basified with 25% aqueous NaOH, and extracted with CH_2Cl_2 (4 × 10 mL). The extract was washed with H_2O (2 × 10 mL) and saturated aqueous NaCl (10 mL), dried (K_2CO_3), and concentrated in vacuo to give (±)-elaeokanine A (1) (0.13 g, 91%) as a pale orange oil. This material was identical (IR, TLC) with a sample of the alkaloid and the mass spectrum matched that reported.[16]

Identical acid treatment of indolizidine **29c** gave upon workup a brown oil. Flash chromatography over silica gel (EtOAc/Et_3N, 95:5) yielded (±)-elaeokanine A (1) (43% from amine bisacetal **15**) as a yellow oil: IR (CCl_4) 2970, 2885, 2805, 2740, 1674, 1635, 1462, 1425, 1395, 1385, 1278, 1205, 1046, 911, 850, 728 cm^{-1}; ^1H NMR ($CDCl_3$) δ 6.88 (d of t, 1 H, J = 4.2, 1.8 Hz), 3.46 (t, 1 H, J = 8.5 Hz), 2.26–2.97 (m, 8 H), 1.67–1.92 (m, 4 H), 1.36 (t of q, 2 H, J = 8, 8 Hz), 0.92 (t, 3 H, J = 8 Hz); ^{13}C NMR ($CDCl_3$) δ 200.6, 141.9, 136.8, 58.6, 52.6, 45.0, 39.1, 29.3, 25.4, 22.3, 18.0, 13.7; mass spectrum, m/e 193 (M^+), 192, 178, 165, 164, 150 (100%), 123, 122, 120, 95. These spectral data were identical with those for (±)-elaeokanine A (1) as prepared from **29a**.

(±)-Elaeokanine C (2) and (±)-7-Epielaeokanine C (32). Indolizidine **29c** was prepared as previously described from amine **15** (1.11 g, 4.74 mmol) and β-keto ester **30c** (2.37 g, 10.8 mmol). Crude **29c** was added to a stirred solution of ammonium formate (5.0 g, 79.4 mmol) in MeOH (100 mL) at room temperature. Palladium (10%) on activated carbon (0.68 g, 0.64 mmol) was added to this solution and the resulting suspension was stirred at room temperature for 1 h. The catalyst was then removed by filtration under argon. The recovered catalyst was extracted with methanol (3 × 50 mL), and the combined filtrate and extract were concentrated in vacuo. The residue was dissolved in CH_2Cl_2 (100 mL) and extracted with 5% aqueous HCl (3 × 100 mL). Ice (~100 g) was added to the aqueous layer and the mixture was basified to pH 10 with 50% aqueous NaOH. The resulting sodium was then extracted with EtOAc (4 × 150 mL). The extract was dried (K_2CO_3) and concentrated in vacuo to give 0.30 g (30%) of a 1:1 mixture of **2** and **32**, which was separated by preparative TLC (hexane/triethylamine, 4:1, developed ~15 times) into **2** (oil) and **32** (oil). An additional 0.30 g (30%) of **32** (which is apparently more H_2O soluble than **2**) was obtained by NaCl saturation of the aqueous layer followed by additional extraction with EtOAc (3 × 150 mL). Thus, overall, there were obtained 0.15 g (15%) of **2** and 0.45 g (45%) of **32** (yields based on **15**).

(±)-Elaeokanine C (2): IR ($CHCl_3$) 3400, 2960, 2935, 2875, 2810, 1708, 1460, 1373, 1163, 1040 cm^{-1}; ^1H NMR ($CDCl_3$) δ 4.26 (br s, 1 H), 3.80 (br s, 1 H), 3.06 (t, 1 H, J = 8.8 Hz), 2.87 (d, 1 H, J = 11.0 Hz), 2.40–2.62 (m, 5 H), 2.22 (q, 1 H, J = 9.8 Hz), 1.70–2.00 (m, 5 H), 1.63 (t of q, 2 H, J = 8, 8 Hz), 1.4 (m,1 H), 0.93 (t, 3 H, J = 8 Hz); ^{13}C NMR ($CDCl_3$) δ 213.6, 65.1, 58.3, 58.0, 53.0, 46.0, 45.0, 32.0, 28.8, 20.4, 16.5, 13.4; mass spectrum, m/e 211 (M^+), 182, 168, 167, 152, 150, 140, 124, 97 (100%), 96; these spectral data were identical with authentic spectra provided by Professor Shono. The methiodide of **2** was prepared in benzene at 40 °C with excess iodomethane (4 h). The crude methiodide was collected by filtration and recrystallized from EtOAc to yield the pure derivative as white needles; mp 207–208 °C (lit.[16] mp 203–205 °C).

(±)-7-Epielaeokanine C (**32**): IR ($CHCl_3$) 3615, 3400, 2965, 2940, 2880, 2805, 1708, 1463, 1377, 1160, 1043, 1002 cm^{-1}; ^1H NMR ($CDCl_3$) δ 4.33 (br s, 1 H), 3.81 (d of t, 1 H, J = 4.5, 10.5 Hz), 3.00–3.10 (m, 2 H), 2.42–2.62 (m, 3 H), 1.38–2.14 (m, 11 H), 0.92 (t, 3 H, J = 7.9 Hz); ^{13}C NMR ($CDCl_3$) δ 212.7, 71.1, 64.6, 61.4, 52.5, 49.4, 47.7, 34.0, 28.1, 21.4, 16.1, 13.4; mass spectrum, m/e 211 (M^+), 182, 168, 167, 152, 140, 126, 124, 100, 97 (100%), 96; precise mass calcd for $C_{12}H_{21}NO_2$ 211.1572, found 211.1554. These spectral data were identical with those sent to us by Professor Kametani for (±)-7-epielaeokanine C (**32**).

2-[2-((4,4-Dimethoxybutyl)amino)ethyl]-1,3-dioxolane (37). Amine **37** was prepared from amine **21** (5.0 g, 38 mmol) and 2-(2-bromoethyl)-1,3-dioxolane (2.3 g, 13 mmol) in a manner directly analogous to the preparation of amine **15** (110 °C, 2 h). This procedure afforded **37** (1.65 g, 54%) as a light yellow oil: bp 125–130 °C/0.65 Torr; IR (neat) 3590, 3340, 2950, 2890, 2840, 1470, 1460, 1410, 1390, 1365, 1195, 1090, 950, 910 cm^{-1}; ^1H NMR ($CDCl_3$) δ 4.93 (t, 1 H, J = 4.7 Hz), 4.38 (t, 1 H, J = 5.5 Hz), 3.82–4.00 (m, 4 H), 3.31 (s, 6 H), 2.75 (t, 2 H, J = 6.8 Hz), 2.62 (t, 2 H, J = 7.0 Hz), 1.87 (d of t, 2 H, J = 4.7, 6.8 Hz), 1.51–1.65 (m, 4 H), 1.35 (br s, 1 H); ^{13}C NMR ($CDCl_3$) δ 104.3, 103.7, 64.7, 52.6, 49.7, 44.8, 33.9, 30.2, 25.1; mass spectrum, m/e 218 (M – CH_3), 202 (M – OCH_3), 130, 114, 101, 87 (100%), 85, 84, 75, 73.

Anal. Calcd for $C_{11}H_{23}NO_4$: C, 56.63; H, 9.94; N, 6.00. Found: C, 56.46; H, 9.96; N, 5.93.

2-[2-((4,4-Dimethoxybutyl)amino)ethyl]-1,3-dioxane (38). Amine **38** was prepared from amine **21** (7.1 g, 53 mmol) and 2-(2-bromoethyl)-1,3-dioxane (4.5 g, 23 mmol) in a manner directly analogous to the preparation of amine **15** (90 °C, 2 h). This procedure afforded **38** (3.1 g, 54%) as a light yellow oil: bp 113–114 °C/0.1 Torr; IR (neat) 3600, 3350, 2960, 2850, 1470, 1382, 1248, 1197, 1130, 1090, 1055, 1010, 980, 950 cm^{-1}; ^1H NMR ($CDCl_3$) δ 4.72 (t, 1 H, J = 5 Hz), 3.5–4.5 (m, 5 H), 3.33 (s, 6 H), 2.5–2.9 (m, 4 H), 1.35–2.0 (m, 9 H); ^{13}C NMR ($CDCl_3$) δ 104.3, 101.3, 66.8, 52.5, 49.6, 44.7, 35.3, 30.2, 25.7, 25.1; mass spectrum, m/e 232 (M – CH_3), 216 (M – OCH_3), 144, 130, 114, 101 (100%), 84.

Anal. Calcd for $C_{12}H_{25}NO_4$: C, 58.27; H, 10.19; N, 5.66. Found: C, 57.78; H, 10.18; N, 5.50.

Acknowledgment. This investigation was supported by the donors of the Petroleum Research Fund, administered by the American Chemical Society. We thank Dr. Catherine E. Costello (Massachusetts Institute of Technology) for the high-resolution mass spectra (National Institutes of Health Resource Grant FR00317 from the Division of Research Facilities and Resources), Merck Sharp and Dohme Research Laboratories for general support, and Drs. J. A. Lamberton, T. Watanabe, T. Kametani, and T. Shono for providing samples and spectra of the natural and synthetic alkaloids.

Yuehchukene Analogues

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Yuehchukene and the bisnoryuehchukenes have been synthesized by the dimerization of β-(dehydroprenyl)indole and its demethyl derivative, respectively. Several routes of preparation of the monomers were developed. These β-indolyl dienes were used in Diels–Alder reactions, the products of one of which served as intermediates in the synthesis of some seconoryuehchukenes.

Yuehchukene, a chemical constituent of *Murraya paniculata* (L.) Jack present in small amount in the roots of the rutaceous Chinese plant *Yueh-Chu*, has been reported to possess potent antiimplantation activity in the rat.[1] In

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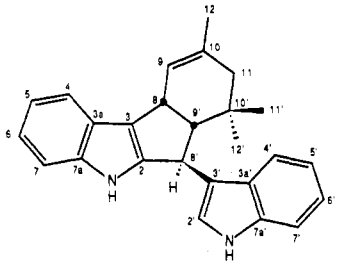
view of its consequent potential as an antifertility agent, it became important to prepare substances structurally somewhat different from, but related to, the yuehchukene configuration (1) in order to determine the change in bi-



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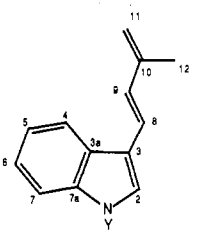
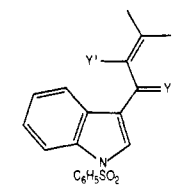


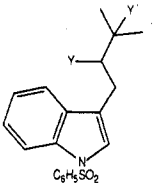
2a Y = H
b Y = $C_6H_5SO_2$

ological activity engendered by the alteration in structure. Prior to the synthesis of two types of yuehchukene analogues, the bisnoryuehchukenes and the 2,8′-seconoryuehchukenes, a reinvestigation of the preparation of β-(dehydroprenyl)indole (**2a**)[2,3] and its dimerization into yuehchukene (**1**)[2] was undertaken.

