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Opening of Ring C in Ruthenium-Catalyzed Rearrangements of 15,16-Epoxybeyerane Diterpenes Hydroxylated at C-12

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Rearrangements catalyzed by ruthenium acetylacetonate of *ent*-1β-acetoxy-15α,16α-epoxybeyeranes with axial or equatorial hydroxyl groups at C-12 were carried out. The expected rearrangement products (*ent*-kaur-15-ene and *ent*-kaur-16-ene) were isolated mainly from the 12-axial-hydroxyl compound. However, when the 12-equatorial-hydroxyl group was present, it participated in a process involving ring opening and cyclization from rear to give C-12 epimerized *ent*-kaur-15-ene and *ent*-kaur-16-ene compounds, as well as *ent*-16(*R*)-kauran-12-one, *via* concerted 12→16 hydride migration. On the basis of deuterium labeling experiments, the ring C opening and cyclization process seems to occur through an aldehyde intermediate.

Introduction

Many rearrangements of diterpene compounds have been published.[1-11] Normally these rearrangements can be explained as the result of an electron deficiency, principally at C-16 in the case of epoxybeyeranes, which promotes a series of biomimetic rearrangements as indicated in the general schemes of McAlles and McCrindle.[12,13] In only one case[7] was the formation of a carbocation at C-15 considered responsible for the rearrangement of beyerane compounds.

Other functional groups on the rings could participate in the rearrangement process to give either products with different skeletons from those indicated previously,[13] or products with same skeleton but with a different mode of functionalization. Alternatively, variations in the yields could have occurred modifying the proportions of the products thus obtained. The influence of C-14 and C-15 substituents in different configurations over rearrangement of *ent*-15α,16α-epoxybeyeranes[8] and *ent*-16β,-17-epoxykauranes[10] has been reported. The participation of neighboring groups in solvolysis processes was also proved.[14] On the basis of these observations, the influence of the functionalization at C-12 on the rearrangement processes of *ent*-15α,16α-epoxybeyeranes was studied.

Results and Discussion

Deoxygenation of the natural product 1-acetyljativatriol (**1**)[15,16] at C-17 *via* the 17-chlorinated compound (**2**, see Experimental Section) gives *ent*-1β-acetoxy-12α-hydroxybeyer-15-ene (**3**), which was epoxidized to give the *ent*-15α,16α-epoxy derivative **4**.

Treatment of **4** with ruthenium acetylacetonate (Ru-acac)[8] in chloroform provided the "normal" rearrangement products[1] *ent*-kaur-15-ene derivative **5** (20%), *ent*-kaur-16-ene derivative **6** (20%), as well as the chlorinated derivative **7** (10%). Mass spectrometry of **7** demonstrated the presence of the chlorine. ^{1}H NMR experiments indicated that the chlorine was situated at C-16, with a *trans*-disposition with respect to the *ent*-15α-hydroxy group (J = 3.8 Hz). The epoxy opening mantained the configuration in oxygenated carbon, and the hydroxyl group thus formed was *trans* with respect to the chlorine. Moreover, the geminal proton to the hydroxyl was near to C-20 methyl group, which was probed by NOE experiments. Thus, hydroxyl group must be situated at C-15 (*ent*-α) and the chlorine atom at C-16 (*ent*-β). Thus the opening of the original *ent*-15α,16α-epoxy group could be due to HCl, generated from solvent ($CHCl_3$) under the reaction conditions. Apparently the C-12 axial hydroxyl group does not take part in the process. To study the possible influence of the configuration at C-12, the alcohol **4** was oxidized, to give the epoxy ketone **8** (90%), which was reduced with $NaBH_4$ or $NaBD_4$ to obtain **4** (25%) and **9** (70%), or **10** (70%) and **11** (25%), respectively.

The rearrangement of the C-12 equatorial alcohol **9** gave *ent*-kaur-15-ene **5** (10%), *ent*-kaur-16-ene **6** (25%), ketone product **12** (35%), and aldehyde (**13**) in very low yield (5%). It is clear that, in addition to skeletal rearrangement, epimerization at C-12 also occurred leading to the alcohols **5** and **6**; unchanged equatorial alcohol **9** was also recovered (20%).

