aluminum hydride; *tert*-butyl alcohol, dimethyl sulfoxide, pyridine, and hexamethylphosphoramide (HMPA) were distilled from calcium hydride; dichloromethane, carbon tetrachloride, diodomethane, and methyl iodide were distilled from phosphorus pentoxide; ammonia was distilled from the tank and then from a blue lithium or sodium solution; acetone was analytical reagent grade distilled from potassium permanganate; formic acid was distilled from boric anhydride. "Petroleum ether" refers to the "Analyzed Reagent" grade hydrocarbon fraction, bp 30–60°, which is supplied by J. T. Baker Co., Phillipsburg, N.J., and was not further purified.

Reactions described as run under nitrogen or argon employed a mercury bubbler arranged so that the system could be alternately evacuated and filled with the inert gas and left under a positive pressure.

Microanalyses were performed by Spang Microanalytical Laboratory, Ann Arbor, Mich.

(32) In cases where products were isolated 'by solvent extraction", the procedure generally followed was to extract the aqueous layer with several portions of the indicated solvent; then the organic layers were combined and washed with water, followed by saturated brine. The organic layer was dried over anhydrous sodium or magnesium sulfate, then filtered, and the solvent was evaporated from the filtrate under reduced pressure (water aspirator) using a rotary evaporator. The use of the terms "base wash" or "acid wash" indicate washing the combined organic layers with saturated aqueous sodium bicarbonate solution or with dilute aqueous hydrochloric acid, respectively, prior to the aforementioned washing with water.

(33) F. Uhlig and H. R. Snyder, *Adv. Org. Chem.*, **1**, 35 (1960).

(34) Preparative GLC under the same conditions described above[31] except that the following columns were used: (a) 5% SE-30 on Chromosorb W AW-DMCS (6 ft × 0.125 in); (b) 10% Carbowax 20M on Chromosorb W AW-DMCS (10 ft × 0.25 in).

(35) For spectra, see R. I. Trust, Ph.D. Thesis, California Institute of Technology, 1974.

(36) A. J. C. Wilson, *Nature (London)*, **150**, 152 (1942).

(37) E. R. Howells, D. C. Phillips, and D. Rogers, *Acta Crystallogr.*, **3**, 210 (1950).

(38) D. J. Duchamp, Program and Abstracts, ACA Meeting, Bozeman, Mont., 1964, Paper B-14, p 29.

(39) J. Karle and H. Hauptmann, *Acta Crystallogr.*, **3**, 181 (1950).

(40) See paragraph at end of paper regarding supplementary material.

Rearrangements in the Photolevopimaric Acid Series. A Paradigm of Bicyclo[2.2.0]- and Bicyclo[2.1.1]hexane Chemistry[1,2]

Werner Herz,* M. Gopal Nair, and Doraiswamy Prakash

Department of Chemistry, The Florida State University, Tallahassee, Florida 32306

Received October 15, 1974

Unexpected rearrangements of photolevopimaric acid derivatives are described. Hydroboration–oxidation of methyl levopimarate (**3c**) gave the previously reported *exo*-bicyclo[2.2.0]hexanol **7a** and a new tertiary alcohol **12a** which was prepared independently from the epoxide **5**. Treatment of **5** with Lewis acids resulted in rearrangement to **6**. Mercuric acetate oxidation of **3c** resulted in conversion to **13**. Contrary to an earlier report, Jones oxidation of **7a** proceeded with rearrangement to the bicyclo[2.1.1]hexanone **20**, whose structure was established by degradation to the cyclopentanone **30**, acid cleavage to **35**, base-catalyzed cleavage to **36**, and degradation of the latter to the drimane derivative **38**. Treatment of the *endo*-bicyclo[2.1.1]hexyl tosylate **23a** with tosyl chloride resulted in rearrangement to a bicyclo[3.1.0]hexane derivative, the new resin acid isomer methyl isophotolevopimarate (**39**). An unusual oxidation of the *exo*-bicyclo[2.2.0]hexanol **7a** to the lactone **14a** and **14b** with Fétizon's reagent was observed. Solvolytic reactions of the *exo*-bicyclo[2.2.0]hexyl tosylate **7c** resulted in rearrangement to the bicyclo[2.1.1]hexane derivatives **44** and **45**.

