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Synthesis of Dibarrelane, a Dibicyclo[2.2.2]octane Hydrocarbon

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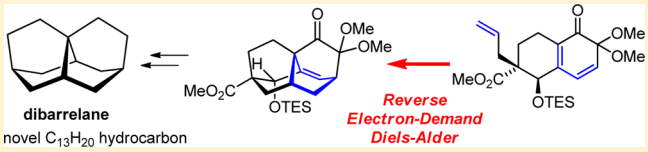
Supporting Information

ABSTRACT: The synthesis of a novel hydrocarbon, dibarrelane, has been accomplished in 11 steps via an intramolecular REDDA reaction of a masked *o*-benzoquinone, followed by Clemmensen reduction and Barton decarboxylation. The twisted structure of the tetracyclic dibarrelane skeleton was also clarified via X-ray crystallography. Finally, it was proposed that dibarrelane has C_2 symmetry rather than C_{2v} symmetry.



Highly symmetrical cage hydrocarbons such as prismane, cubane, dodecahedrane, and fullerene have attracted chemists with their simple and beautiful chemical structures (Figure 1a).[1] While the synthesis of symmetrical cage hydrocarbons continues to be a challenging subject in organic chemistry, synthetic efforts have resulted in novel methodologies in organic synthesis and have also provided valuable knowledge in physical organic chemistry. Most of the symmetrical skeletons have been artificially designed through imagination and computational study; however, nature occasionally produces an unprecedented cage compound possessing a highly symmetrical skeleton.[2]

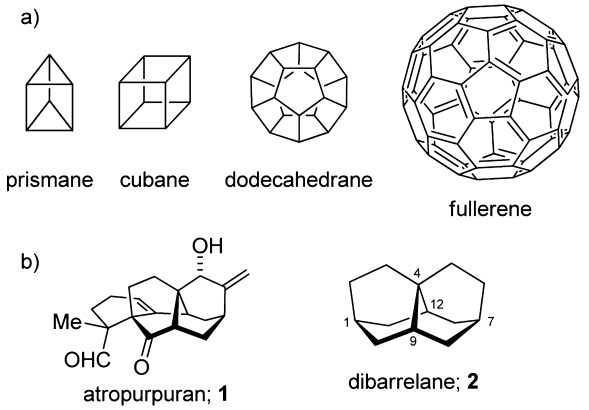


Figure 1. (a) Example of highly symmetrical cage hydrocarbons. (b) Structures of atropurupuran (**1**) and its core skeleton, dibarrelane (**2**).

We have been investigating the total synthesis of a unique pentacyclic diterpene, atropurpuran[3,4] (**1**) (Figure 1b). Atropurpuran possesses a cage-like skeleton with C_{2v} symmetry, tetracyclo[5.3.3.$0^{4,9}$.$0^{4,12}$]tridecane (**2**), which includes two bicyclo[2.2.2]octane units fused by two C−C single bonds.[5] We have named this simple $C_{13}H_{20}$ hydrocarbon "dibarrelane" after "barrelene", bicyclo[2.2.2]octa-2,5,7-triene.[6] Dibarrelane possesses one quaternary carbon which is shared by six six-membered rings. All cyclohexanes may adopt a boatlike conformation. Dibarrelane **2** is a potent component of polycyclic hydrocarbons (Figure 2). Fusion of bicyclo[2.2.2]-octane to dibarrelane at the C1−C10 and C1−C11 bonds gives a hexacyclic compound, tribarrelane **3**. The further extension of bicyclo[2.2.2]octanes in the same fashion will give the D_{5h}-symmetric cyclopentabarrelane **4**.[7] On the other hand, fusion of bicyclo[2.2.2]octane to **2** at the C1−C2 and C1−C10 bonds gives an isomer of **3**, isotribarrelane **5**, which possesses axial chirality. The intriguing structural features of **2** provided a strong motivation for the synthesis of dibarrelane hydrocarbons. We report herein the synthesis, structure, and properties of **2**.

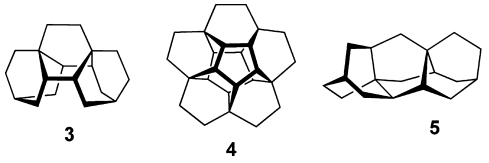


Figure 2. Example of cage hydrocarbons based on dibarrelane.

The synthetic strategy to attain dibarrelane is shown in Scheme 1. It was envisaged that the construction of the dibarrelane skeleton **8** could be achieved by an intramolecular reverse-electron-demand Diels−Alder (REDDA) reaction of a masked *o*-benzoquinone (MOB) 7.[8] MOB **7** would be prepared from tetralone **6** by introduction of methoxycarbonyl and allyl groups. Due to the dense array of functional groups on **9**, there are a variety of options for the order of defunctionalization. Dibarrelane-1-carboxylic acid **9** was chosen as the precursor of **2**,[9] and Barton decarboxylation[10] of 7 completes the synthesis of dibarrelane **2**.