The formation of ketone **12** could be explicable in terms of the rearrangement of *ent*-beyerane to *ent*-kaurane with concerted migration of the hydride from C-12 to C-16 to give a 16(*R*) configuration (path a of Figure 1). This migration was confirmed by rearrangement of C-12 deuterated alcohol (product **10**), which gave four analogous products (**14**–**17**) to those described from **9**. Thus ketone **16** had the deuterium atom on C-16, which confirmed the proposed migration. Moreover, deutera-

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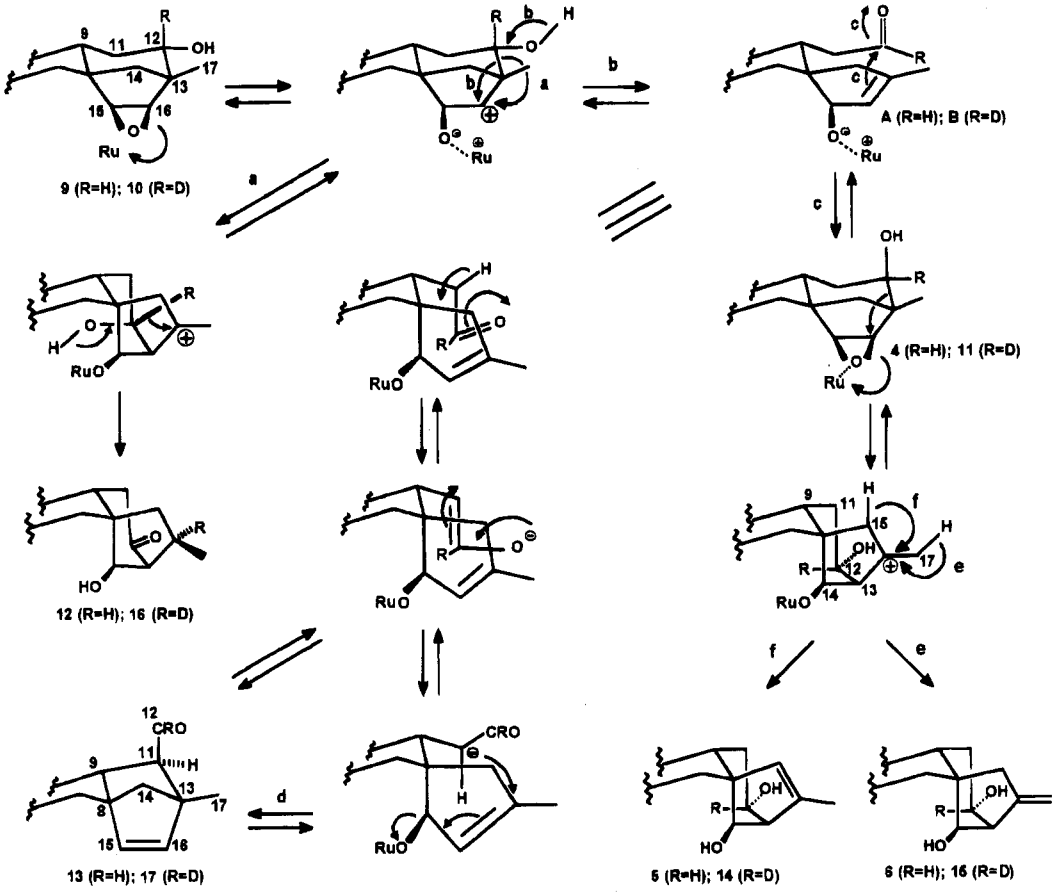

Figure 1. Proposed mechanism of rearrangement of epoxy compounds **4**, **9**, **10**, and **11**.