The observations which are described in the present report are the result of work originally aimed at the synthesis of 14-deuteriolevopimaric acid (**1b**). This substance was desired to help clarify the nature of the intramolecular hydrogen transfer which occurs on irradiation of the levopimaric acid–cyclopentenedione adduct **2**,[3,4] a problem which was eventually solved by X-ray analysis of one of the photolysis products.[5]

The simplest path to **1b** appeared to be introduction of deuterium in some fashion at C-14 of the photolevopimaric acid skeleton **3a**, since thermal reversion of the valence isomerization **1a** → **3a**[6,7] has been described.[7] The rearrangements which negated this approach and will be described in this report constitute not only an instructive paradigm of bicyclo[2.2.0]- and bicyclo[2.1.1]hexane chemistry, but illustrate several other unusual reactions which presumably occur because these strained systems are part of a relatively rigid diterpene skeleton. See Scheme I.

Attempts to Prepare Bicyclo[2.2.0]hexanone 8. Our failure to effect direct introduction of deuterium into **3c**[8a] forced us to investigate more circuitous routes to **3d** by way of **8**, which are outlined in Scheme II. The preparation of **8** from **7a** has been reported previously[7]; although Dauben and Coates did not discuss the stereochemistry of **7a** and **8**, it seemed likely that these substances possessed the configurations indicated in Scheme II, thus necessitating further reduction of **8** to **9**, which has the correct stereochemistry for bimolecular elimination to **3d**. However, as the reported[7] overall yield of **8** was rather low, we first explored its preparation from the epoxide **5**.

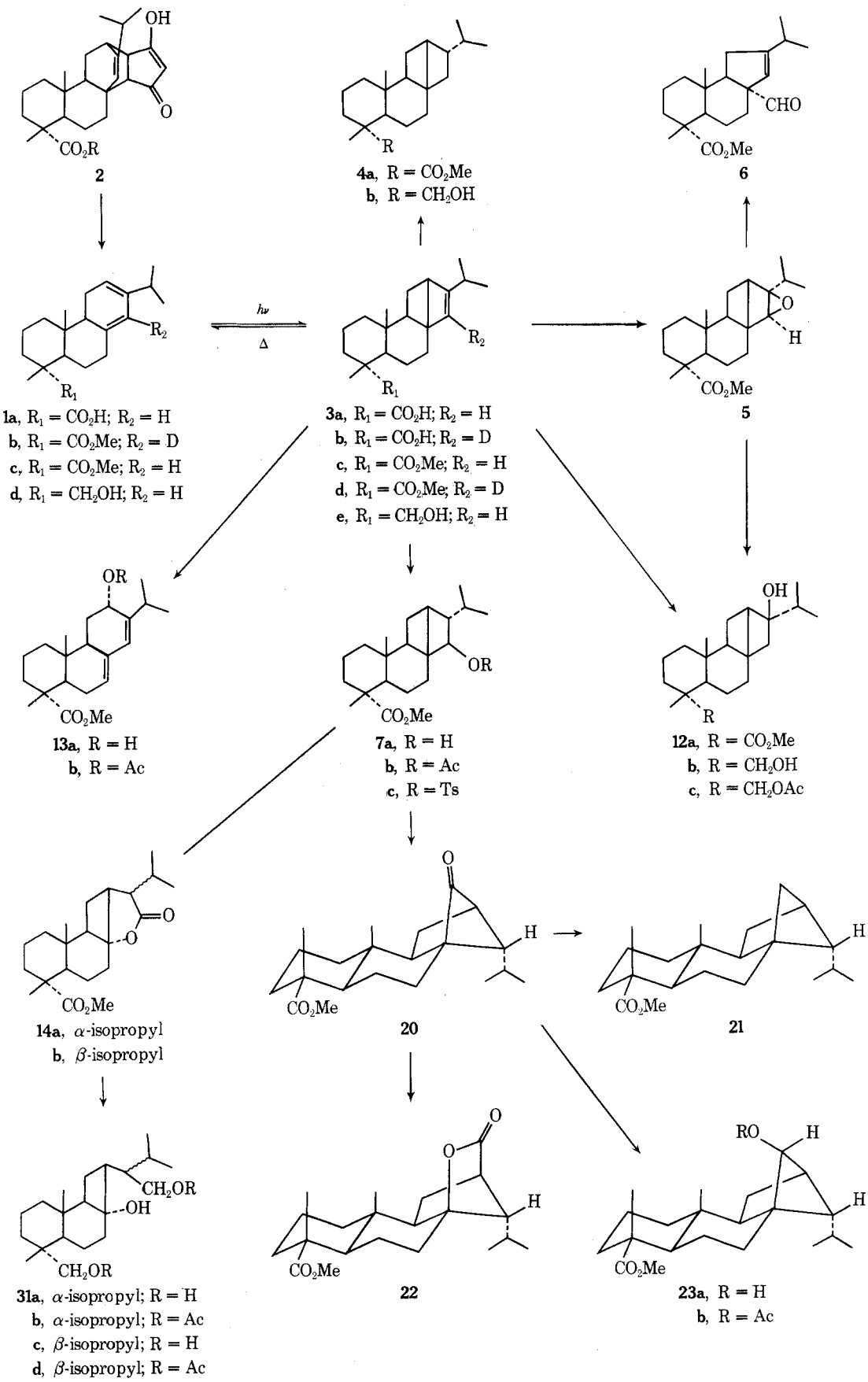
This substance, isolated in 81% yield, was assigned the exo configuration depicted in Scheme II because of the appearance of H-14 as a narrowly split doublet (J = 2.5 Hz) at 3.82 ppm. The W arrangement for such long-range coupling of H-14 to H-12 is achieved only if H-14 is α; this is also consonant with the deduction, from models, that the least hindered side of **3c** is the β face.