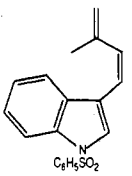
β-(Dehydroprenyl)indole (2a). An early approach to diene **2a** proved to be unimpressive from the point of view of yield. Bromination of 1-(phenylsulfonyl)-3-prenylindole (**3a**) gave dibromide **4a** (97%), whose dehydrobromination



3a, Y = H_2, Y′ = H
b, Y = H_2, Y′ = Br
c, Y = O, Y′ = H
d, Y = H, OH, Y′ = H



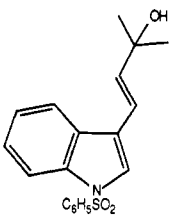
4a, Y = Br
b, Y = H



5

with DBU afforded a ca. 2:1:1 mixture of indoles **2b**, **3b**, and **5**, respectively, from which upon silica-induced isomerization there could be obtained diene **2b** and bromide **3b** in only 27% and 14% yields, respectively.

Friedel–Crafts acylation[4] of *N*-(phenylsulfonyl)indole[3] with β,β-dimethylacryloyl chloride produced ketone **3c**[3] (94%), thereby greatly improving the yield of this substance prepared previously by other means.[3] Whereas reduction of the latter with sodium borohydride in trifluoroacetic acid yielded undesired compound **4b** (38%), reduction of the ketone with lithium aluminum hydride had led earlier[3] to the important intermediate alcohol **3d** in high yield. On "drying" of the latter with a large quantity of magnesium sulfate in methylene chloride solution, it rearranged into alcohol **6** (99%). Bisulfate-



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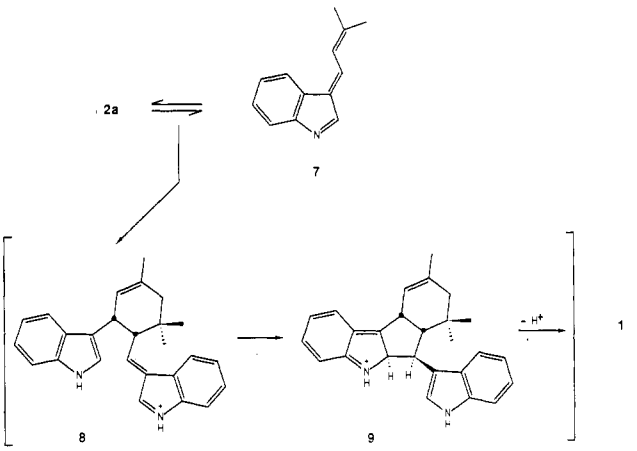
Scheme I

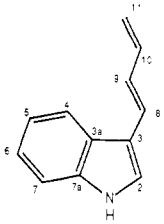


promoted dehydration of this alcohol produced diene **2b** (98%). Hydrolysis of the latter with potassium hydroxide and 18-crown-6 ether in acetonitrile solution gave β-(dehydroprenyl)indole (**2a**)[2,3] (78%). The reverse reaction could be executed in 80% yield with benzenesulfonyl chloride and base under phase-transfer conditions.

The dimerization of β-(dehydroprenyl)indole (**2a**), i.e., its conversion into yuehchukene (**1**), has been achieved in 10% yield under acid catalysis and has been formulated as proceeding by way of stepwise, sequential carbon–carbon bond formation between the diene **2a** and its conjugate acid, two cationic cyclizations, and deprotonation.[2,5] A mechanistically more plausible path for the complex dimerization, especially one accommodating the product stereochemistry, involves initial tautomerization of the trienamine **2a**, Diels–Alder reaction of the dienic β-(dehydroprenyl)indole (**2a**) with the dienophilic tautomer **7** (or, more likely, its N-protonated form), and cyclization of the endo product (**8**) in a sterically least encumbering manner (Scheme I). A design of favorable conditions for the reaction sequence in light of this most likely mechanism, in the face of the fragility of the starting material and intermediates, and in view of the ease of acid-catalyzed polymerization of diene **2a** had to be based on the necessity of permitting easy proton transfer while maintaining neutrality of the medium. After much experimentation it was discovered that heating diene **2a** in ethylene glycol solution at 155 °C in air leads reproducibly to yuehchukene (**1**) in 24% yield. The highly reduced product yield observed in reactions in the absence of air indicated that the **2a** → **7** change did not follow the normal course of tautomerization, but was probably due to an oxidation–reduction sequence, i.e., electron transfer from trienamine **2a** to oxygen,[6] hydrogen transfer from a solvent methylene group to the resultant **2a** cation radical, and N-deprotonation by any of a variety of solvent- and oxygen-derived oxyanions.

Bisnoryuehchukenes (18a and 18b). A possibly facile synthesis of the 12,12′-bisdemethyl derivative of yuehchukene was based on the above synthesis of the natural product itself and required the preparation of demethyl-β-(dehydroprenyl)indole (**10**) and its dimerization. The construction of the diene was initiated by the reaction of crotonyl chloride with the Grignard reagent from indole and methylmagnesium bromide[3] and led to the desired carbonyl compound **11a**, albeit in low yield (21%), and to

(1) Kong, Y.-C.; Cheng, K.-F.; Cambie, R. C.; Waterman, P. G. *J. Chem. Soc., Chem. Commun.* **1985**, 47.
(2) Cheng, K.-F.; Kong, Y.-C.; Chan, T.-Y. *J. Chem. Soc., Chem. Commun.* **1985**, 48.
(3) Wenkert, E.; Angell, E. C.; Ferreira, V. F.; Michelotti, E. L.; Piettre, S. R.; Sheu, J.-H.; Swindell, C. S. *J. Org. Chem.* **1986**, *51*, 2343.
(4) Cf.: Ketcha, D. M.; Gribble, G. W. *J. Org. Chem.* **1985**, *50*, 5451.
(5) Despite the pictorialization of the reaction sequence revealing nonconcertedness, the path was called a Diels–Alder reaction by the authors.[2]
(6) Cf.: Malhotra, S. K.; Hostyneck, J. J.; Lundin, A. F. *J. Am. Chem. Soc.* **1968**, *90*, 6565.



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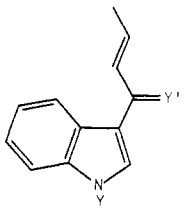
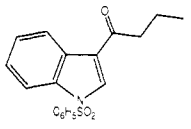


11a, Y = H, Y' = O
b, Y = $C_6H_5SO_2$, Y' = O
c, Y = p-$MeC_6H_4SO_2$, Y' = O
d, Y = $C_6H_5SO_2$, Y' = H, OH

a product of unusual structure (**12**) (24%).[7] To justify the formation of the latter material, it is necessary to invoke a Michael condensation between the Grignard reagent (**13**) and crotonyl chloride with chloride loss and deprotonation. Acylation of the resultant ketene, elimination of acylketene, and Michael condensation of the Grignard reagent with the thus-formed β-ethylideneindolenine (**14**) lead to indole **12** (Scheme II). Substance **11a** could be N-phenylsulfonylated by treatment with benzenesulfonyl chloride or *p*-toluenesulfonyl chloride and base under phase-transfer conditions.[8] However, the products **11b** (71%) and **11c** (83%) were obtained more easily and directly by the Friedel–Crafts reaction[4] of crotonyl chloride with *N*-(phenylsulfonyl)indole[3,9] or *N*-(*p*-tolylsulfonyl)indole[9] (95 and 83% yields, respectively).

Reduction of ketone **11b** with a variety of hydrides gave mixtures of alcohol **11d** and ketone **15** (see Experimental Section), but reduction with sodium borohydride in the



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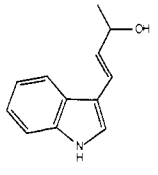

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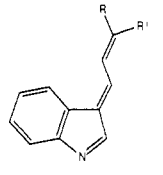
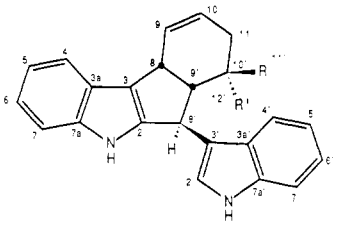


17a, R = Me, R' = H
b, R = H, R' = Me

presence of cerium trichloride afforded the alcohol (99%) exclusively. Hydrolysis of the sulfonamide **11d** with sodium hydroxide in aqueous ethanol yielded quantitatively a mixture of diene **10** and alcohol **16**. Apparently hydroxide ion not only had catalyzed tautomerization of the primary product(s), **17a** and/or **17b** (i.e., into **10**), but also had undergone nucleophilic addition to the terminal olefinic carbon of the intermediate crotylideneindolenine(s).

When mixtures of diene **10** and allyl alcohol **16** in ethylene glycol solution were heated at 155 °C, the product (19%) was a ca. 4:1 mixture of hexacycles **18a** and **18b**. As



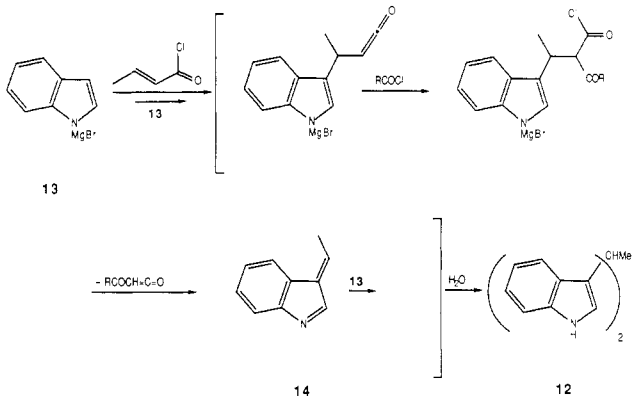
18a, R = Me, R' = H
b, R = H, R' = Me

(7) The low overall product yield of the reaction may have been due in part to magnesium indolate acting as a base not only toward product **11a** (i.e., NH proton transfer) but also toward crotonyl chloride (i.e., dehydrochlorination yielding vinylketene).

(8) Indole **11b** was also the product (94%) of the reaction of compound **11a** with benzenesulfonyl chloride and potassium carbonate in 2-butanone (see Experimental Section).

(9) Illi, V. O. *Synthesis* **1979**, 136.

Scheme II



13

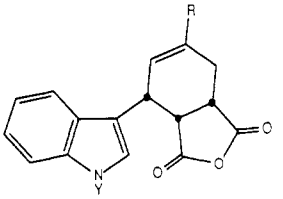
14

12

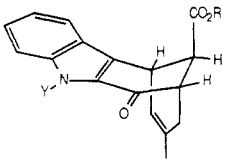
in the synthesis of yuehchukene (**1**) (Scheme I), the dimerization of diene **10** had followed the endo Diels–Alder reaction path. Furthermore, indolenines **17a** and **17b** (or their conjugate acids) had acted as dienophiles with ca. 4:1 kinetic preference.

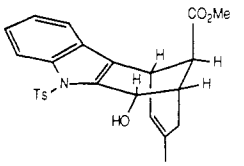
The stereochemical assignment of compound **18a** at carbon **10'** was based on the coupling constants between protons at carbons 8, 8', 9', and 10'. Protons H-8' and H-9' were found to show a *J* value of 7 Hz. In addition, proton H-9' exhibited only one other coupling (12 Hz). Since a large coupling constant between protons H-8 and H-9' was expected because of their cis configuration, the dihedral angle between protons H-9' and H-10' should approach 90° and the resulting coupling constant should be small. As an inspection of a molecular model reveals, having H-10' in an axial orientation in both **18a** and **18b** results in a large dihedral angle between protons H-9' and H-10' and thus a large coupling constant—a fact not observed. On the other hand, placing H-10' into an equatorial orientation (and thus the methyl substituent into an axial one) causes the H-9'/H-10' angle to approach 90° in **18a**, yielding a very small coupling constant. The same considerations for **18b** lead to a dihedral angle of about 50°.