tion was also suggestive of the possible mechanism of this rearrangement—epimerization to give products **5** and **6** from **9**. On the basis of the observation that the deuterium atom remained at C-12 in products **14** and **15**, the formation of a transient aldehyde intermediate **A** (or **B** for deuterated series) (see path b of Figure 1) was proposed, which cycled at the si face to *ent*-beyerane product (epimer at C-12, products **4** or **11**) with the help of Ru-acac. These evolved as indicated above, or to *ent*-kaurane products, with the participation of protons at C-15 (to give *ent*-kaur-15-ene, products **5** or **14**) or C-17 (to give *ent*-kaur-16-ene, products **6** or **15**) (see path c of Figure 1). Such processes could be considered similar to those occurring in the Prins reactions.[17] This mechanism was supported by the isolation of an aldehyde compound (**13** or **17**), which resulted from cyclization of the proposed aldehyde intermediate (**A** or **B**) at its α-position (C-11) to give the bicyclo[2.2.1]heptane **13** (or product **17** when the starting material was deuterated at C-12) (see path d of Figure 1). The ^{1}H NMR signal of the aldehyde group in compound **13** (δ 9.47, 1H, d, J = 6.6 Hz) indicated that this group was vicinal to a methine group. COSY experiments indicated that this proton was coupled to another proton with a signal at δ 2.60 (1H, dd, J_1 = 6.6 Hz, J_2 = 9.3 Hz), which was also coupled to a signal at δ 2.12 (1H, d, J = 9.3 Hz). When starting material was deuterated at C-12, the corresponding signal (δ 2.60) of rearranged aldehyde **17** was a doublet signal (J = 9.3 Hz). C/H correlation experiments indicated that the proton at δ 2.12 was situated at C-9. Hence, the proton signal at δ 2.60 was the signal of a methine group at C-11, and the aldehyde group resulted from the hydroxylated C-12 of starting material **10**. Two doublets (J = 5.6 Hz) due to H-15 and H-16 at δ 6.20 and 5.88, respectively, were observed in the ^{1}H NMR spectrum of the aldehyde **13**, which indicated that both protons were situated between two quaternary carbons. The stereochemistry of the aldehyde group (in **13** or **17**) was established by NOE-difference experiments. Thus it was proved that the methine group at C-15 was near the methyl group at C-20, which defined the stereochemistry of the vinylic portion. On the basis of these observations, we concluded that a new bicyclo[2.2.1]-octane structure was formed. Stereochemistry at C-11 was tentatively assigned, although the experimental value ($J_{9,11}$ = 9.3 Hz) was midway between the calculated values[18] for the two configurations at C-11. However, the 11(R)-configuration was more stable (E = 54.5 kcal/mol) than 11(S)-configuration (E = 60.5 kcal/mol), and regardless of their mode of formation, both structures can be interconverted by keto—enol tautomerism. Moreover, the notable chemical shift of H-9 (δ 2.12) was in accord with the spatial situation in the minimum energy conformation for the 11(R)-epimer, in which oxygen of the aldehyde group was close to H-9.

The process of rearrangement from epoxybeyeranes to kauranes is usually admitted as a concerted process that is able to be influenced by the presence of substituents on the α-position to the carbenium ion that is originated in said rearrangements. However, the formation of this aldehyde compound, and the epimerizations detected at C-12, indicated that in the case of epoxybeyeranes with

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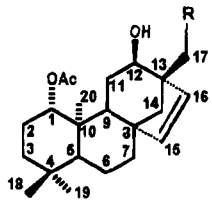
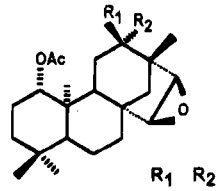
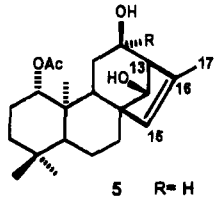


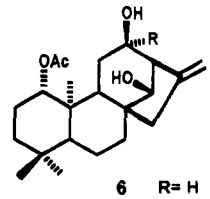
1 R=OH
2 R= Cl
3 R= H



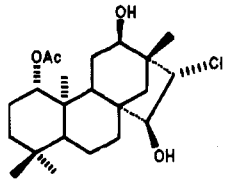
	R_1	R_2
4	OH	H
9	H	OH
10	D	OH
11	OH	D



5 R= H
14 R= D



6 R= H
15 R= D



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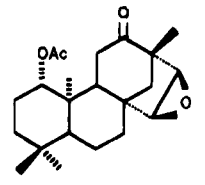

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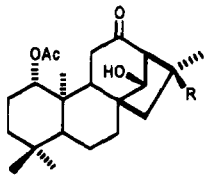
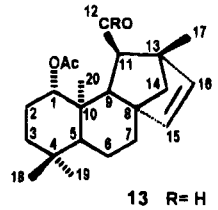


12 R= H
16 R= D



13 R= H
17 R= D

an equatorial hydroxyl on this carbon (C-12) which takes part in the carbenium ion, the rerrangement was not concerted, but occurred through aldehyde intermediates, in a process analogous to the Prins and retro-Prins reactions.

Experimental Section

Isolation of Starting Product. *ent*-1β-Acetoxy-12α,17-dihydroxybeyer-15-ene (1-acetyljativatriol, **1**), used as starting product for this work, was isolated from *Sideritis pusilla*.[16]