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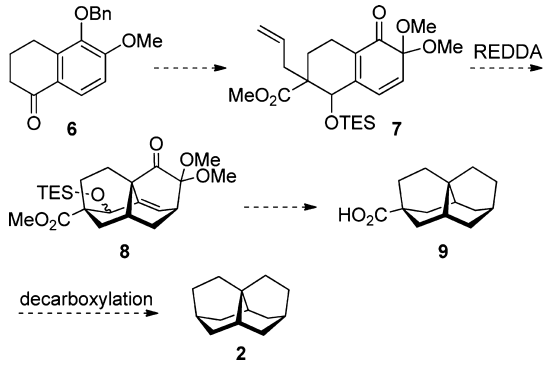
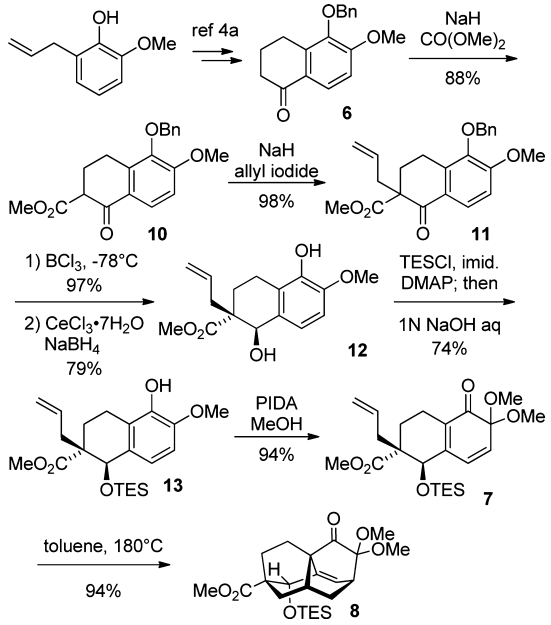
Scheme 1. Synthetic Strategy toward Dibarrelane



Synthesis of the tetracyclic compound **8** commenced with the methoxycarbonylation of tetralone **6**, which was prepared from *o*-eugenol on a multigram scale[4a] (Scheme 2). The

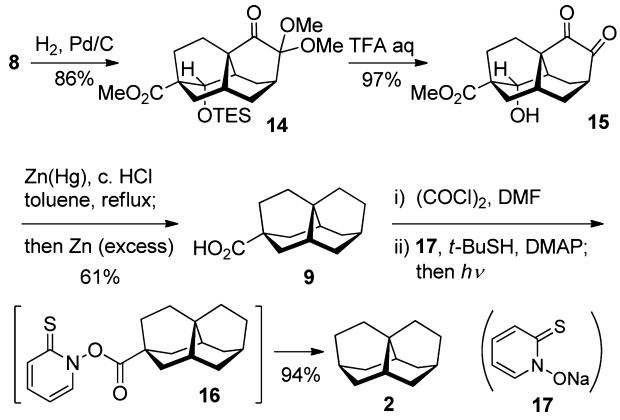
Scheme 2. Construction of Tetracyclic Skeleton



requisite vinyl group (dienophile for the REDDA reaction) was introduced by allylation of the active methine carbon of **10** to give keto ester **11**. After removal of a Bn group with BCl_3, reduction of ketone under Luche conditions afforded alcohol **12** as a single isomer.[11] The resulting secondary alcohol **12** was transformed into **13** by silyl etherification and selective deprotection of phenol. Oxidative dearomatization of phenol **13** with (diacetoxy)iodobenzene (PIDA) in the presence of MeOH provided MOB **7**. The intramolecular REDDA reaction of MOB **7** in toluene (180 °C, in a sealed tube) successfully proceeded to give tetracyclic compound **8** in high yield (94%).

Defunctionalization of the dibarrelane skeleton was then accomplished (Scheme 3). First, hydrogenation of the *anti*-Bredt double bond of **8** was carried out to obtain the α-keto acetal **14** in 86% yield. Treatment of **14** with an 80% aqueous TFA solution in CH_2Cl_2 caused hydrolysis of the dimethyl acetal concurrent with deprotection of the secondary alcohol to give the α-diketone **15**. Surprisingly, **15** was directly converted into dibarrelane-1-carboxylic acid **9** under Clemmensen reduction conditions.[12] It is noteworthy that the unexpected

Scheme 3. Synthesis of Dibarrelane



reduction of a secondary alcohol took place under these reaction conditions.[13] Finally, Barton decarboxylation of **9** occurred via acyloxypyridine-2-thione intermediate **16** to afford the volatile hydrocarbon **2** in 94% yield. Sublimation of **2** at 45−50 °C (bath temperature) gave a dendritic crystal (mp 90−93 °C in a sealed capillary). Dibarrelane **2** has a terpene-like odor, and the ^{13}C NMR in $CDCl_3$ has six sharp signals at 38.2, 32.3, 31.2, 27.4, 27.1, and 26.7 ppm, indicative of the symmetrical structure of dibarrelane.