Diels–Alder Reactions. In view of the cycloaddition process presumably playing a central role in the dimerization of dienes **2a** and **10**, it became of interest to learn whether such β-indolyl dienes undergo unambiguous Diels–Alder reactions. Hence the dienes **10**, **2a**, and **2b** were exposed to maleic anhydride in benzene solution at room temperature. The cycloadducts formed quantitatively, but their yields dropped on chromatographic workup: **19a** (60%), **19b** (69%), and **19c** (79%), respectively.



19a, R = Y = H
b, R = Me, Y = H
c, R = Me, Y = $C_6H_5SO_2$





20a, R = Y = H
b, R = Me, Y = H
c, R = Me, Y = p-$MeC_6H_4SO_2$

21

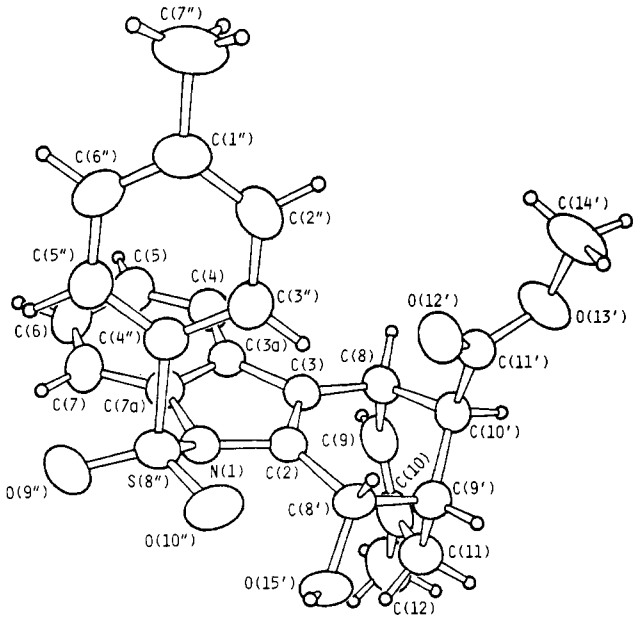


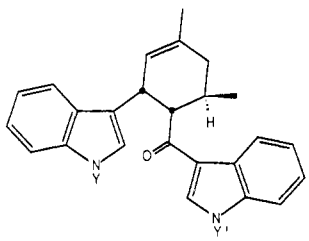
Figure 1. Structure and solid-state conformation of one enantiomer of **21**; small circles represent hydrogen atoms.

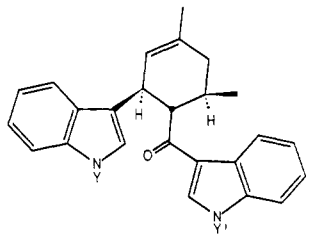
It is noteworthy that the reactions were exceedingly fast (0.5 h), being retarded (7 h) only by the presence of a phenylsulfonyl substituent on the indole nitrogen. These observations reinforce the likelihood of a Diels–Alder step at an early stage of the diene dimerization process.

On the assumption of the interaction of the indole unit of adduct **19b** with its anhydride moiety possibly leading to the ring skeleton of yuehchukene (**1**), the compound was exposed to boron trifluoride. The resultant keto acid (67%), however, proved to possess structure **20a**, as revealed by a single-crystal X-ray analysis of hydroxy ester **21**, prepared by the sequential esterification (95%) of acid **20a**, N-tosylation (91%) of ester **20b**, and sodium borohydride–cerium trichloride reduction (96%) of keto ester **20c**.

The crystal structure of **21** was solved by direct methods.[10] Full-matrix least-squares refinement of atomic parameters converged at $R = 0.036$ ($R_w = 0.057$)[11] over 3489 reflections. A view of the solid-state conformation is presented in Figure 1. Final atomic parameters and interatomic distances and angles are included in the Supplementary Material.[12] Bond lengths and angles in **21** all lie close to expected values. At N_1, the mean bond angle is 115.8° and thus the geometry is pyramidal. The conformation about the S–N bond [1.673 (2) Å][13] is in accord with that normally found in structures possessing equal, or similar, N–S–O angles wherein the sp^3-nitrogen lone pair is oriented such that it lies near to the bisector of the O–S–O bond angle.[14] In crystals of **21**, the hydroxy hydrogen atom is approximately equidistant from a sulfonamide oxygen atom in the reference molecule and the ester carbonyl oxygen atom of a molecule related by a crystallographic center of symmetry, and consequently this hydroxy group is involved in a bifurcated hydrogen bond.

The ease of cycloaddition of β-(dehydroprenyl)indole (**2a**) indicated the possibility of approaching a secoyuehchukene skeleton (as well as the natural product itself) by Diels–Alder chemistry. Unfortunately, the first attempt, the interaction of diene **2a** with enone **3c** in mesitylene or dimethylformamide at 155 °C, failed to give any adduct, but caused total destruction of the diene and recovery of starting ketone. Since the latter could be anticipated to be a poor dienophile, the same reaction was carried out with enone **11c** (in xylene at 125 °C) in place of enone **3c** as dienophile. Whereas this reaction was also destructive to the diene **2a** (requiring the use of excess of the substance), it nevertheless led to endo adduct **22a** (40%), exo adduct **23a** (36%), and yuehchukene (**1**) (4%). Alkaline hydrolysis of the adducts gave the bisindoles **22b** (87%) and **23b** (67%), respectively, and base-induced tosylation of the endo adduct (**22a**) produced ditosyl derivative **22c** (86%).

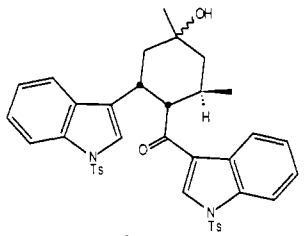




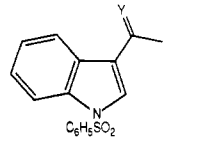
22a, Y = H, Y' = p-$MeC_6H_4SO_2$
b, Y = Y' = H
c, Y = Y' = p-$MeC_6H_4SO_2$

23

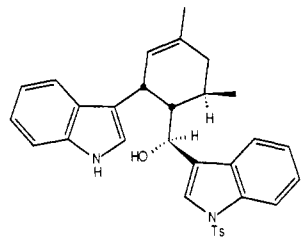
Reduction of the keto groups of compounds **22** and **23** proved to be difficult. An attempt to reduce ketone **22c** with sodium borohydride in trifluoroacetic acid[4] led quantitatively merely to the product (**24**) of double-bond hydration. The same product was obtained by treatment



24



25a, Y = O
b, Y = N-NHTs



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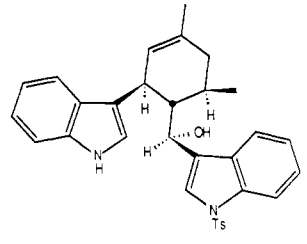
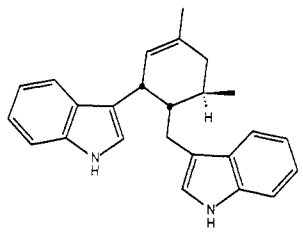
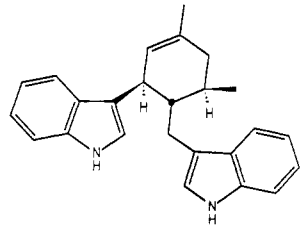


27



28



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(10) Crystallographic calculations were performed on PDP11/44 and MicroVAX II computers by use of the Enraf-Nonius SDP suite of programs incorporating the direct methods program MULTAN11/82.
(11) $R = \sum||F_o| - |F_c||/\sum|F_o|$; $R_w = [\sum w(|F_o| - |F_c|)^2/\sum w|F_o|^2]^{1/2}$.
(12) See the paragraph at the end of this paper.
(13) Selected bond angles and torsion angles in one enantiomer of **21** follow: N_1–$S_{8''}$–$O_{9''}$ = N_1–$S_{8''}$–$O_{10''}$ = 106.6 (1)°; C_2–N_1–$S_{8''}$–$O_{10''}$ = −37.1 (1)°, C_{7a}–N_1–$S_{8''}$–$O_{9''}$ = 57.4 (1)°.
(14) Kalman, A.; Czugler, M.; Argay, G. *Acta Crystallogr., Sect. B* **1981**, *B37*, 868.
(15) Hydrogen-bonded distances follow: $O_{15'}\cdots O_{10''}$ = 2.829 (2) Å, $H_{15'}\cdots O_{10''}$ = 2.34 (2) Å; $O_{15'}\cdots O_{12'}$ = 3.103 (2) Å, $H_{15'}\cdots O_{12'}$ = 2.50 (2) Å ($O_{12'}$ at $-x$, $1 - y$, $1 - z$).

of ketone **22c** with trifluoroacetic acid alone. The latter ketone was inert to thioketal or tosylhydrazone formation. This lack of reactivity was due to serious steric hindrance rather than electronic factors, as shown by the facile conversion of 1-(phenylsulfonyl)-3-acetylindole (**25a**)[4] into its tosylhydrazone (**25b**) (98%). Treatment of the Diels–Alder adducts **22a** and **23a** with lithium aluminum hydride produced alcohols **26** (98%) and **27** (94%), respectively. The steric crowding around the carbonyl groups of the starting ketones appears to be so great as to impose on their aroyl groups a highly preferred rotamer population and to restrict the hydride reduction to occurring solely from one face of the carbonyl groups. The stereochemistry of the hydroxy carbon centers of alcohols **26** and **27** is presented tentatively as shown based on these considerations. Unfortunately, the alcohols could not be used further, since desulfonylation and subsequent reduction gave poor product yields.

Reduction of compounds **22b** and **23b** with lithium aluminum hydride in *N*-methylmorpholine at 100 °C yielded 12′-demethyl-2,8′-secoyuehchukene (**28**) (50%) and 12′-demethyl-8-iso-2,8′-secoyuehchukene (**29**) (44%), respectively.

Finally, it is worth noting that the results of the cycloaddition of diene **2a** and dienophile **11c** may have a bearing on the Diels–Alder portion of the dimerization of dienes **2a** and **10**. If it is assumed that the dienophilic behavior of the indolenines **7** and **17** parallels that of enone **11c**, the **2a** → **7** and **10** → **17** reactions could have produced ca. 1:1 endo–exo product mixtures. Since, however, only the endo intermediates can engage in the subsequent reaction of the **8** → **9** type, the exo intermediates being expected to undergo polymerization, the yields of yuehchukene (**1**) and the bisnoryuehchukenes (**18a** and **18b**) would be 50% at best. This fact may be responsible at least in part for the low yields of the dimerization processes.

Experimental Section

Melting points were recorded on a Reichert micro hot stage and are uncorrected. Infrared spectra were measured on methylene chloride solutions and ultraviolet spectra on methanol solutions. ^{1}H NMR spectra of deuteriochloroform solutions were recorded at 90 or 300 MHz and ^{13}C NMR spectra of deuteriochloroform solutions at 75.5 MHz. Complete ^{1}H NMR and ^{13}C NMR assignments of the products were obtained by COSY NMR and ^{13}C–^{1}H correlated spectroscopies, respectively. The carbon shifts are in parts per million downfield from Me_4Si; $\delta(Me_4Si) = \delta(CDCl_3) + 76.9$ ppm. Unless otherwise indicated, all reactions were carried out under a nitrogen atmosphere, all organic extracts were washed with brine and dried over anhydrous $MgSO_4$, and all chromatographic separations were executed on silica gel. The product purity on which yields are based was determined to be ≥95% on the basis of ^{1}H NMR spectral and/or TLC analysis, unless stated otherwise.