Chlorination of Product 1. In a 100 mL flask, 2 g of product **1** was treated with 20 mL of Py, 10 mL of Cl_4C, and 5 g of Ph_3P.[15] The reaction mixture was refluxed in argon atmosphere for 2 h; the mixture was extracted with CH_2Cl_2, washed with saturated aqueous $KHSO_4$, and dried with anhydrous Na_2SO_4. Chromatography over silica gel yielded *ent*-1β-acetoxy-17-chloro-12α-hydroxybeyer-15-ene (**2**) (1200 mg, 60%): mp 168–70 °C; $[\alpha]_D$ +8.2° ($CHCl_3$, *c* 1); IR ν_{max} (neat, cm^{-1}) 3492, 3050, 1710, 1253; ^1H MNR δ 5.30 (2 H, s), 4.52 (1 H, dd, J_1 = 4.9 Hz, J_2 = 10.8 Hz), 3.99 (1 H, br d , J = 5.1 Hz), 3.78 (1 H, d, J = 10.8 Hz), 3.35 (1 H, d, J = 10.8 Hz), 1.99 (3 H, s), 0.87, 0.84, and 0.82 (3 H each, s); ^{13}C NMR see Table 1; CIMS, *m/z* (%) $[M + 1]^+$ 381 (8), 365 (13), 363 (32), 345 (4), 323 (14), 321 (42), 285 (100). Anal. Found: C, 69.16; H, 8.91. Calcd for $C_{22}H_{33}O_3Cl$: C, 69.36; H, 8.73.

Reduction of Product 2. A 1150 mg amount of product **2** was dissolved in 24 mL of toluene, and a solution of 4.5 mL of tri-n-butyltin hydride and azoisobutyronitrile in 15 mL of toluene was added. The mixture was refluxed for 10 h, concentrated, and dissolved in diethyl ether. After a solution of KF was added and the precipitate was filtered, the filtrate was dried and concentrated to obtain *ent*-1β-acetoxy-12α-hydroxybeyer-15-ene (**3**) (990 mg, 86%): mp 135–37 °C; $[\alpha]_D$ +48.5° ($CHCl_3$, *c* 1); IR ν_{max} (neat, cm^{-1}) 3348, 1735, 1245; ^1H MNR δ 5.70 (1 H, d, J = 5.7 Hz), 5.53 (1 H, d, J = 5.7 Hz), 4.50 (1 H, dd, J_1 = 4.9 Hz, J_2 = 10.7 Hz), 3.58 (1 H, br d , J = 5.2 Hz), 1.96 (3 H, s), 1.02, 0.84, 0.82, and 0.80 (3 H each, s); ^{13}C NMR see Table 1; CIMS, *m/z* (%) $[M + 1]^+$ 347 (2), 329 (46), 269 (98), 243 (30), 287 (100). Anal. Found: C, 76.16; H, 10.19. Calcd for $C_{22}H_{34}O_3$: C, 76.26; H, 9.89.

Table 1. ^{13}C NMR Chemical Shifts of Compounds 2–9[a]

C	2	3	4	5	6	7	8	9
1	82.0	82.1	82.5	84.3	84.0	82.5	82.0	82.3
2	24.9	24.9	24.8	25.5	25.5	24.8	24.7	24.9
3	39.2	39.2	38.9	39.4	39.2	39.0	39.2	39.2
4	33.0	33.0	33.0	33.2	33.2	32.6	33.0	32.9
5	55.1	55.1	55.2	54.9	55.1	55.4	54.8	55.0
6	19.9	21.3	19.6	18.3	19.3	19.8	19.4	19.6
7	36.8	37.1	31.6	29.8	30.9	32.6	33.3	32.5
8	50.0	48.2	44.4	55.1	49.6	46.0	45.3	44.4
9	49.3	49.2	52.0	50.2	57.0	51.7	51.7	56.1
10	41.7	41.7	42.0	43.5	43.3	42.4	42.3	42.2
11	32.6	32.6	32.9	30.6	32.1	30.5	43.1	31.8
12	66.3	71.1	72.1	70.2	69.8	71.0	210.3	76.4
13	53.5	50.0	45.1	60.2	59.1	46.4	53.9	43.8
14	49.6	52.9	39.1	77.8	74.5	45.8	40.1	44.3
15	138.1	137.4	55.5	132.5	44.5	80.6	55.5	55.7
16	132.9	137.0	59.7	139.6	148.5	77.6	59.2	58.1
17	48.7	21.3	17.7	17.9	109.2	21.1	13.9	17.4
18	33.0	33.0	32.9	33.2	33.2	33.1	32.9	32.9
19	21.5	21.5	21.4	21.5	21.5	21.6	21.3	21.3
20	11.0	10.9	12.7	15.0	15.2	11.7	13.2	12.7
CH_3	22.1	22.1	22.0	22.1	22.1	21.8	22.0	22.0
CO	170.7	170.7	170.6	170.5	170.8	170.7	170.4	170.9

[a] The ^{13}C chemical shifts are given in δ values (ppm) relative to $CDCl_3$ signals.