Although the crystals were not suitable for X-ray analysis, the dibarrelane skeleton was unambiguously confirmed via X-ray crystallographic analysis of carboxylic acid **9**[14] (Figure 3).

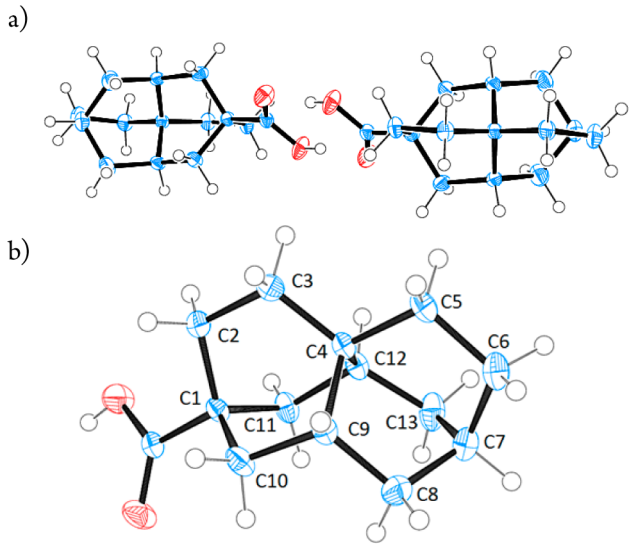


Figure 3. Ortep drawings of carboxylic acid **9**: (a) dimeric structure; (b) monomeric structure. Thermal ellipsoids are drawn at the 50% probability level.

Carboxylic acid **9** forms a dimer via intermolecular hydrogen bonding in its crystalline form, and it was surprising to find that the dimer is a set of enantiomers (Figure 3a), because carboxylic acid **9** was thought to be achiral. The ORTEP structure and representative details of the monomer (right side of Figure 3a) are shown in Figure 3b and Table 1. Similar to the case for adamantane, all bond lengths are 1.54 ± 0.02 Å and all C−C−C bond angles are 109.5 ± 1.5° except for the bridgehead carbons (C4, C9, and C12). The bond angles of bridgehead methines C8−C9−C10 and C11−C12−C13 are

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Table 1. Selected Geometric Parameters for Carboxylic Acid 9 and Dibarrelane 2

	9		
	exptl[a]	theor[b]	2 theor[b]
	Distances (Å)		
C1−C11	1.548(2)	1.552	1.540
C4−C12	1.542(2)	1.555	1.557
C6−C7	1.545(3)	1.540	1.540
C7−C13	1.532(3)	1.542	1.542
C11−C12	1.550(2)	1.561	1.563
C12−C13	1.553(2)	1.559	1.558
	Angles (deg)		
C3−C4−C5	111.5(1)	111.8	111.7
C9−C4−C12	106.6(1)	106.3	106.3
C8−C9−C10	113.4(1)	113.9	113.9
C11−C12−C13	113.4(1)	113.5	113.9
C1−C2−C3−C4	9.3(2)	12.7	11.1
C4−C5−C6−C7	10.7(2)	11.8	11.1
C7−C8−C9−C4	7.7(2)	9.7	9.1
C4−C9−C10−C1	12.6(2)	15.7	14.8
C1−C11−C12−C4	7.9(2)	9.8	9.1
C4−C12−C13−C7	12.9(2)	15.2	14.8

[a]X-ray structure reported in this work. [b]DFT calculations were performed with the Gaussian 09 program for structure minimization with the B3LYP/6-31G* method.

113.4°, and those of quaternary carbon C3−C4−C5 and C9−C4−C12 are 111.5 and 106.6°, respectively. These results are consistent with those of computational calculation.[15]

Other characteristic structural features of carboxylic acid **9** are follows: the C1−C2−C3−C4 and C4−C5−C6−C7 torsion angles are ca. 10°, resulting in a twist in the two bicyclo[2.2.2]-octanes (the torsion angle between C2−C3 and C5−C6 is 17.85°). The distances between the 1,5-diaxial hydrogens on the bottom crownlike eight-membered ring are not the same; e.g. the H8ax−H11ax distance is 2.720 Å, and that between H10ax and H13ax is 3.864 Å. These results demonstrate that the dibarrelane skeleton apparently does not have σ symmetry in the crystalline state. The twisted dibarrelane skeleton might be the result of a diminished H−H diaxial interaction (between H8ax−H10ax and H11ax−H13ax). The H8ax−H10ax and H11ax−H13ax distances are 2.162 and 2.167 Å, respectively, still smaller than the van der Waals radii. As a result, the dibarrelane skeleton becomes chiral, and the crystals of carboxylic acid **9** pack so as to grow a dimer composed of a set of enantiomers.