β-Crotonylindole (11a). A 3 M ethereal solution of methylmagnesium bromide (17.75 mL, 52.5 mmol) was added to a solution of 6.17 g (52.5 mmol) of indole in 160 mL of dry benzene at 0 °C, and the mixture was stirred for 1 h. Thereafter, 5.23 g (50 mmol) of crotonyl chloride was added dropwise, and the stirring was continued for 45 min. The mixture was poured into 300 mL of saturated sodium carbonate solution, which was extracted with ether. The extract was dried and evaporated, and the residue was chromatographed. Elution with 2:1 hexane–ethyl acetate gave 1.12 g (24%) of crystalline indole **12**: mp 158–159 °C (CH_2Cl_2–hexane) (lit.[16] 156 °C); UV λ_{max} 225 nm (ϵ 35 860), 283 (10 000), 292 (8830); IR NH 3465 (s), C=C 1620 (m) cm^{-1}; ^{1}H NMR δ 1.85 (d, 3, Me, J = 7.1 Hz), 4.66 (q, 1, CH, J = 7 Hz), 6.90 (d, 2, α-Hs, J = 1.9 Hz), 7.05–7.60 (m, 8, Ar Hs); MS m/e 260 (M$^+$, 47%), 245 (base), 117 (84), 90 (35), 89 (24).

Further elution gave 2.0 g (21%) of crystalline indole **11a**: mp 173–174 °C (CH_3CN); UV (CH_2Cl_2) λ_{max} 229 nm (ϵ 5970), 254 (4520), 283 (1920), 290 (1760); IR NH 3450 (s), C=O 1660 (s), C=C 1605 (s) cm^{-1}; ^{1}H NMR δ 1.96 (dd, 3, Me, J = 1.1, 6.7 Hz), 6.80 (dd, 1, β-olefinic H, J = 1.2, 15.0 Hz), 7.05 (dq, 1, α-olefinic H, J = 6.7, 15.0 Hz), 7.25–7.84 (m, 4, aryl Hs), 7.89 (s, 1, indolyl α-H); MS m/e 185 (M$^+$, 70%), 144 (base), 116 (26), 89 (32). Anal. Calcd for $C_{12}H_{11}NO$: C, 77.81; H, 5.99; N, 7.56. Found: C, 78.01; H, 6.19; N, 7.63.

1-(Phenylsulfonyl)-3-crotonylindole (11b). A mixture of 185.2 mg (1 mmol) of ketone **11a**, 553 mg (4 mmol) of potassium carbonate, and 354 mg (2 mmol) of benzenesulfonyl chloride in 4 mL of 2-butanone was refluxed for 5 h. After cooling, 20 mL of methylene chloride was added, and the solution was filtered and evaporated. Direct crystallization afforded 275 mg (94%) of colorless ketone **11b**: mp 118–119 °C (ether–hexane); UV λ_{max} 209 nm (ϵ 25 940), 235 (20 450), 301 (11 440); IR C=O 1667 (s), C=C 1620 (s), SO_2 1380 (s), 1170 (s) cm^{-1}; ^{1}H NMR δ 2.02 (dd, 3, Me, J = 1.3, 6.7 Hz), 6.80 (dq, 1, α-olefinic H, J = 1.3, 15.4 Hz), 7.11 (dq, 1, β-olefinic H, J = 6.7, 15.0 Hz), 7.33–8.36 (m, 9, aryl Hs), 8.21 (s, 1, indolyl α-H); MS m/e 325 (M$^+$, 51%), 184 (20), 156 (65), 141 (21), 128 (31), 115 (20), 77 (base), 69 (49), 51 (28). Anal. Calcd for $C_{18}H_{15}NO_3S$: C, 66.44; H, 4.65; N, 4.30. Found: C, 66.51; H, 4.89; N, 4.24.

Phase-Transfer N-Phenylsulfonylations of Indoles (General Procedure). Indole 11a. A mixture of 185.2 mg (1 mmol) of ketone **11a**, 34 mg (0.1 mmol) of tetra-*n*-butylammonium hydrogen sulfate, 265 mg (1.5 mmol) of benzenesulfonyl chloride, and 1 mL of 50% aqueous potassium hydroxide solution in 4 mL of benzene was stirred vigorously at room temperature for 15 min. The mixture was poured into 15 mL of water and extracted with methylene chloride. The extract was dried over potassium carbonate and evaporated, and the residue was chromatographed. Elution with 4:1 hexane–ethyl acetate afforded 230 mg (71%) of crystalline ketone **11b**.

By the use of the same procedure ketone **11a** and *p*-toluenesulfonyl chloride were converted into ketone **11c** (83%): mp 138–139 °C (CH_2Cl_2–C_6H_{14}); UV λ_{max} 210 nm (ϵ 27 260), 240 (26 940), 300 (13 050); IR C=O 1666 (s), C=C 1612 (s), SO_2 1377 (s), 1170 (s) cm^{-1}; ^{1}H NMR δ 2.01 (dd, 3, olefinic Me, J = 1.3, 6.8 Hz), 2.36 (s, 3, aryl Me), 6.79 (dq, 1, olefinic α-H, J = 1.3, 15.3 Hz), 7.10 (dq, 1, olefinic β-H, J = 6.8, 15.3 Hz), 7.26–8.38 (m, 8, aryl Hs), 8.23 (s, 1, indolyl α-H); MS m/e 339 (M$^+$, 43%), 156 (30), 155 (35), 91 (base), 69 (35). Anal. Calcd for $C_{19}H_{17}NO_3S$: C, 67.23; H, 5.05; N, 4.13. Found: C, 67.01; H, 5.14; N, 4.14.

Friedel–Crafts Acylation of (Phenylsulfonyl)indoles. Crotonyl chloride (4.59 g, 43.9 mmol) was added dropwise at room temperature to 5.86 g (43.9 mmol) of aluminum trichloride in 330 mL of dry methylene chloride and the resultant clear, colorless solution was stirred for 15 min. A solution of 11.3 g (43.95 mmol) of 1-(phenylsulfonyl)indole[3,9] in 110 mL of dry methylene chloride was added dropwise over a 15-min period and stirring was continued for 30 min. The mixture was poured carefully into 500 mL of saturated sodium hydrogen carbonate solution, and the organic layer was separated. The aqueous layer was extracted with additional methylene chloride, and the combined organic layers were washed with brine, dried, and evaporated. Crystallization of the crude product (methylene chloride–hexane) gave 13.58 g (95%) of colorless, crystalline ketone **11b**.

By this method ketone **11c** was prepared in 94% yield.

In a similar way, ketone **3c** was obtained in 96% yield; mp, IR spectrum, and ^{1}H NMR spectrum identical with those of an authentic sample.[3,9]

Alcohol 11d. A mixture of 325 mg (1 mmol) of ketone **11b** and 372.6 mg (1 mmol) of cerium chloride heptahydrate in 8 mL of methanol was heated until the ketone was dissolved (45 °C). Sodium borohydride (37.8 mg, 1 mmol) was added carefully and the stirring was continued for 5 min. Ammonium chloride solution (1 mL, 1 M) was added, and the mixture was poured into water and extracted with methylene chloride. The extract was dried and evaporated, giving 324 mg (99%) of colorless, oily alcohol **11d**: UV λ_{max} 213 nm (ϵ 33 490), 252 (14 220), 282 (4770), 290 (4620); IR OH 3598 (m), C=C 1608 (w), SO_2 1375 (s), 1178 (s) cm^{-1}; ^{1}H NMR δ 1.77 (d, 3, Me, J = 5.5 Hz), 5.40 (d, 1, OCH, J = 5.0 Hz), 5.85 (m, 2, olefinic Hs), 7.20–8.02 (m, 10, aryl Hs); MS m/e 327

(16) Kamal, A.; Qurechi, A. A. *Tetrahedron* **1963**, *19*, 513.

(M^+, 35%), 309 (17), 284 (19), 186 (25), 168 (base), 167 (73), 145 (30), 144 (40), 115 (22), 77 (49); exact mass 327.0920, calcd for $C_{18}H_{17}NO_3S$ 327.0913.

1-(Phenylsulfonyl)-3-butyrylindole (15). A mixture of 38 mg (1.0 mmol) of lithium aluminum hydride and 325.4 mg (1 mmol) of ketone **11b** in 20 mL of dry tetrahydrofuran was stirred at 0 °C for 1 h. Ethyl acetate (3 mL) was added dropwise and the mixture was allowed to warm to room temperature. It then was poured into 30 mL of water and extracted with methylene chloride. The extract was washed with brine, dried over potassium carbonate, and evaporated. Chromatography of the residue and elution with a 2:1 mixture of hexane and ethyl acetate gave 147 mg (45%) of colorless, crystalline ketone **15**: mp 120–121 °C (CH_2Cl_2–C_6H_{14}, −15 °C); UV λ_{max} 208 nm (ϵ 31 110), 223 (21 840), 268 (8310), 275 (9170), 288 (9600); IR C=O 1670 (s), C=C 1600 (w), SO_2 1382 (s), 1372 (s) cm^{-1}; ^1H NMR δ 1.03 (t, 3, Me, J = 7.4 Hz), 1.78 (m, 2, CH_2), 2.88 (t, 2, $COCH_2$, J = 7.4 Hz), 7.32–8.38 (m, 9, aryl Hs), 8.22 (s, 1, indolyl α-H); MS m/e 327 (M^+, 26%), 284 (87), 186 (24), 143 (26), 141 (56), 77 (base). Anal. Calcd for $C_{18}H_{17}NO_3S$: C, 66.02; H, 5.23; N, 4.28. Found: C, 65.78; H, 5.29; N, 4.21.

Further elution afforded 144 mg (44%) of colorless, oily alcohol **11d**.

1-(Phenylsulfonyl)-3-isopentylindole (4b). A mixture of 34 mg (0.1 mmol) of ketone **3c** and 68 mg (1.8 mmol) of sodium borohydride in 3 mL of a 1:1 mixture of trifluoroacetic acid and methylene chloride was stirred at room temperature for 12 h and then poured into 15 mL of a sodium hydrogen carbonate solution, which was extracted with methylene chloride. The extract was dried and evaporated, and the residue was chromatographed. Elution with 4:1 hexane–ethyl acetate gave 12 mg (38%) of colorless, crystalline indole **4b**: mp 114–115 °C (hexane); UV λ_{max} 215 nm (ϵ 30 100), 254 (14 430), 282 (4590), 290 (4280); IR C=C 1620 (w), SO_2 1368 (s), 1173 (s) cm^{-1}; ^1H NMR δ 0.94 (d, 6, methyls, J = 6.0 Hz), 1.57 (m, 2, CH_2), 1.60 (sept, 1, H-10, J = 6.0 Hz), 2.64 (t, 2, benzyl Hs, J = 9.0 Hz), 7.20–8.00 (m, 9, aryl Hs), 7.31 (s, 1, H-2); MS m/e 327 (M^+, 29%), 271 (62), 270 (27), 130 (base), 129 (21), 77 (37); exact mass 327.1298, calcd for $C_{19}H_{21}NO_2S$ 327.1290.

Hydrolysis of Sulfonamide 11d. A solution of 1.64 g (5 mmol) of alcohol **11d** and 10.5 g (187.5 mmol) of potassium hydroxide in 62.5 mL of a 4:1 ethanol–water mixture was heated at 50–52 °C for 2 h. It then was poured into 100 mL of water and extracted with ether. The extract was washed with brine, dried (K_2CO_3), and evaporated to give 880 mg (99%) of a 1:1 mixture of alcohol **16** and diene **10**. This mixture was used directly in the dimerization process. Alcohol **16**: ^1H NMR δ 1.38 (d, 3, Me, J = 6.3 Hz), 4.01 (m, 1, CH), 6.13 (dd, 1, H-9, J = 7.9, 16.0 Hz), 6.70 (d, 1, H-8, J = 16.0 Hz), 7.15–7.88 (m, 5, aryl Hs).