Epoxidation of Product 3. A solution of **3** (950 mg) in 5 mL of $CHCl_3$ was treated with 950 mg of m-CPBA. After 12 h at room temperature, the reaction mixture was washed with aqueous $FeSO_4$ (10%), aqueous $HNaCO_3$ (5%), and water, dried with $MgSO_4$, and concentrated under vacuum to obtain 920 mg of *ent*-1β-acetoxy-15α,16α-epoxy-12α-hydroxybeyerane (**4**, 97%): colorless gum; $[\alpha]_D$ +5.8° ($CHCl_3$, *c* 1); IR ν_{max} (neat, cm^{-1}) 3428, 1735, 1722, 1246; ^1H NMR δ 4.51 (1 H, dd, J_1 = 4.9 Hz, J_2 = 10.8 Hz), 3.71 (1 H, br d , J = 5.8 Hz), 3.36 (1 H, d, J = 3.0 Hz), 3.01 (1 H, d, J = 3.0 Hz), 2.00 (3 H, s), 1.07, 1.06, 0.87, and 0.84 (3 H each, s); ^{13}C NMR see Table 1; CIMS, *m/z* (%) $[M + 1]^+$ 363 (30), 345 (25), 303 (95), 285 (83), 279 (100).

Rearrangement of Product 4. A mixture of product **4**, ruthenium acetylacetonate (20 mg), and 15 mL of $CHCl_3$ was heated at 140 °C in a sealed tube (6 h). Then, when the solution cooled to room temperature, it was concentrated and directly chromatographed to give 40 mg of *ent*-1β-acetoxy-12α,-14α-dihydroxykaur-15-ene (**5**, 20%); [mp 210–12 °C; $[\alpha]_D$ +1.0° ($CHCl_3$, *c* 1); IR ν_{max} (neat, cm^{-1}) 3428, 1713, 1251; ^1H NMR δ 5.06 (1 H, m), 4.55 (1 H, dd, J_1 = 5.2 Hz, J_2 = 10.5 Hz) 4.04 (1 H, ddd, J_1 = 10.0 Hz, J_2 = 7.5 Hz, J_3 = 3.2 Hz), 3.94 (1 H, br s), 2.61 (1 H, d, J = 3.0 Hz), 2.03 (3 H, s), 1.82, 1.13, 0.85, and 0.80 (3 H each, s); ^{13}C NMR see Table 1; CIMS, *m/z* (%) $[M + 1]^+$ 363 (0.1), 345 (9), 303 (100). Anal. Found: C, 72.90; H, 9.50. Calcd for $C_{22}H_{34}O_4$: C, 72.89; H, 9.45.], 40 mg of *ent*-1β-acetoxy-12α,14α-dihydroxykaur-16-ene (**6**, 20%) [mp 228–30 °C; $[\alpha]_D$ −7.6° ($CHCl_3$, *c* 1); IR ν_{max} (neat, cm^{-1}) 3402, 1735, 1245; ^1H NMR δ 5.10 (2H, br s), 4.50 (1 H, dd, J_1 = 5.1 Hz, J_2 = 10.6 Hz) 4.05 (1 H, br s), 3.92 (1 H, ddd, J_1 = 9.8 Hz, J_2 = 6.0 Hz, J_3 = 3.6 Hz), 2.70 (1 H, d, J = 3.0 Hz), 2.00 (3 H, s), 1.12, 0.85, and 0.82 (3 H each, s); ^{13}C NMR see Table 1; CIMS, *m/z* (%) $[M + 1]^+$ 363 (5), 345 (57), 303 (100). Anal. Found: C, 72.71; H, 9.81. Calcd for $C_{22}H_{34}O_4$: C, 72.89; H, 9.45.], and 20 mg of *ent*-1β-acetoxy-16β-chloro-12α,15α-dihydroxybeyerane (**7**, 10%) [colorless gum; $[\alpha]_D$ −17.0° ($CHCl_3$, *c* 1); IR ν_{max} (neat, cm^{-1}) 3444, 1708, 1260; ^1H MNR δ 4.55 (1 H, dd, J_1 = 5.2 Hz, J_2 = 10.5 Hz), 4.27 (1 H, dd, J_1 = 3.8 Hz, J_2 = 2.2 Hz), 3.75 (1 H, ddd, J_1 = 5.9 Hz, J_2 = 3.9 Hz, J_3 = 1.9 Hz), 3.72 (1 H, d, J = 3.8 Hz), 2.02 (3 H, s), 1.08, 1.03, 0.86, and 0.82 (3 H

Table 2. ^{13}C NMR Chemical Shifts of Compounds 10–17[a]

