. O. Gülacar, F. Mermoud, F. J. Winkler, and A. Buchs, *Helv. Chim. Acta*, 1984, **67**, 488.
- For leading reviews, see: (a) K. Levsen and H. Schwarz, *Angew. Chem., Int. Ed. Engl.*, 1976, **15**, 509; (b) 'Collision Spectroscopy,' ed. R. G. Cooks, Plenum Press, New York, 1978; (c) K. Levsen and H. Schwarz, *Mass Spectrom. Rev.*, 1983, **2**, 77; (d) 'Tandem Mass Spectrometry,' ed. F. W. McLafferty, Wiley, New York, 1983.
- K. P. Madhusudanan, Chandan Singh, and D. Fraise, *Org. Mass Spectrom.*, 1986, **21**, 131.
- H. Budzikiewicz, *Org. Mass Spectrom.*, 1988, **23**, 561.
- F. J. Winkler, F. O. Gülacar, F. Mermoud, and A. Buchs, *Helv. Chim. Acta*, 1983, **66**, 929.
- A. G. Harrison, 'Chemical Ionization Mass Spectrometry,' CRC Press, Boca Raton, 1983.
- J. Bredt and H. Ahren, *J. Prakt. Chem.*, 1926, **112**, 377.

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