Although an X-ray crystallographic analysis of dibarrelane **2** itself was unsuccessful, the structural analysis of carboxylic acid **9** strongly suggests a distorted structure for dibarrelane. In other words, dibarrelane might have C_2 symmetry rather than the originally anticipated C_{2v} symmetry. A precise structural analysis of the dibarrelane skeleton, particularly an experimental proof of the chiral nature (both in crystalline form and in solution), would be quite interesting. The results of DFT calculations for geometry optimization of dibarrelane **2** indicated that the C_2-symmetric conformations are the most stable (Table 1). However, there is almost no difference in energy between C_2-symmetric and C_{2v}-symmetric conformations (ca. 1.1 kJ/mol).[16] Therefore, it is suggested that the energy barrier for conformational interconversion is quite low.[17]

In summary, the synthesis of a novel hydrocarbon, dibarrelane, has been accomplished in 11 steps from tetralone **6** via an intramolecular REDDA reaction of a masked *o*-benzoquinone, followed by Clemmensen reduction and Barton decarboxylation. The twisted structure of the tetracyclic dibarrelane skeleton was also clarified via X-ray crystallography. Finally, it was proposed that dibarrelane has C_2 symmetry rather than C_{2v} symmetry. Further structural analyses of the dibarrelane skeleton along with a synthetic study of cage hydrocarbons based on dibarrelane are currently underway.

EXPERIMENTAL SECTION

General Methods. Flash column chromatography was performed with silica gel (50−200 μm). Solvents for chromatography are listed as volume/volume ratios. Analytical thin-layer chromatography was performed using commercial silica gel plates. Infrared spectra were recorded in reciprocal centimeters (cm^{-1}). High-resolution mass spectra (HRMS) were obtained by a hybrid quadrupole time-of-flight (TOF) mass spectrometer for electrospray ionization (ESI) and a double-focusing magnetic sector (DFS) mass spectrometer for fast atom bombardment (FAB) and electroimpact ionization (EI). ^{1}H NMR spectra were acquired at 400 and 600 MHz. Chemical shifts are reported in delta (δ) units in parts per million (ppm) relative to the singlet at 7.26 ppm for chloroform-*d* and the quintet at 2.05 ppm for acetone-d_6. ^{13}C NMR spectra were acquired at 100 and 125 MHz. Chemical shifts are reported (ppm) relative to the central line of the triplet at 77.0 ppm for chloroform-*d* and the septet at 29.84 ppm for acetone-d_6.

Methyl 5-(Benzyloxy)-6-methoxy-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylate (10). To a solution of NaH (55%, 0.926 g, 21.24 mmol) and dimethyl carbonate (2.76 mL, 31.86 mmol) in toluene (20 mL) was added tetralone **6**[4a] (1.00 g, 3.54 mmol) at room temperature. The reaction mixture was stirred at 80 °C for 10 h. The reaction mixture was cooled to 0 °C, and H_2O followed by 1 M aqueous HCl was carefully added to the reaction mixture. The aqueous layer was extracted with CH_2Cl_2,, and the combined organic layers were washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The residue was purified by silica gel chromatography with (hexane/EtOAc 8/1 to 5/1) to afford keto ester **10** (1.06 g, 88% yield) as a mixture of tautomers (keto form:enol form 2:1): R_f = 0.43 (hexane/EtOAc 3/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 12.43 (s, 1/3H), 7.88 (d, J = 8.8 Hz, 2/3H), 7.56 (d, J = 8.5 Hz, 1/3H), 7.44−7.28 (m, 5H), 6.92 (d, J = 8.8 Hz, 2/3H), 6.84 (d, J = 8.5 Hz, 1/3H), 5.55 (s, 4/3H), 4.97 (s, 2/3H), 3.94 (s, 2H), 3.91 (s, 1H), 3.78 (s, 1H), 3.75 (s, 2H), 3.50 (dd, J = 10.3, 4.6 Hz, 2/3H), 3.00 (ddd, J = 17.5, 5.9, 4.6 Hz, 2/3H), 2.73−2.64 (m, 4/3H), 2.39 (dd, J = 8.9, 7.0 Hz, 2/3H), 2.32 (dddd, J = 13.5, 9.9, 9.9, 4.7 Hz, 2/3H), 2.20 (dddd, J = 13.5, 5.9, 4.9, 4.9 Hz, 2/3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 192.1, 173.0, 170.8, 165.2, 157.2, 155.0, 143.8, 138.2, 137.4, 137.2, 133.9, 128.41, 128.36, 128.30, 128.28, 128.1, 128.0, 125.4, 125.2, 123.3, 121.1, 110.3, 109.5, 95.1, 74.6, 74.4, 55.8, 55.7, 53.9, 52.2, 51.4, 25.8, 21.8, 21.1, 20.0; IR (ATR) 2950, 1738, 1676, 1590, 1438, 1270, 1205, 1075 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{20}H_{20}NaO_5$ 363.1202, found 363.1212.