C	10	11	12	13	14	15	16	17
1	82.2	82.5	83.9	82.9	84.3	84.0	83.9	82.9
2	24.8	24.9	25.4	24.3	25.4	25.6	25.4	24.3
3	39.0	38.9	39.2	39.7	39.3	39.1	39.3	39.7
4	32.8	32.9	33.0	33.0	33.2	33.2	33.3	33.0
5	54.9	55.2	54.9	56.4	54.8	55.0	54.9	56.4
6	19.4	19.6	19.6	20.1	18.3	19.3	19.6	20.1
7	32.3	31.6	32.3	32.3	30.6	30.9	32.3	32.4
8	44.1	44.4	51.5	55.3	55.1	49.5	51.6	56.1
9	56.0	52.0	55.1	65.9	50.2	57.0	55.1	65.8
10	42.1	42.0	43.7	43.1	43.7	43.3	43.7	43.0
11	31.5	32.9	37.2	62.4	30.6	30.2	37.2	62.4
12			213.5	204.9			213.4	
13	43.6	45.2	67.0	55.3	60.1	59.0	67.0	55.3
14	44.1	39.2	75.4	63.1	77.8	74.5	75.5	63.2
15	55.5	55.5	47.6	137.3	132.5	44.5	47.6	137.2
16	57.9	59.9	35.8	139.2	139.6	148.5		139.2
17	17.1	17.7	23.7	17.6	18.3	109.1	23.8	17.6
18	32.8	32.9	33.1	33.7	33.2	33.2	33.1	33.7
19	21.2	21.4	21.5	21.7	21.5	21.4	21.5	21.7
20	12.5	12.8	13.7	13.7	14.9	15.2	13.7	13.7
CH_3	21.9	22.1	22.0	22.1	22.1	22.0	22.1	22.1
CO	170.6	170.6	170.7	171.4	170.5	170.6	170.7	171.4

[a] The ^{13}C chemical shifts are given in δ values (ppm) relative to $CDCl_3$ signals.

each, s); ^{13}C NMR see Table 1; CIMS, m/z (%) $[M + 1]^+$ 399 (1.2), 341 (4.9), 339 (16.3), 323 (33), 321 (100), 303 (45), 285 (52.7).]

Oxidation of Product 4. A 700 mg sample of product **4** was dissolved in acetone (15 mL) and was oxidized with Jones's reagent, stopped with a few drops of methanol, diluted with water, extracted with CH_2Cl_2, dried with $MgSO_4$, and evaporated under vacuum. After CC, 665 mg of *ent*-1β-acetoxy-15α,-16α-epoxybeyer-12-one (**8**, 95%) was isolated: mp 135–37 °C; $[\alpha]_D$ −98.2° ($CHCl_3$, *c* 1); IR ν_{max} (neat, cm^{-1}) 1735, 1712, 1242; ^1H NMR δ 4.45 (1 H, dd, J_1 = 4.7 Hz, J_2 = 10.8 Hz), 3.60 (1 H, d, J = 2.9 Hz), 3.20 (1 H, d, J = 2.9 Hz) 2,47 (1 H, dd, J_1 = 11.7 Hz, J_2 = 16.8 Hz), 2.20 (1 H, dd, J_1 = 6.7 Hz, J_2 = 16.8 Hz), 2.06 (3 H, s), 1.13, 1.12, 0.89, and 0.87 (3 H each, s); ^{13}C NMR see Table 1; CIMS, m/z (%) $[M + 1]^+$ 361 (3), 343 (1), 301 (100), 283 (25). Anal. Found: C, 72.96; H, 9.17. Calcd for $C_{22}H_{32}O_4$: C, 73.30; H, 8.95.

Reduction of Product 8. A solution of product **8** (300 mg) in 15 mL of EtOH was treated with 50 mg of $NaBH_4$.The mixture was stirred for 8 h at room temperature. The solution was slowly acidified with HCl, diluted with water, and extracted with CH_2Cl_2. The organic layer was treated with $MgSO_4$ and concentrated under vacuum. After CC, 75 mg of **4** (25%) and 210 mg of *ent*-1β-acetoxy-15α,16α-epoxy-12β-hydroxybeyerane (**9**, 70%) were obtained. **9**: mp 140–42 °C; $[\alpha]_D$ +0.8° ($CHCl_3$, *c* 1); IR ν_{max} (neat, cm^{-1}) 3469, 1735, 1703, 1256; ^1H NMR δ 4.49 (1 H, dd, J_1 = 5.1 Hz, J_2 = 10.6 Hz), 3.50 (1 H, dd, J_1 = 9.7 Hz, J_2 = 6.6 Hz), 3.38 (1 H, d, J = 3.0 Hz), 3.26 (1 H, d, J = 3.0 Hz), 1.90 (3 H, s), 1.10, 1.09, 0.85, and 0.83 (3 H each, s); ^{13}C NMR see Table 1; CIMS, m/z (%) $[M + 1]^+$ 363 (6), 362 (7), 345 (29), 303 (56), 285 (100). Anal. Found: C, 72.52; H, 9.85. Calcd for $C_{22}H_{34}O_4$: C, 72.89; H, 9.45.