Rapid chromatography of 200 mg of this mixture and elution with a 4:1 hexane–ethyl acetate mixture permitted the isolation of 37 mg of pure solid diene **10**: mp 96–97 °C; UV λ_{max} 204 nm (ϵ 8320), 230 (10 130), 280 (7300), 308 (9550); IR NH 3464 (s), C=C 1634 (s), 1610 (w) cm^{-1}; ^1H NMR δ 5.06 (dd, 1, H-11, J = 1.1, 10.2 Hz), 5.25 (dd, 1, H-11′, J = 1.1, 16.8 Hz), 6.53 (dt, 1, H-10, J = 9.7, 16.8 Hz), 6.76 (d, 1, H-8, J = 15.6 Hz), 6.84 (dd, 1, H-9, J = 9.0, 15.6 Hz), 7.15–7.90 (m, 5, aryl Hs); MS m/e 169 (M^+, 74%), 168 (base), 167 (46); exact mass 169.0884, calcd for $C_{12}H_{11}N$ 169.0890.

Magnesium Sulfate Promoted Rearrangement of Alcohol 3d. A mixture of 341.4 mg (1 mmol) of alcohol **3d**[3] and 43 g (360 mmol) of anhydrous magnesium sulfate in 150 mL of methylene chloride was stirred at room temperature for 2 h. The mixture was filtered and the solution evaporated to give 340 mg (99%) of pure, oily alcohol **6**: UV λ_{max} 221 nm (ϵ 32 110), 248 (14 760), 266 (12 850), 273 (11 850), 296 (9320); IR OH 3596 (m), C=C 1604 (w), SO_2 1374 (s), 1179 (s) cm^{-1}; ^1H NMR δ 1.14 (s, 6, Me), 6.43 (d, 1, H-9, J = 6.2 Hz), 6.67 (d, 1, H-8, J = 6.2 Hz), 7.25–8.00 (m, 9, aryl Hs), 7.58 (s, 1, indolyl α-H); MS m/e 323 ($[M - H_2O]^+$, 18%), 182 (base), 181 (20), 167 (86), 77 (36); exact mass ($M^+ - H_2O$) 323.0996, calcd for $C_{19}H_{17}NO_2S$ 323.0978.

1-(Phenylsulfonyl)-3-(dehydroprenyl)indole (2b). A mixture of 170.7 mg (0.5 mmol) of alcohol **6** and 138 mg (1 mmol) of sodium hydrogen sulfate monohydrate in 30 mL of methylene chloride was stirred at room temperature for 3 h. Filtration and evaporation of the solvent afforded 158 mg (98%) of slightly yellow, solid diene **2b**: mp 99–101 °C; UV (CH_3CN) λ_{max} 224 nm (ϵ 15 390), 247 (14 200), 281 (13 000), 289 (13 000); IR C=C 1728 (m), 1605 (m), SO_2 1369 (s), 1173 (s) cm^{-1}; ^1H NMR δ 1.98 (s, 3, Me), 5.08, 5.12 (s, 1 each, 2 H-11), 6.58 (d, 1, H-9, J = 16.3 Hz), 6.96 (d, 1, H-8, J = 16.3 Hz), 7.25–8.01 (m, 9, aryl Hs), 7.65 (s, 1, H-2); MS m/e 323 (M^+, 42%) 218 (36), 183 (49), 182 (base), 181 (32), 180 (32), 168 (28), 167 (69), 110 (27), 109 (33), 78 (47), 77 (73); exact mass 323.0975, calcd for $C_{19}H_{17}NO_2S$ 323.0978.

The same product was obtained as a crude brown oil when 183 mg (1 mmol) of diene **2a**[3] was treated with 176 mg (1 mmol) of benzenesulfonyl chloride under phase-transfer conditions (vide supra). Chromatography of this oil on neutral alumina (activity III) and elution with a 4:1 hexane–ethyl acetate mixture led to 259 mg (80%) of pure diene **2b**.

β-(Dehydroprenyl)indole (2a). A solution of 161.6 mg (0.5 mmol) of diene **2b**, 13 mg (0.05 mmol) of 18-crown-6 ether, and 308 mg (5.5 mmol) of potassium hydroxide in 15 mL of acetonitrile was refluxed for 2 h. After cooling, the mixture was poured into water and extracted with ether. The extract was dried (K_2CO_3) and evaporated. Chromatography on neutral alumina (activity III) and elution with a 2:1 hexane–ethyl acetate mixture gave 71 mg (78%) of β-(dehydroprenyl)indole (**2a**), identical with an authentic sample.[3]

Dibromide 4a. A solution of 80 mg (0.5 mmol) of bromine in 1 mL of chloroform was added dropwise to a stirred solution of 162.7 mg (0.5 mmol) of 1-(phenylsulfonyl)-3-prenylindole (**3a**)[3] in 3 mL of chloroform. After 5 min the solvent was evaporated and the residue was chromatographed. Elution with a 9:1 hexane–ethyl acetate mixture afforded 235 mg (97%) of colorless, oily indole **4a**: IR C=C 1605 (w), SO_2 1370 (s), 1172 (s) cm^{-1}; ^1H NMR δ 1.92, 2.00 (s, 3 each, methyls), 3.08 (dd, 1, H-8, J = 11.0, 15.3 Hz), 3.94 (dd, 1, H-8, J = 1.5, 15.3 Hz), 4.40 (dd, 1, H-9, J = 1.5, 11.0 Hz), 7.23–8.00 (m, 10, aryl Hs); MS m/e 483 (M^+, 11%), 324 (21), 270 (87), 182 (32), 141 (48), 77 (base); exact mass 482.9503, calcd for $C_{19}H_{19}NO_2SBr_2$ 482.9504.

Dehydrobromination of Indole 4a. A mixture of 194 mg (0.4 mmol) of indole **4a** and 122 mg (0.8 mmol) of DBU in 2 mL of ethylene chloride was stirred at room temperature for 3 h. Evaporation of the solvent gave an orange oil consisting of a 2:1:1 mixture of **2b**, **3b**, and **5**. Chromatography of the oil gave 35 mg (27%) of oily diene **2b**. Further elution afforded 23 mg (14%) of colorless, crystalline indole **3b**: mp 110–111 °C (ether–hexane); UV λ_{max} 208 nm (ϵ 28 710), 254 (10 760), 282 (3290), 290 (3140); IR (CCl_4) SO_2 1385 (s), 1180 (s) cm^{-1}; ^1H NMR δ 1.90, 1.95 (s, 3 each, methyls), 3.86 (s, 2, CH_2), 7.20–7.99 (m, 10, aryl Hs); MS m/e 405 (M^+, 10%), 257 (84), 183 (74), 182 (97), 168 (base), 167 (70), 141 (21), 115 (21), 77 (99); exact mass 405.0217, calcd for $C_{19}H_{18}BrNO_2S$ 405.0219.

Yuehchukene (1) and Bisnoryuehchukenes 18a and 18b. A mixture of 1.83 g (10 mmol) of diene **2a** and 10 mL of water in 250 mL of distilled ethylene glycol was heated at 152–155 °C under an air atmosphere. The reaction was followed by TLC on silica gel using a 8:1:1 hexane–ether–ethyl acetate mixture and was found usually to be complete after 2 h. After cooling, the mixture was poured into water (300 mL), and a 1 M aqueous sodium hydroxide solution was added slowly up to pH 7. The mixture was extracted once with 250 mL of methylene chloride. Brine (75 mL) was added to the aqueous phase, which was extracted with additional methylene chloride (2 × 250 mL). The extract was dried (Na_2SO_4) and evaporated. The residue was adsorbed on alumina and chromatographed on silica gel in the dark. Elution with a degassed 8:1:1 hexane–ether–ethyl acetate mixture afforded, on evaporation of the solvent under nitrogen, 440 mg (24%) of yuehchukene (**1**) as a pale yellow, amorphous powder: UV, IR, and ^1H NMR spectra identical with those of an authentic sample;[17] ^{13}C NMR δ 24.1 (C-12), 29.0 (C-11′), 29.2 (C-12′), 33.8 (C-10′), 38.0 (C-8′), 38.7 (C-8), 41.2 (C-11), 61.0 (C-9′), 111.6 (C-7 or C-7′), 111.9 (C-7′ or C-7), 118.5 (C-3′), 118.6 (C-5), 119.5 (C-5′), 119.7 (C-4′), 119.8 (C-4), 120.5 (C-3), 120.6 (C-6), 122.3 (C-2′), 122.9 (C-9), 123.9 (C-6′), 124.2 (C-3a), 126.8 (C-3a′), 130.1 (C-2), 136.5 (C-7a′), 140.2 (C-7a), 145.6 (C-10).

By the same method 880 mg of the crude oil obtained from dehydration–deprotection of alcohol **11d** gave 167 mg (19%) of

(17) Kindly supplied by Drs. K.-F. Cheng and Y.-C. Kong.

a 4:1 mixture of 11′α- and 11′β-bisnoryuehchukenes (**18a** and **18b**) as a slightly yellow powder: UV λ_{max} 206 nm (ε 20160), 225 (32340), 274 (7280), 282 (8100), 290 (7190); IR NH 3480 (s), 3420 (s), C=C 1616 (w), 1580 (w) cm^{-1}; ^{1}H NMR (α isomer) δ 1.19 (d, 3, H-11′, J = 6.9 Hz), 1.89 (dd, 1, H-11, J = 4.0, 17.2 Hz), 2.11 (m, 1, H-10′), 2.49 (ddd, 1, H-11, J = 2.5, 5.0, 17.2 Hz), 2.98 (dd, 1, H-9′, J = 7.0, 12.0 Hz), 4.00 (d, 1, H-8, J = 2.0 Hz), 4.60 (d, 1, H-8′, J = 7.0 Hz), 5.71 (dm, 1, H-10, J = 5.0 Hz), 6.13 (dd, 1, H-9, J = 2.0, 10 Hz), 7.03–7.64 (m, 8, aryl Hs), 7.05 (d, 1, H-2′, J = 2.1 Hz); ^{13}C NMR (α isomer) δ 20.6 (C-11′), 28.3 (C-10′), 29.3 (C-11), 36.0 (C-8), 39.9 (C-8′), 58.5 (C-9′), 111.2 (C-7 or C-7′), 111.6 (C-7′ or C-7), 118.1 (C-3′), 118.2 (C-5), 119.2 (C-3), 119.3 (C-5′), 119.4 (C-4′), 119.5 (C-4), 120.5 (C-6), 121.8 (C-2′ or C-6′), 122.0 (C-6′ or C-2′), 123.5 (C-10), 124.8 (C-3a), 126.5 (C-3a′), 128.7 (C-9), 130.0 (C-2), 136.5 (C-7a′), 140.3 (C-7a); MS m/e 338 (M$^+$, base), 323 (17%), 296 (21), 295 (19), 283 (19), 269 (22), 257 (22), 256 (18), 221 (27), 206 (27), 130 (57), 118 (17), 117 (15); exact mass 338.1782, calcd for $C_{24}H_{22}N_2$ 338.1781.