Methyl 2-Allyl-5-(benzyloxy)-6-methoxy-1-oxo-1,2,3,4-tetrahydronaphthalene-2-carboxylate (11). To a solution of keto ester **10** (2.13 g, 6.27 mmol) in THF (60 mL) was added NaH (55%, 0.274 g, 6.27 mmol) portionwise at 0 °C. After the mixture was stirred for 10 min at 0 °C, allyl iodide (2.29 mL, 25.1 mmol) was added. The reaction mixture was stirred at 0 °C for 3 h. The reaction was quenched with saturated aqueous NH_4Cl solution, and the aqueous layer was extracted with CH_2Cl_2. The combined organic layers were washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The residue was purified by silica gel chromatography with (hexane/EtOAc 6/1) to afford keto ester **11** (2.35 g, 98% yield) as a colorless oil: R_f = 0.41 (hexane/EtOAc 4/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89 (d, J = 8.8 Hz, 1H), 7.44−7.30 (m, 5H), 6.93 (d, J = 8.8 Hz, 1H), 5.79 (dddd, J = 16.9, 10.6, 7.2, 7.2 Hz, 1H), 5.14−5.06 (m, 2H), 5.00 (s, 2H), 3.96 (s, 3H), 3.65 (s, 3H), 2.88 (ddd, J =

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17.9, 5.2, 5.2 Hz, 1H), 2.73 (ddd, J = 17.9, 10.0, 4.9 Hz, 1H), 2.69 (dd, J = 14.1, 7.2 Hz, 1H), 2.60 (dd, J = 14.1, 7.2 Hz, 1H), 2.41 (ddd, J = 13.9, 5.2, 4.9 Hz, 1H), 1.98 (ddd, J = 13.9, 10.0, 5.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 194.0, 172.1, 157.0, 143.7, 138.0, 137.3, 133.5, 128.41, 128.36, 128.2, 125.7, 125.5, 118.8, 110.4, 74.3, 56.9, 55.8, 52.3, 38.5, 29.9, 20.2; IR (ATR) 3019, 2950, 1731, 1676, 1589, 1489, 1440, 1280, 1214, 1076 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{23}H_{24}NaO_5$ 403.1515, found 403.1521.

(1*R,2*S**)-Methyl 2-Allyl-1,5-dihydroxy-6-methoxy-1,2,3,4-tetrahydronaphthalene-2-carboxylate (12).** To a solution of Bn ether **11** (1.27 g, 4.37 mmol) in CH_2Cl_2 (30 mL) was added dropwise a 1.0 M solution of BCl_3 in heptane (11.37 mL, 11.37 mmol) at −78 °C. After it was stirred for 3 h at −78 °C, the reaction mixture was quenched with MeOH (0.5 mL) and diluted with water. The aqueous layer was extracted with CH_2Cl_2. The combined organic layer was washed with brine, dried over Na_2SO_4, filtered, and concentrated in vacuo. The residue was purified by flash column chromatography (hexane/EtOAc 6/1 to 2/1) to afford the phenol (0.984 g, 97%) as a white solid: R_f = 0.24 (hexane/EtOAc 4/1); mp 105 °C (from EtOAc/hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.69 (d, J = 8.8 Hz, 1H), 6.85 (d, J = 8.8 Hz, 1H), 5.84 (dddd, J = 16.9, 10.1, 7.4, 7.0 Hz, 1H), 5.75 (s, 1H), 5.18−5.08 (m, 2H), 3.95 (s, 3H), 3.67 (s, 3H), 2.99 (ddd, J = 17.9, 5.3, 5.3 Hz, 1H), 2.88 (ddd, J = 17.9, 9.7, 4.8 Hz, 1H), 2.74 (dd, J = 14.0, 7.0 Hz, 1H), 2.66 (dd, J = 14.0, 7.4 Hz, 1H), 2.54 (ddd, J = 13.8, 5.3, 4.9 Hz, 1H), 2.10 (ddd, J = 13.8, 9.7, 5.3 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 194.2, 172.1, 150.0, 141.8, 133.5, 129.2, 125.8, 121.0, 118.7, 108.6, 57.1, 56.1, 52.3, 38.5, 29.8, 19.4; IR (ATR) 3461, 3219, 2948, 1728, 1493, 1435, 1276, 1218, 996 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{16}H_{18}NaO_5$ 313.1046, found 313.1043. To a solution of the phenol (3.30 g, 11.3 mmol) and $CeCl_3{\cdot}7H_2O$ (10.9 g, 29.4 mmol) in MeOH (100 mL) was added $NaBH_4$ (1.14 g, 29.4 mmol) at −10 °C. The reaction mixture was stirred at the same temperature for 3 h. The reaction mixture was quenched with saturated aqueous NH_4Cl solution, and MeOH was removed by a rotary evaporator. The residue was diluted with EtOAc and H_2O, and the mixture was separated. The aqueous layer was extracted with CH_2Cl_2, and the combined organic layers were washed with brine, dried with Na_2SO_4, and concentrated in vacuo. The residue was purified by flash column chromatography (hexane/EtOAc 8/1 to 2/1) to afford **12** (2.63 g, 79%) as a white solid: R_f = 0.19 (hexane/EtOAc = 4/1); mp 136−138 °C (from EtOAc/hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.00 (d, J = 8.3 Hz, 1H), 6.78 (d, J = 8.3 Hz, 1H), 5.86 (dddd, J = 16.9, 10.2, 7.4, 7.0 Hz, 1H), 5.68 (s, 1H), 5.14−5.05 (m, 2H), 4.93 (brs, 1H), 3.87 (s, 3H), 3.65 (s, 3H), 2.79 (ddd, J = 18.2, 6.3, 6.3 Hz, 1H), 2.68 (ddd, J = 18.2, 7.2, 7.2 Hz, 1H), 2.63 (dd, J = 13.8, 7.0 Hz, 1H), 2.37−2.29 (m, 2H), 2.12−2.00 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 175.6, 145.3, 142.5, 133.9, 130.8, 121.9, 119.7, 118.0, 108.8, 70.5, 56.0, 51.7, 50.2, 37.4, 25.1, 20.0; IR (ATR) 3460, 3229, 2947, 1727, 1493, 1434, 1276, 1218, 996 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{16}H_{20}NaO_5$ 315.1202, found 315.1205.