Reduction of Product 8 with BD_4Na. A 300 mg sample of product **8** was dissolved in 15 mL of EtOH, 50 mg of $NaBD_4$ was added at room temperature, and the mixture was worked up as indicated above to obtain 210 mg of *ent*-1β-acetoxy-12α-deutero-15α,16α-epoxy-12β-hydroxybeyerene (**10**, 70%) [mp 210–12 °C; $[\alpha]_D$ +4.2° ($CHCl_3$, *c* 1); IR ν_{max} (neat, cm^{-1}) 3436, 1712, 1247; ^1H NMR δ 4.52 (1 H, dd, J_1 = 4.5 Hz, J_2 = 10.0 Hz), 3.40 (1 H, d, J = 3.1 Hz), 3.27 (1 H, d, J = 3.1 Hz), 2.0 (3 H, s), 1.12, 1.11, 0.87, and 0.85 (3 H each, s); ^{13}C NMR see Table 2; CIMS, m/z (%) $[M + 1]^+$ 364 (0.7), 346 (28), 304 (64), 286 (100). Anal. Found: C, 72.73; H, 8.81. Calcd for $C_{22}H_{33}DO_4$: C, 72.69; H, 9.15.] and 75 mg of 78 *ent*-1β-acetoxy-12β-deutero-15α,16α-epoxy-12α-hydroxybeyerane (**11**, 25%) [mp 228–30 °C; $[\alpha]_D$ +6.0° ($CHCl_3$, *c* 1); IR ν_{max} (neat, cm^{-1}) 3493, 1713, 1247; ^1H NMR δ 4.51 (1 H, dd, J_1 = 4.8 Hz, J_2 = 10.7 Hz), 3.36 (1 H, d, J = 3.0 Hz), 3.00 (1 H, d, J = 3.0 Hz), 2.00 (3 H, s), 1.07, 1.05, 0.87 ,and 0.84 (3 H each, s); ^{13}C NMR see Table 2; CIMS, m/z (%) $[M + 1]^+$ 364 (11), 346 (13), 304 (78), 286 (100). Anal. Found: C, 72.50; H, 8.76. Calcd for $C_{22}H_{33}DO_4$: C, 72.69; H, 9.15.]

Rearrangement of Product 9. An amount of 200 mg of product **9** was treated with ruthenium acetylacetonate for 3 h with the above indicated reaction conditions and directly chromatographed to give 20 mg of product **5** (10%), 50 mg of product **6** (25%), 70 mg of *ent*-1β-acetoxy-14α-hydroxy-(16*R*)-kauran-12-one (**12**, 35%) [mp 198–200 °C; $[\alpha]_D$ −6.8° ($CHCl_3$, *c* 1); IR ν_{max} (neat, cm^{-1}) 3457, 1738, 1711, 1237; ^1H NMR δ 4.55 (1 H, dd, J_1 = 5.3 Hz, J_2 = 10.3 Hz), 4.22 (1 H, d, J = 3.0 Hz), 2.70 (1 H, d, J = 17.0 Hz) 2.52 (1 H, br s), 2.50 (1 H, dd, J_1 = 17.0 Hz, J_2 = 10.2 Hz), 2.06 (3 H, s), 1.16 (3 H, d, J = 7.1 Hz), 0.93, 0.86, and 0.79 (3 H each, s); ^{13}C NMR see Table 2; CIMS, m/z (%) $[M + 1]^+$ 363 (1.3), 345 (1.5), 303 (100). Anal. Found: C, 72.77; H, 9.73. Calcd for $C_{22}H_{34}O_4$: C, 72.89; H, 9.45.] and 10 mg of *ent*-1β-acetoxy-13(12→11)-*abeo*-beyer-15-en-12-one **13** (5%) [mp 190 °C dec; $[\alpha]_D$ −48.0° ($CHCl_3$, *c* 1); IR ν_{max} (neat, cm^{-1}) 1735, 1240, 1028; ^1H NMR δ 9.46 (1 H, d, J = 6.6 Hz), 6.20 (1 H, d, J = 5.6 Hz), 5.88 (1 H, d, J = 5.6 Hz), 4.53 (1 H, dd, J_1 = 6.0 Hz, J_2 = 10.3 Hz), 2.60 (1 H, dd, J_1 = 6.6 Hz, J_2 = 9.3 Hz), 2.12 (1 H, d, J = 9.3 Hz), 1.92 (3 H, s), 1.15, 0.98, 0.89, and 0.85 (3 H each, s); ^{13}C NMR see Table 2; EIMS, m/z (%) $[M]^+$ 344 (1.5), 284 (7.0), 269 (8.3), 93 (100). Anal. Found: C, 76.38; H, 9.64. Calcd for $C_{22}H_{32}O_3$: C, 76.70; H, 9.36.]