Maleic Anhydride Cycloadducts 19a, 19b, and 19c. A mixture of 183 mg (1 mmol) of diene **2a** and 98 mg (1 mmol) of maleic anhydride in 5 mL of benzene was stirred at room temperature for 0.5 h. Evaporation of the solvent gave 281 mg of almost pure adduct **19b** (by ^{1}H NMR spectral analysis). Chromatography and elution with 4:1 hexane–ethyl acetate led to 194 mg (69%) of slightly yellow, gummy adduct **19b**: UV λ_{max} 222 nm (ε 29160), 274 (5220), 284 (5480), 291 (4920); IR NH 3475 (m), C=O 1852 (m), 1780 (s) cm^{-1}; ^{1}H NMR δ 1.88 (s, 3, Me), 2.44 (dd, 1, H-11, J = 7.8, 17.0 Hz), 2.79 (dd, 1, H-11, J = 2.0, 17.0 Hz), 3.47 (m, 1, α-keto-α-C(11) H, J = 2.0, 7.8 Hz), 3.59 (dd, 1, α-keto-α-C(8) H, J = 6.4, 8.5 Hz), 4.12 (br s, 1, H-8), 5.92 (br s, 1, H-9), 7.00 (d, 1, H-2, J = 3.0 Hz), 7.12–7.57 (m, 4, aryl Hs); MS m/e 281 (M$^+$, 95%), 208 (32), 183 (81), 182 (42), 168 (base), 167 (20), 90 (26), 89 (27), 77 (22); exact mass 281.1052, calcd for $C_{17}H_{15}NO_3$ 281.1052.

By the same method the reaction between 17 mg (0.1 mmol) of diene **10** and 9.8 mg (0.1 mmol) of maleic anhydride produced, after chromatography and elution with 4:1 hexane–ethyl acetate, 16 mg (60%) of gummy cycloadduct **19a**: UV λ_{max} 206 nm (ε 17200), 222 (27820), 276 (4600), 282 (4970), 291 (4300); IR NH 3479 (m), C=O 1855 (w), 1786 (s) cm^{-1}; ^{1}H NMR δ 2.52 (m, 1, H-11), 2.95 (ddd, 1, H-11, J = 1.2, 4.6, 17.1 Hz), 3.48 (dt, 1, α-keto-α-C(11) H, J = 2.2, 9.2 Hz), 3.64 (dd, 1, α-keto-α-C(8) H, J = 6.6, 9.2 Hz), 4.20 (t, 1, H-8, J = 5.7 Hz), 6.11 (m, 1, H-9), 6.28 (m, 1, H-10), 7.04 (d, 1, H-2, J = 2.5 Hz), 7.11–7.60 (m, 4, aryl Hs); MS m/e 267 (M$^+$, 58%), 194 (26), 169 (95), 168 (base), 167 (23); exact mass 267.0881, calcd for $C_{16}H_{13}NO_3$ 267.0893.

Similarly, reaction between 32 mg (0.1 mmol) of diene **2b** and 9.8 mg (0.1 mmol) of maleic anhydride in 1 mL of benzene at room temperature for 7 h gave 42 mg (100%) of nearly pure (by ^{1}H NMR analysis) cycloadduct **19c**. Chromatography and elution with 4:1 hexane–ethyl acetate led to 33 mg (79%) of colorless, crystalline **19c**: mp 75–77 °C; UV (CH_3CN) λ_{max} 231 nm (ε 40910), 244 (26500), 270 (20710), 309 (26660); IR C=O 1851 (m), 1780 (s), C=C 1606 (w), SO_2 1371 (s), 1178 (s) cm^{-1}; ^{1}H NMR δ 1.92 (s, 3, H-12), 2.44 (dd, 1, H-11, J = 7.5, 16.0 Hz), 2.80 (dd, 1, H-11, J = 2.0, 16.0 Hz), 3.54 (dt, 1, α-keto-α-C(11) H, J = 2.0, 9.3 Hz), 3.60 (dd, 1, α-keto-α-C(8) H, J = 6.5, 9.3 Hz), 3.92 (br s, 1, H-8), 5.93 (d, 1, H-9, J = 1.6 Hz), 7.03 (s, 1, H-2), 7.21–7.95 (m, 9, aryl Hs); MS m/e 421 (M$^+$, 45%), 182 (base), 167 (32), 77 (28); exact mass 421.1009, calcd for $C_{23}H_{19}NO_5S$ 421.0982).

Cyclization of Anhydride 19b. Boron trifluoride etherate (142 mg, 1 mmol) was added dropwise into a solution of 281 mg (1 mmol) of indole **19b** in 5 mL of dry benzene, and the resulting mixture was stirred for 6 h at room temperature. It then was poured into water and extracted with ethyl acetate. The extract was dried and evaporated, and the residue was chromatographed. Elution with 4:1 ethyl acetate–methylene chloride afforded 188 mg (67%) of crystalline acid **20a**: sublimation point ca. 230 °C; mp 294–295 °C (chloroform); UV λ_{max} 210 nm (ε 18690), 238 (15650), 317 (14930); IR OH 3677 (m), NH 3450 (m), C=O 1707 (m), 1652 (s), C=C 1610 (w) cm^{-1}; ^{1}H NMR δ 1.57 (s, 3, Me), 2.08 (dd, 1, H-11, J = 9.7, 18.6 Hz), 2.67 (dd, 1, H-11, J = 7.5, 18.6 Hz), 3.33–3.39 (m, 2, α-keto Hs), 4.19 (m, 1, H-8), 6.04 (d, 1, H-9, J = 5.7 Hz), 7.10–7.83 (m, 4, aryl Hs); MS m/e 281 (M$^+$, base), 208 (47%), 201 (29), 168 (22), 167 (28), 144 (47), 117 (21); exact mass 281.1057, calcd for $C_{17}H_{15}NO_3$ 281.1050.

Ester 20b. A solution of 281 mg (1 mmol) of acid **20a** and 1 drop of sulfuric acid in 10 mL of methanol was refluxed for 24 h. The mixture was poured into saturated sodium hydrogen carbonate and extracted with methylene chloride. The extract was dried and evaporated. Chromatography of the residue and elution with 7:3 hexane–ethyl acetate gave 280 mg (95%) of colorless, crystalline ester **20b**: sublimation point ca. 190 °C; mp 243–245 °C (CH_2Cl_2–C_6H_{14}); UV λ_{max} 211 nm (ε 20040), 238 (17130), 317 (17090); IR NH 3460 (m), C=O 1738 (s), 1664 (s) cm^{-1}; ^{1}H NMR δ 1.60 (s, 3, Me), 2.19 (d, 1, H-11, J = 19.0 Hz), 2.60 (dd, 1, H-11, J = 8.0, 19.0 Hz), 3.30 (t, 1, α-CO_2H, J = 2.8 Hz), 3.46 (dd, 1, α-keto H, J = 1.5, 8.0 Hz), 3.52 (s, 3, OMe), 4.13 (dd, 1, H-8, J = 2.8, 5.6 Hz), 5.96 (d, 1, H-9, J = 5.6 Hz), 7.13–7.74 (m, 4, aryl Hs); MS m/e 295 (M$^+$, base), 208 (65%), 168 (20), 167 (19), 144 (48); exact mass 295.1209, calcd for $C_{18}H_{17}NO_3$ 295.1206.

N-Sulfonylation of Keto Ester 20b. By the general procedure for the reactions conducted under phase-transfer conditions (vide supra), 295 mg (1 mmol) of indole **20b** was induced to react with 190 mg (1 mmol) of p-toluenesulfonyl chloride to give 409 mg (91%) of colorless, crystalline indole **20c**: mp 81–82 °C (CH_2Cl_2–C_6H_{14}); UV λ_{max} 206 nm (ε 33110), 222 (21380), 267 (8410), 277 (8620), 307 (14780); IR C=O 1732 (s), 1675 (s), C=C 1601 (m), SO_2 1370 (s), 1169 (s) cm^{-1}; ^{1}H NMR δ 1.54 (s, 3, Me), 2.16 (d, 1, H-11, J = 19.0 Hz), 2.40 (s, 3, aryl Me), 2.49 (dd, 1, H-11, J = 7.7, 19.0 Hz), 3.19 (t, 1, α-CO_2 H, J = 2.7 Hz), 3.44 (br d, 1, α-keto H, J = 7.7 Hz), 3.51 (s, 3, OMe), 4.07 (d, 1, H-8, J = 6.0 Hz), 5.83 (d, 1, H-9, J = 6.0 Hz), 7.28–8.30 (m, 8, aryl Hs); MS m/e 449 (M$^+$, 67%), 385 (55), 294 (30), 266 (51), 235 (24), 234 (base), 207 (41), 206 (69), 180 (21), 91 (32); exact mass 449.1294, calcd for $C_{25}H_{23}NO_5S$ 449.1295.

Hydroxy Ester 21. A solution of 224.5 mg (0.5 mmol) of ketone **20c** and 186.3 mg (0.5 mmol) of cerium chloride heptahydrate in 8 mL of methanol was added dropwise to 19 mg (0.5 mmol) of sodium borohydride. The mixture was stirred for 0.5 h and 10 mL of saturated ammonium chloride was added. The mixture then was poured into water and extracted with ethyl acetate. The extract was dried (Na_2SO_4) and evaporated to give 216 mg (96%) of solid alcohol **21**: mp 144–145 °C (ether–hexane); UV λ_{max} 206 nm (ε 23420), 220 (20260), 259 (8900), 293 (3030); IR OH 3550 (m), C=O 1730 (s), C=C 1600 (w), SO_2 1360 (s), 1170 (s) cm^{-1}; ^{1}H NMR δ 1.63 (s, 3, Me), 2.28 (dd, 1, H-11, J = 7.0, 19.5 Hz), 2.32 (s, 3, aryl Me), 2.92 (d, 1, H-11, J = 19.5 Hz), 3.11 (t, 1, α-CO_2 H, J = 2.9 Hz), 3.29 (m, 1, bridgehead H), 3.43 (s, 3, OMe), 3.78 (d, 1, H-8, J = 6.4 Hz), 4.20 (d, 1, OH, J = 3.5 Hz), 5.62 (dd, 1, OCH, J = 3.5, 7.2 Hz), 5.82 (d, 1, H-9, J = 6.4 Hz), 7.16–8.08 (m, 8, aryl Hs); MS m/e 451 (M$^+$, 5%), 433 (5), 297 (25), 296 (base), 264 (33), 236 (20), 218 (22), 144 (63), 91 (30); exact mass 451.1443, calcd for $C_{25}H_{25}NO_5S$ 451.1452.

Ketones 22a and 23a. A mixture of 339.4 mg (1 mmol) of ketone **11c** and 183 mg (1 mmol) of diene **2a** in 5 mL of dry xylene was heated at 125 °C for 8 h. Another 183 mg (1 mmol) of the diene was added and heating was continued for an additional 8 h. This procedure was repeated three times, until the ketone had been consumed (total amount of diene, 5 equiv; total time, 40 h). The solvent then was evaporated and the residue chromatographed. Elution with a 4:1 hexane–ethyl acetate mixture afforded 25 mg (7%) of starting ketone, followed by 68 mg (4.5%) of solid yuehchukene (**1**). Further elution gave 210 mg (40%) of colorless, crystalline ketone **22a**: mp 201–202 °C (CH_2Cl_2–C_6H_{14}); UV λ_{max} 210 nm (ε 52000), 222 (50400), 285 (14370), 292 (14155); IR NH 3473 (s), C=O 1668 (s), C=C 1600 (m), SO_2 1375 (s), 1178 (s) cm^{-1}; ^{1}H NMR δ 0.99 (d, 3, Me, J = 6.2 Hz), 1.84 (s, 3, olefinic Me), 1.92 (dd, 1, H-11, J = 9.0, 16.2 Hz), 2.31 (m, 1, H-10′), 2.35 (s, 3, aryl Me), 2.43 (m, 1, H-11), 3.44 (dd, 1, H-9′, J = 5.4, 10.1 Hz), 4.17 (br s, 1, H-8), 5.62 (d, 1, H-9, J = 3.1 Hz), 6.42–7.92 (m, 12, aryl Hs), 6.81 (d, 1, H-2, J = 2.1 Hz), 8.30 (s, 1, H-2′); MS m/e 522 (M$^+$, 11%), 231 (46), 224 (41), 183 (base), 182 (54), 168 (55); exact mass 522.1955, calcd for $C_{32}H_{30}N_2O_3S$ 522.1975. Anal. Calcd for $C_{32}H_{30}N_2O_3S$: N, 5.36. Found: N, 5.17.