(1*R,2*S**)-Methyl 2-Allyl-5-hydroxy-6-methoxy-1-((triethylsilyl)oxy)-1,2,3,4-tetrahydronaphthalene-2-carboxylate (13).** To a solution of alcohol **12** (5.10 g, 17.4 mmol) in DMF (50 mL) was added imidazole (5.93 g, 87.2 mmol), TESCl (13.1 mL, 87.2 mmol), and DMAP (0.53 g, 4.35 mmol) at 0 °C, and the mixture was stirred at room temperature for 16 h. The reaction was quenched with a saturated $NaHCO_3$ solution, and the organic layer was separated. The aqueous layer was extracted with ether, and the combined organic layers were washed with brine, dried over Na_2SO_4, filtered, and concentrated under reduced pressure. To the crude di-TES ether were added THF (80 mL) and 1 M NaOH solution (100 mL) at room temperature, the mixture was stirred for 4 h, and the mixture was neutralized with 1 M HCl solution. The resulting mixture was extracted with EtOAc, and the organic layer was washed with brine, dried over Na_2SO_4, filtered, and concentrated under reduced pressure. The residue was purified by silica gel chromatography with hexane/EtOAc (10/1) to afford **13** (5.24 g, 74%) as a white solid: R_f = 0.51 (hexane/EtOAc = 4/1); mp 64−65 °C (from EtOAc/hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.75 (d, J = 8.3 Hz, 1H), 6.67 (d, J = 8.3 Hz, 1H), 5.82 (dddd, J = 16.9, 10.6, 7.8, 7.0 Hz, 1H), 5.62 (s, 1H), 5.10−5.03 (m, 2H), 4.90 (brs, 1H), 3.85 (s, 3H), 3.50 (s, 3H), 2.79 (ddd, J = 18.2, 7.6, 3.7 Hz, 1H), 2.72 (ddd, J = 18.2, 9.5, 7.0 Hz, 1H), 2.60 (dd, J = 13.7, 7.0 Hz, 1H), 2.35 (dd, J = 13.7, 7.8 Hz, 1H), 2.18−2.02 (m, 2H), 0.85 (t, J = 7.9 Hz, 9H), 0.50 (q, J = 7.9 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 174.7, 145.4, 142.7, 134.0, 131.4, 122.7, 120.5, 117.6, 107.6, 71.8, 55.9, 51.9, 51.3, 40.4, 23.9, 20.2, 6.9, 5.4; IR (ATR) 3435, 2955, 2876, 1716, 1495, 1277, 1053, 1007 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{22}H_{34}NaO_5Si$ 429.2067, found 429.2070.

(1*R,2*S**)-Methyl 2-Allyl-6,6-dimethoxy-5-oxo-1-((triethylsilyl)oxy)-1,2,3,4,5,6-hexahydronaphthalene-2-carboxylate (7).** To a solution of phenol **13** (5.24 g, 12.8 mmol) in MeOH/CH_2Cl_2 (2/3 v/v, 100 mL) was added PIDA (4.53 g, 14.1 mmol) portionwise at 0 °C. The reaction mixture was stirred for 30 min at 0 °C, and saturated $NaHCO_3$ solution was added. The resulting mixture was extracted two times with CH_2Cl_2, and the organic layers were dried over Na_2SO_4, filtered, and concentrated under reduced pressure. The residue was purified by silica gel chromatography with hexane/EtOAc (15/1) to afford MOB **7** (5.26 g, 94% yield) as a yellow oil: R_f = 0.35 (hexane/EtOAc = 6/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.29 (m, 2H), 5.76 (dddd, J = 16.9, 10.7, 8.0, 6.8 Hz, 1H), 5.10−5.03 (m, 2H), 4.53 (s, 1H), 3.61 (s, 3H), 3.36 (s, 3H), 3.33 (s, 3H), 2.53 (dd, J = 13.5, 6.8 Hz, 1H), 2.41 (ddd, J = 19.9, 6.8, 3.1 Hz, 1H), 2.33−2.21 (m, 2H), 1.99 (ddd, J = 13.5, 6.3, 3.1 Hz, 1H), 1.86 (ddd, J = 13.5, 9.6, 6.8 Hz, 1H), 0.96 (t, J = 7.9 Hz, 9H), 0.66 (q, J = 7.9 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 195.8, 174.3, 145.6, 133.2, 132.3, 130.4, 129.1, 118.2, 91.2, 70.8, 51.6, 51.3, 50.2, 50.1, 38.9, 24.1, 19.6, 6.9, 5.6; IR (ATR) 2953, 2877, 1731, 1672, 1435, 1217, 1061, 1004, 728 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{23}H_{36}NaO_6Si$ 459.2173, found 459.2174.