Rearrangement of Product 10. A 200 mg sample of product **10** was treated with ruthenium acetylacetonate for 3 h with the above indicated reaction conditions and directly chromatographed to give 20 mg of *ent*-1β-acetoxy-12β-deutero-12,14α-dihydroxykaur-15-ene (**14**, 10%) [mp 217–19 °C; $[\alpha]_D$ 0.0° ($CHCl_3$, *c* 1); IR ν_{max} (neat, cm^{-1}) 3416, 1713, 1244; ^1H NMR δ 5.07 (1 H, br s), 4.55 (1 H, dd, J_1 = 5.2 Hz, J_2 = 10.5 Hz), 3.94 (1 H, br s), 2.65 (1 H, br s), 2.00 (3 H, s), 1.82, 1.13, 0.85 and 0.81 (3 H each, s); ^{13}C NMR see Table 2; EIMS, m/z (%) $[M]^+$ 363 (0.2), 303 (5.4), 288 (2.0), 285 (3.5), 43 (100). Anal. Found: C, 72.60; H, 8.83. Calcd for $C_{22}H_{33}DO_4$: C, 72.69; H, 9.15.], 40 mg of *ent*-1β-acetoxy-12β-deutero-12α,14α-dihydroxy-kaur-16-ene (**15**, 25%) [mp 228–30 °C; $[\alpha]_D$ −6.9° ($CHCl_3$, *c* 1); IR ν_{max} (neat, cm^{-1}) 3402, 1732, 1242 cm^{-1}; ^1H NMR δ 4.96 (2 H, br s), 4.50 (1 H, dd, J_1 = 5.1 Hz, J_2 = 10.6 Hz) 4.00 (1 H, br s), 2.65 (1 H, br s), 1.98 (3 H, s), 1.10, 0.86, and 0.80 (3 H each, s); ^{13}C NMR see Table 2; EIMS, m/z (%) $[M]^+$ 363 (0.2), 303 (7.1), 285 (5.6), 267 (2.6), 43 (100). Anal. Found: C, 72.76; H, 8.78. Calcd for $C_{22}H_{33}DO_4$: C, 72.69; H, 9.15.], 70 mg of *ent*-1β-acetoxy-16α-deutero-14α-hydroxykauran-12-one (**16**, 35%) [mp syrup; $[\alpha]_D$ +4.2° ($CHCl_3$, *c* 1); IR ν_{max} (neat, cm^{-1}) 3456, 1735, 1706, 1237; ^1H NMR δ 4.55 (1 H, dd, J_1 = 5.3 Hz, J_2 = 10.3 Hz), 4.22 (1 H, br s), 2.70 (1 H, d, J = 17.1 Hz), 2.52 (1 H, br s), 2.49 (1 H, dd, J_1 = 17.1 Hz, J_2 = 10.2 Hz) 2.06 (3 H, s), 1.15, 0.93, 0.86, and 0.79 (3 H each, s); ^{13}C NMR see Table 2; EIMS, m/z (%) $[M]^+$ 363 (0.8), 303 (5.0), 286 (7.5), 268 (7.3), 43 (100).], and 10 mg of *ent*-1β-acetoxy-12-deutero-13(12→11)-*abeo*-beyer-15-en-12-one (**17**) (5%) [mp 190 °C dec; $[\alpha]_D$ −50.0° ($CHCl_3$, *c* 1); IR ν_{max} (neat, cm^{-1}) 1735, 1242; ^1H NMR δ 6.20 J = 5.5 Hz), 5.88 (1 H, d, J = 5.5 Hz), 4.43 (1 H, dd, J_1 = 5.9 Hz, J_2 = 10.2 Hz), 2.59 (1 H, d J = 9.3 Hz), 2.12 (1H, d, J = 9.3 Hz) 1.92 (3 H, s), 1.15, 0.97, 0.89, and 0.85 (3 H each, s); ^{13}C NMR see Table 2; EIMS, m/z (%) $[M]^+$ 345 (1.7), 285 (7.3), 270 (8.5), 255 (2.6), 93 (100). Anal. Found: C, 76.31; H, 8.68. Calcd for $C_{22}H_{31}DO_3$: C, 76.48; H, 9.04.]

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Supplementary Material Available: Copies of ^1H NMR spectra of **4**, **7**, and **16** (3 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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