More elution gave 190 mg (36%) of colorless, crystalline ketone **23a**: mp 275–276 °C (CH_2Cl_2–C_6H_{14}, −15 °C); UV (EtOH) λ_{max} 210 nm (ε 47610), 221 (43720), 278 (13070), 285 (13560), 292 (13230); IR NH 3471 (s), C=O 1652 (s), C=C 1602 (s), SO_2 1379 (s), 1173 (s) cm^{-1}; ^{1}H NMR δ 0.91 (d, 3, Me, J = 6.4 Hz), 1.81 (s, 3, olefinic Me), 2.09 (dd, 1, H-11, J = 16.0, 17.3 Hz), 2.24 (dd, 1, H-11, J = 3.2, 17.3 Hz), 2.35 (s, 3, aryl Me), 2.41 (m, 1, H-10′),

3.46 (dd, 1, H-9′, J = 9.7, 10.5 Hz), 4.06 (d, 1, H-8, J = 9.7 Hz), 5.54 (s, 1, H-9), 6.84 (d, 1, H-2, J = 2.1 Hz), 7.12–8.32 (m, 12, aryl Hs), 7.56 (s, 1, H-2′); MS m/e 522 (M^+, 23%), 367 (48), 298 (50), 224 (base), 223 (42), 208 (35), 183 (38), 182 (38), 168 (42), 155 (41), 144 (79), 91 (23). Anal. Calcd for $C_{32}H_{30}N_2O_3S$: C, 73.53; H, 5.79; N, 5.36. Found: C, 72.83; H, 5.85; N, 5.20.

Ketones 22b and 23b. A mixture of 261.3 mg (0.5 mmol) of ketone **22a** and 173 mg (1.25 mmol) of potassium carbonate in a 4:4:1 acetonitrile–methanol–water mixture was heated at 52 °C for 2 h. After cooling, the mixture was poured into water and extracted with methylene chloride. The extract was dried and evaporated, and the residue was chromatographed. Elution with 4:1 hexane–ethyl acetate gave 160 mg (87%) of colorless, crystalline ketone **22b**: mp 164–165 °C (acetone–hexane); UV λ_{max} 218 nm (ϵ 26 380), 241 (6780), 262 (6440), 285 (7920), 292 (8420); IR NH 3462 (s), C=O 1648 (s), C=C 1619 (w), 1602 (w) cm^{-1}; ^1H NMR δ 1.03 (d, 3, Me, J = 6.0 Hz), 1.83 (s, 3, olefinic Me), 1.88 (dd, 1, H-11, J = 10.7, 17.6 Hz), 2.35 (dd, 1, H-11, J = 5.4, 17.6 Hz), 2.47 (m, 1, H-10′), 3.44 (dd, 1, H-9′, J = 5.3, 10.2 Hz), 4.19 (br s, 1, H-8), 5.63 (d, 1, H-9, J = 3.5 Hz), 6.61–8.07 (m, 8, aryl Hs), 6.81 (d, 1, H-2, J = 2.2 Hz), 7.83 (d, 1, H-2, J = 2.7 Hz); MS m/e 368 (M^+, 34%) 224 (16), 183 (35), 182 (34), 168 (39), 144 (base), 130 (27); exact mass 368.1880, calcd for $C_{25}H_{24}N_2O$ 368.1887.

By the same method 261.3 mg (0.5 mmol) of ketone **23a** was converted into 120 mg (67%) of ketone **23b**: mp 207–208 °C (acetone–hexane); UV λ_{max} 212 nm (ϵ 40 170), 217 (40 872), 244 (13 050), 263 (12 110), 286 (12 420), 292 (13 090); IR NH 3462 (s), C=O 1640 (s), C=C 1623 (w), 1606 (w) cm^{-1}; ^1H NMR δ 0.90 (d, 3, Me, J = 6.5 Hz), 1.80 (s, 3, olefinic Me), 2.01 (dd, 1, H-11, J = 13.5, 17.5 Hz), 2.21 (dd, 1, H-11, J = 4.7, 17.5 Hz), 2.39 (m, 1, H-10′), 3.29 (t, 1, H-9′, J = 10.6 Hz), 4.50 (d, 1, H-8, J = 8.6 Hz), 5.58 (s, 1, H-9), 6.76 (d, 1, H-2′, J = 1.8 Hz), 6.91 (d, 1, H-2, J = 2.7 Hz), 7.06–8.43 (m, 8, aryl Hs); MS m/e 368 (M^+, 16%), 224 (27), 144 (base). Anal. Calcd for $C_{25}H_{24}N_2O$: C, 81.49; H, 6.56; N, 7.60. Found: C, 81.56f; H, 6.72; N, 7.54.

12′-Demethyl-2,8′-secoyuehchukene (28) and 12′-Demethyl-8-iso-2,8′-secoyuehchukene (29). A mixture of 75 mg (0.20 mmol) of ketone **22b** and 360 mg (9.48 mmol) of lithium aluminum hydride in 10 mL of dried N-methylmorpholine was heated at 100–102 °C for 1.5 h. After cooling, the mixture was added slowly to 30 mL of stirred brine[18] and extracted with methylene chloride. The extract was dried (K_2CO_3) and evaporated, and the residue was chromatographed. Elution with 4:1 hexane–ethyl acetate gave 36 mg (50%) of colorless, crystalline product **28**: mp 228–230 °C (CH_2Cl_2–C_6H_{14}); UV λ_{max} 206 nm (ϵ 19 050), 224 (33 400), 276 (5400), 283 (6030), 292 (5480); IR NH 1458 (s), C=C 1598 (w), 1585 (w) cm^{-1}; ^1H NMR δ 1.07 (d, 3, Me, J = 7.0 Hz), 1.66 (d, 1, H-11, J = 17.5 Hz), 1.79 (s, 3, olefinic Me), 1.98 (m, 1, H-10′), 2.27–2.53 (m, 4, H-11, H-9′, H-8′), 4.04 (br s, 1, H-8), 5.60 (s, 1, H-9), 6.90–7.64 (m, 8, aryl Hs), 6.80 (d, 1, H-2, J = 1.7 Hz), 6.99 (d, 1, H-2′, J = 2.1 Hz); ^{13}C NMR δ 19.6 (C-11′), 23.4 (C-12), 23.8 (C-8′), 27.6 (C-10′), 33.0 (C-8), 34.1 (C-11), 42.0 (C-9′), 110.5 (C-7 or C-7′), 110.7 (C-7′ or C-7), 114.6 (C-3′), 117.5 (C-3), 117.8 (C-5′), 118.1 (C-5), 118.5 (C-4′), 119.0 (C-4), 120.6 (C-6), 120.9 (C-6′), 121.6 (C-2), 122.3 (C-9), 122.7 (C-2′), 127.1 (C-3a or C-3a′), 127.2 (C-3a′ or C-3a), 131.8 (C-10), 136.0 (C-7a or C-7a′), 136.3 (C-7a′ or C-7a); MS m/e 354 (M^+, 94%), 246 (26), 224 (26), 223 (52), 208 (23), 184 (28), 183 (63), 182 (44), 170 (25), 168 (45), 130 (base); exact mass 354.2112, calcd for $C_{25}H_{26}N_2$ 354.2096.

Use of the same procedure on 74 mg (0.2 mmol) of ketone **23b** led to 16 mg (22%) of starting ketone and 24 mg (33%; 44% based on consumed starting ketone) of product **29** as a pale yellow solid: mp 69–70 °C; UV λ_{max} 222 nm (ϵ 53 270), 226 (53 980), 278 (12 890), 284 (14 040), 292 (12 660); IR NH 3465 (s), C=C 1604 (w), 1592 (w) cm^{-1}; ^1H NMR δ 1.04 (d, 3, Me, J = 6.0 Hz), 1.69 (s, 3, olefinic Me), 1.88–2.16 (m, 4, H-9′, H-10′, Hs-11), 2.79–2.97 (m, 2, Hs-8′), 3.52 (br s, 1, H-8), 5.43 (s, 1, H-9), 6.84 (d, 1, H-2, J = 1.7 Hz), 6.87 (d, 1, H-2, J = 2.2 Hz), 6.90–7.51 (m, 8, aryl Hs); ^{13}C NMR δ 20.6 (C-11′), 23.3 (C-12), 26.2 (C-8′), 33.4 (C-10′), 39.3 (C-8), 39.3 (C-11), 44.9 (C-9′), 110.6 (C-7 or C-7′), 111.0 (C-7′ or C-7), 114.9 (C-3′), 118.7 (C-5), 118.8 (C-5′), 119.2 (C-4′), 119.9 (C-4), 120.0 (C-3), 121.4 (C-6′), 121.5 (C-6), 121.8 (C-2 and C-2′), 125.4 (C-9), 126.8 (C-3a′), 128.3 (C-3a), 132.1 (C-10), 135.7 (C-7a′), 136.6 (C-7a); MS m/e 354 (M^+, 19%), 224 (37), 223 (base), 208 (65), 131 (21), 130 (71); exact mass 354.2106, calcd for $C_{25}H_{26}N_2$ 354.2096.

Alcohols 26 and 27. A mixture of 164.5 mg (0.315 mmol) of ketone **22a** and 36 mg (0.945 mmol) of lithium aluminum hydride in 10 mL of dry tetrahydrofuran was stirred at room temperature for 0.5 h. Ethyl acetate (1 mL) was added dropwise, and the mixture was stirred for 5 min and then poured into water and extracted with methylene chloride. The extract was washed with brine, dried (Na_2SO_4), and evaporated to give 162 mg (98%) of nearly pure alcohol **26**. Chromatography and elution with 4:1 hexane–ethyl acetate induced some decomposition, affording 106 mg (64%) of colorless, crystalline alcohol **26**: mp 108–110 °C (CH_2Cl_2–C_6H_{14}, −15 °C); UV λ_{max} 206 nm (ϵ 44 410), 220 (53 490), 255 (13 680), 283 (9210), 291 (8550); IR OH 3520 (m), NH 3465 (s), C=C 1600 (w), SO_2 1375 (s), 1179 (s) cm^{-1}; ^1H NMR δ 1.12 (d, 3, Me, J = 6.5 Hz), 1.74 (m, 1, H-11), 1.74 (s, 3, olefinic Me), 1.79 (d, 1, OH, J = 6.6 Hz), 2.14 (m, 1, H-10′), 2.25 (m, 1, H-11), 2.30 (s, 3, aryl Me), 2.47 (dt, 1, H-9′, J = 5.5, 7.6 Hz), 3.73 (br s, 1, H-8), 5.10 (t, 1, H-8′, J = 6.4 Hz), 5.46 (br s, 1, H-9), 6.98 (d, 1, H-2, J = 2.2 Hz), 7.08–8.03 (m, 12, aryl Hs), 7.30 (s, 1, H-2′); MS m/e 524 (M^+, 24%), 506 (45), 352 (40), 351 (72), 300 (43), 234 (40), 223 (26), 183 (79), 182 (38), 168 (44), 155 (35), 130 (33), 117 (54), 91 (base); exact mass 524.2161, calcd for $C_{32}H_{32}N_2O_3S$ 524.2130.