(2*S,4a*R**,7*S**)-Methyl 6,6-Dimethoxy-5-oxo-1-((triethylsilyl)oxy)-2,3,4,5,6,7-hexahydro-1*H*-2,4a-ethano-4,7-methanonaphthalene-2-carboxylate (8).** A solution of MOB **7** (5.26 g, 12.0 mmol) in dry toluene (100 mL) was heated to 180 °C for 16 h in a sealed tube. The reaction mixture was transferred into a round-bottom flask, and the solvent was removed in vacuo. The residue was purified by silica gel column chromatography with hexane/EtOAc (50/1 to 10/1) to afford cycloadduct **8** (4.95 g, 94% yield) as a colorless oil: R_f = 0.38 (hexane/EtOAc = 6/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.31 (dd, J = 6.7, 1.8 Hz, 1H), 4.78 (d, J = 1.8 Hz, 1H), 3.65 (s, 3H), 3.35 (s, 3H), 3.27 (s, 3H), 2.34−2.23 (m, 2H), 2.18 (ddd, J = 9.3, 6.2, 6.2 Hz, 1H), 2.03−1.90 (m, 2H), 1.83 (dd, J = 13.7, 9.0 Hz, 1H), 1.64−1.54 (m, 2H), 1.36, (ddd, J = 14.0, 5.7, 3.1 Hz, 1H), 1.32 (dd, J = 13.7, 4.6 Hz, 1H), 0.96 (t, J = 7.8 Hz, 9H), 0.63 (q, J = 7.8 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 205.1, 173.9, 143.6, 125.5, 95.3, 76.2, 54.2, 52.7, 51.6, 50.3, 49.4, 42.2, 39.6, 34.8, 34.5, 27.9, 18.5, 6.8, 4.8; IR (ATR) 2953, 2876, 1731, 1241, 1153, 1115, 1090, 1055, 734 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{23}H_{36}NaO_6Si$ 459.2173, found 459.2170.

(2*S,4a*R**,7*S**)-Methyl 6,6-Dimethoxy-5-oxo-1-((triethylsilyl)oxy)octahydro-1*H*-2,4a-ethano-4,7-methanonaphthalene-2-carboxylate (14).** To a solution of unsaturated ester **8** (0.745 g, 1.71 mmol) in EtOH (10 mL) was added 10% Pd/90% C (0.200 g, 10 mol % Pd) under an argon atmosphere. The argon was purged with H_2, and the mixture was stirred under an H_2 atmosphere for 2.5 h. The reaction mixture was filtered over Celite and concentrated in vacuo. The residue was purified by silica gel column chromatography with hexane/EtOAc (10/1) to give ester **14** (0.644 g, 86%) as a colorless oil: R_f = 0.51 (hexane/EtOAc = 4/1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.19 (dd, J = 9.0, 1.4 Hz, 1H), 3.65 (s, 3H), 3.30 (s, 3H), 3.29 (s, 3H), 2.35 (m, 1H), 2.24−2.00 (m, 4H), 1.95−1.82 (m, 3H), 1.77−1.67 (m, 2H), 1.58−1.46 (m, 3H), 0.95 (t, J = 7.8 Hz, 9H), 0.58 (q, J = 7.8 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 209.3, 175.7, 97.0, 70.8, 51.5, 50.1, 49.3, 47.3, 45.7, 36.1, 33.8, 32.0, 30.7, 30.2, 27.4, 21.4, 20.5, 6.8, 4.7; IR (ATR) 2950, 2875, 1729, 1459, 1246, 1152, 1106, 1055 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{23}H_{38}NaO_6Si$ 461.2329, found 461.2326.