By the same method ketone **23a** (120 mg, 0.23 mmol) was converted into 113 mg (94%) of nearly pure alcohol **27** whose chromatography and elution with 4:1 hexane–ethyl acetate gave 42 mg (35%) of crystalline alcohol **27**: mp 115–116 °C (CH_2Cl_2–C_6H_{14}, −15 °C); UV λ_{max} 208 nm (ϵ 34 640), 220 (41 870), 259 (11 960), 284 (8470), 292 (7800); IR OH 3495 (m), NH 3470 (s), C=C 1600 (w), SO_2 1371 (s), 1178 (s) cm^{-1}; ^1H NMR δ 0.75 (d, 3, Me, J = 6.0 Hz), 1.73 (s, 3, olefinic Me), 1.87 (dd, 1, H-11, J = 7.5, 17.0 Hz), 1.97 (d, 1, OH, J = 5.2 Hz), 2.08 (dd, 1, H-11, J = 2.6, 17.0 Hz), 2.24 (s, 3, aryl Me), 2.24 (m, 1, H-10′), 2.30 (dd, 1, H-9′, J = 2.2, 9.1 Hz), 3.72 (br s, 1, H-8), 5.12 (d, 1, H-8′, J = 5.2 Hz), 5.49 (s, 1, H-9), 6.63–7.91 (m, 12, aryl Hs), 7.06 (d, 1, H-2, J = 1.3 Hz), 7.48 (d, 1, H-2′, J = 0.9 Hz); MS m/e 524 (M^+, 4%), 224 (42), 223 (base), 208 (39), 117 (18), 91 (34); exact mass 524.2172, calcd for $C_{32}H_{32}N_2O_3S$ 524.2134.

Ketone 22c. N-Sulfonylation of 52.2 mg (0.1 mmol) of ketone **22a** under the general procedure of phase-transfer conditions (vide supra), chromatography of the crude product, and elution with 4:1 hexane–ethyl acetate led to 58 mg (86%) of colorless, crystalline ketone **22c**: mp 213–214 °C (CH_2Cl_2–C_6H_{14}); UV (CH_3CN) λ_{max} 234 nm (24 320), 259 (13 770), 275 (11 850), 288 (11 720); IR C=O 1665 (s), C=C 1598 (m), SO_2 1375 (s), 1173 (s) cm^{-1}; ^1H NMR δ 1.02 (d, 3, Me, J = 6.1 Hz), 1.85 (s, 3, olefinic Me), 1.88 (dd, 1, H-11, J = 9.0, 19.0 Hz), 2.21, 2.35 (s, 3 each, aryl methyls), 2.30–2.41 (m, 2, H-10′ and H-11), 3.45 (dd, 1, H-9′, J = 5.6, 9.3 Hz), 4.03 (br s, 1, H-8), 5.54 (d, 1, H-9, J = 3.8 Hz), 6.56–7.88 (m, 16, aryl Hs), 7.70 (s, 1, H-2), 8.19 (s, 1, H-2′); MS m/e 676 (M^+, 11%), 521 (23), 299 (25), 298 (base), 284 (18), 182 (56), 167 (27), 155 (38), 144 (18), 91 (43); exact mass 676.2073, calcd for $C_{39}H_{36}N_2O_5S_2$ 676.2066.

Ketol 24. A solution of 13.5 mg (0.02 mmol) of ketone **22c** in 0.5 mL of trifluoroacetic acid was stirred at room temperature for 3 h and then poured into water. The mixture was extracted with ethyl acetate. The extract was washed with saturated sodium hydrogen carbonate and brine and dried. Evaporation gave 14 mg (100%) of colorless, solid alcohol **24**: mp 171–172 °C (CH_2Cl_2–C_6H_{14}); UV λ_{max} 208 nm (ϵ 39 350), 258 (12 520), 274 (10 260), 290 (9870); IR OH 3597 (w), C=O 1665 (s), SO_2 1375 (s), 1173 (s) cm^{-1}; ^1H NMR δ 1.17 (d, 3, Me, J = 6.6 Hz), 1.31 (s, 3, olefinic Me), 1.50 (dd, 1, H-11, J = 11.0, 13.4 Hz), 2.02, 2.31 (s, 3 each, aryl methyls), 2.02 (m, 1, H-11), 2.07 (dd, 1, H-9, J = 5.4, 13.9 Hz), 2.47 (dd, 1, H-9, J = 7.2, 13.9 Hz), 2.75 (m, 1, H-10′), 3.37 (dd, H-8, J = 5.6, 7.2 Hz), 3.67 (dd, 1, H-9′, J = 5.6, 11.7 Hz), 6.65–8.17 (m, 18, aryl Hs); MS m/e 676 ($M^+ - H_2O$, 10%), 521 (24), 378 (50), 298 (base), 284 (24), 182 (33), 155 (42), 144 (25), 91 (56); exact mass ($M^+ - H_2O$) 676.2067, calcd for $C_{39}H_{36}N_2O_5S$ 676.2066.

Addition of sodium borohydride (1.5 mg, 0.04 mmol) to a solution of ketone **22c** (13.5 mg, 0.02 mmol) in methylene chloride (0.3 mL) and trifluoroacetic acid (0.3 mL) led to the isolation of the same alcohol (14 mg, 100%).

(18) For unknown reasons, destruction of the excess lithium aluminum hydride with ethyl acetate resulted in the formation of mixtures.

Tosylhydrazone 25b. A mixture of 30 mg (0.1 mmol) of ketone **25a**[4] and 18.6 mg (0.1 mmol) of (*p*-tolylsulfonyl)hydrazine in 2 mL of tetrahydrofuran was stirred at room temperature for 24 h. Evaporation of the solvent and chromatography (1:1 hexane–ethyl acetate) of the residue gave 46 mg (98%) of colorless, crystalline hydrazone **25b**: mp 183–184 °C (CH_2Cl_2–C_6H_{14}); UV λ_{max} 207 nm (ϵ 22 510), 220 (27 510), 270 (13 510), 277 (14 100), 281 (14 150), 294 (13 190); IR NH 3295 (w), C=N 1600 (m), SO_2 1375 (s), 1170 (s) cm^{-1}; ^1H NMR δ 2.17 (s, 3, Me), 2.38 (s, 3, aryl Me), 7.25–8.24 (m, 13, aryl Hs), 7.73 (s, 1, H-2); MS *m/e* 467 (M^+, 20%), 312 (58), 284 (40), 283 (44), 171 (88), 170 (26), 143 (61), 142 (base), 139 (31), 115 (77), 92 (30), 91 (62), 77 (54); exact mass 467.1000, calcd for $C_{23}H_{21}N_3O_4S_2$ 467.0972.

X-ray Crystal Structure Analysis of Compound 21. $C_{25}H_{25}NO_5S$, M_r = 451.55, triclinic, a = 10.803 (3) Å, b = 12.445 (3) Å, c = 9.831 (3) Å, α = 109.85 (2)°, β = 109.39 (2)°, γ = 65.34 (2)°, V = 1101.4 Å^3, Z = 2, D_{calcd} = 1.361 g cm^{-3}, μ(Cu Kα radiation, λ = 1.5418 Å), = 15.8 cm^{-1}. Space group $P1(C_1^1)$ or $P\bar{1}(C_{1i}^1)$ from the Laue symmetry, shown to be the latter by structure solution and refinement. Sample dimensions: 0.16 × 0.22 × 0.54 mm.

Preliminary unit-cell parameters and space group information were obtained from oscillation, Weissenberg, and precession photographs. One hemisphere of intensity data (3911 nonequivalent reflections) was recorded on an Enraf-Nonius CAD-4 diffractometer (Cu Kα radiation, incident-beam graphite monochromator; ω–2θ scans, θ_{max} = 67°), and those 3489 reflections with $I > 3.0\sigma(I)$ were retained for the structure analysis. The data were corrected for the usual Lorentz and polarization effects, and an empirical absorption correction (T_{max}:T_{min} = 1.00:0.91) was also applied. Refined unit-cell parameters were derived from the diffractometer setting angles for 25 reflections (59° < θ < 67°) widely separated in reciprocal space.

The crystal structure was solved by direct methods,[10] assuming at the outset that $P\bar{1}$ was the correct choice of space group. Approximate non-hydrogen atom coordinates were obtained from an *E* map. Hydrogen atoms were all located in a difference Fourier synthesis evaluated following several rounds of full-matrix least-squares adjustment of non-hydrogen atom positional and anisotropic temperature factor parameters. With the inclusion of hydrogen atom positional and isotropic thermal parameters as variables in the subsequent least-squares iterations, the refinement converged at R = 0.036 (R_w = 0.057).[11] Final atomic positional and thermal parameters are in Tables S-1 to S-3.[12]

Neutral atom scattering factors used in the structure-factor calculations were taken from ref 19. In the least-squares iteractions, $\sum w\Delta^2$ [$w = 1/\sigma^2(|F_o|)$, $\Delta = (|F_o| - |F_c|)$] was minimized.

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Supplementary Material Available: Tables of non-hydrogen atom positional and anisotropic temperature factor parameters, hydrogen atom positional and isotropic thermal parameters, interatomic distances, bond angles, and torsion angles for **21** (10 pages). Ordering information is given on any current masthead page.

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Rearrangement of Homobrendane Derivatives. Total Syntheses of Racemic Copacamphor, Ylangocamphor, and Their Homologues

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Rearrangement of a homobrendane derivative **8a** to perhydro-1,4-methanoindene system **9a** could be brought about either by *p*-toluenesulfonic acid or boron trifluoride etherate. Similarly, rearrangement of **8b–d** led to the formation of perhydro-1,4-methanoindene derivatives **9b–d**. On the basis of the location of substituents in the starting material and the product, a probable mechanistic pathway has been suggested. The appropriate modification of the peripheral functionalities in **9** led to efficient total syntheses of (±)-copacamphor (**15a**), (±)-ylangocamphor (16a), and their homologues **15b** and **16b**.

In the course of our study pertaining to the total synthesis of B-seco steroids,[1] we observed that seco diones of the type **3** yielded unusual products depending on the acid and solvent employed.[2] While the reaction of *p*-toluenesulfonic acid (*p*-TsOH) afforded the desired pentaenones, MeOH–HCl reaction of the seco diones **3a** and **3c** yielded isomeric bicyclo[3.2.1]octane derivatives **4** and **5** as the major products along with the tricyclic hydroxy ketone **6**. Conclusive structural assignments and correlation with diagnostic NMR patterns for the isomeric compounds **4** and **5** have been published.[3] The tricyclic hydroxy ketone **6**, a homobrendane derivative, was obtained in 20% yield, and its structure was unambiguously established by spectral as well as X-ray crystal structure analyses.[4,5] Similar homobrendane system has been reported to be formed during acid-[6] or base-catalyzed[7] cyclization. The present paper describes a novel rearrangement of such a homobrendane derivative to the perhydro-1,4-methanoindene skeleton culminating in a facile synthesis of the natural product precursor (±)-copacamphor (**15a**), its C_5-epimer, (±)-ylangocamphor (**16a**), and their C_1-homologues **15b** and **16b**.

Rearrangement. An acid-catalyzed rearrangement of the homobrendane system can be initiated only if a carbocation can be generated at a position other than the

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