(2*S,4a*R**,7*S**)-Methyl 1-Hydroxy-5,6-dioxooctahydro-1*H*-2,4a-ethano-4,7-methanonaphthalene-2-carboxylate (15).** To a solution of TES ether **14** (0.911 g, 2.08 mmol) in CH_2Cl_2 (4 mL) was added a solution of TFA (80% v/v in H_2O, 6.0 mL) at room

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temperature, and the mixture was vigorously stirred for 2 h. The reaction mixture was concentrated in vacuo. The resulting residue was purified by silica gel column chromatography (hexane/EtOAc = 2/1) to afford **15** (559 mg, 97% yield) as a pale yellow solid: R_f = 0.15 (hexane/EtOAc = 1/1); mp 140−142 °C (from CH_2Cl_2); ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.23 (d, J = 9.8 Hz, 1H), 3.73 (s, 3H), 3.27 (br, 1H), 2.89 (ddd, J = 14.7, 3.9, 3.9 Hz, 1H), 2.83 (ddd, J = 5.8, 3.3, 2.8 Hz, 1H), 2.36 (dddd, J = 13.9, 9.8, 4.4, 2.5 Hz,), 2.29−2.01 (m, 4H), 1.97 (ddd, J = 12.7, 3.0, 3.0 Hz, 1H), 1.92−1.76 (m, 4H), 1.72−1.64 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.4, 198.3, 177.0, 67.7, 52.3, 47.5, 45.9, 44.1, 33.4, 32.3, 31.9, 28.6, 26.0, 21.5, 20.6; IR (ATR) 3473, 2953, 2875, 1785, 1717, 1432, 1243, 1049, 1007 cm^{-1}; HRMS (FAB-DFS) calcd for $C_{15}H_{19}O_5$ 279.1232, found 279.1234.

Dibarrelane-1-carboxylic Acid (9). To a solution of $HgCl_2$ (330 mg, 1.22 mmol) in H_2O (24 mL) was added Zn powder (12.0 g, 184 mmol), and the mixture was vigorously stirred for 1 h. The supernatant liquid was removed by decantation. To the residue were added concentrated HCl (60 mL), H_2O (40 mL), and a solution of diketone **15** (559 mg, 2.02 mmol) in toluene (14 mL), and the two-phase mixture was vigorously stirred and heated to reflux. Zn powder (9.0 g) was added portionwise until products converged on a single spot by TLC analysis. After it was cooled to room temperature, the mixture was diluted with Et_2O/H_2O and separated. The aqueous layer was extracted with CH_2Cl_2. The combined organic layers were washed with brine, dried over Na_2SO_4, filtered, and concentrated in vacuo. The residue was purified by silica gel chromatography with hexane/EtOAc (5/1) to afford **9** (269 mg, 61% yield) as a colorless solid: R_f = 0.38 (hexane/EtOAc 2/1); mp 144−145 °C (from CH_2Cl_2/hexane); ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.10 (dddd, J = 13.3, 10.8, 1.4, 1.4 Hz, 2H), 1.89 (ddddd, J = 13.3, 10.8, 2.9, 1.4, 1.4 Hz, 2H), 1.73−1.58 (m, 5H), 1.53−1.44 (m, 4H), 1.33−1.22 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 185.0, 41.1, 39.5, 37.5, 31.8, 30.7, 30.3, 28.7, 28.0, 26.6, 26.4; IR (ATR) 2925, 2855, 2654, 1686, 1458, 1412, 1282, 952 cm^{-1}; HRMS (ESI-TOF) calcd for $C_{14}H_{20}NaO_2$ 243.1355, found 243.1350.

Dibarrelane (2). To a solution of carboxylic acid **9** (78.3 mg, 0.355 mmol) in benzene (4.0 mL) were added DMF (0.08 mL) and $(COCl)_2$ (0.095 mL, 1.11 mmol). The reaction mixture was stirred for 2 h at room temperature and then concentrated in vacuo. The crude acid chloride was obtained and used for the next step without purification. *N*-Hydroxypyridine-2-thione sodium salt **17** (64.0 mg, 0.429 mmol), DMAP (9.0 mg, 0.0737 mmol), and *tert*-butyl mercaptan (0.40 mL, 3.55 mmol) in benzene were refluxed for 10 min, and then the acid chloride in benzene (2.7 mL) was added dropwise to the refluxing solution while irradiating with a 250 W tungsten lamp. After 20 min, the resulting mixture was cooled to room temperature and concentrated in vacuo. The residue was purified by silica gel chromatography with pentane to afford **2** (62.7 mg, 94% yield) as a colorless solid; sublimation at 45−50 °C (bath temperature) gave a dendritic crystal (mp 90−93 °C in a sealed capillary): ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.91−1.83 (m, 4H), 1.65−1.60 (m, 2H), 1.58−1.49 (m, 2H), 1.48−1.42 (m, 4H), 1.27−1.21 (m, 4H), 1.20−1.15 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 38.2 (CH_2, 4C), 32.3 (CH, 2C), 31.2 (CH_2, 2C), 27.4 (C, 1C), 27.1 (CH, 2C), 26.7 (CH_2, 2C); IR (ATR) 2915, 2853, 1455, cm^{-1}; HRMS (EI-DFS) calcd for $C_{13}H_{20}$ 176.1565, found 176.1564.

■ ASSOCIATED CONTENT

Supporting Information

Figures, tables, and a CIF file giving ^{1}H and ^{13}C NMR spectra of all new compounds, results of DFT calculations of compounds **2** and **9**, and crystallographic data for **9**. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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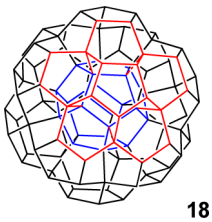

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