Treatment of **5** with acidic reagents generally produced complex mixtures which resisted attempts at separation, but contained no fraction corresponding to **8**. On the other hand, use of boron trifluoride etherate under carefully defined conditions resulted in rearrangement (64% yield) to an unsaturated aldehyde (sharp singlet at 9.3 ppm, broadened vinylic singlet, $W_{1/2}$ = 6.6 Hz, at 5.83 ppm). This substance was assigned structure **6**, formally derivable by the shifts depicted in Scheme III, rather than **10** for the following reason.

By sweeping the methylene region of the ^{1}H NMR spectrum, the center of the H-15 signal was found at 2.07 ppm. Irradiation at this frequency collapsed the isopropyl methyl doublets at 0.90 and 1.06 ppm to singlets and sharpened the vinyl proton signal ($W_{1/2}$ = 2.5 Hz). The existence of allylic coupling between the vinyl proton and H-15 was thus established, an observation which excludes structure **10**. The α configuration of the aldehyde is deduced on mechanistic grounds; an upfield shift of the C-10 methyl resonance to 0.86 ppm may be attributed to the shielding effect of the 12,13 double bond.

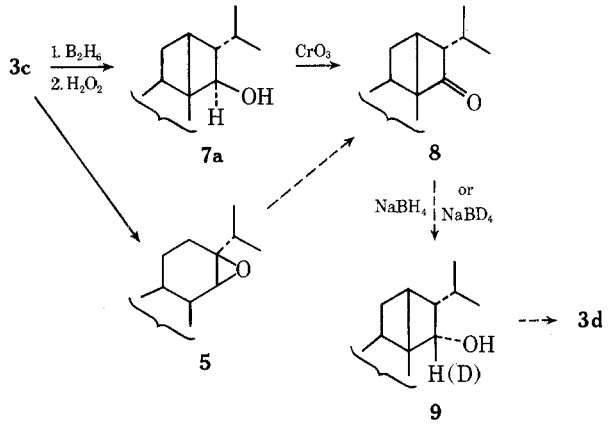
As a result of this rearrangement we returned to Dauben and Coates' method of preparing **8**. Slight modifications in

Scheme I

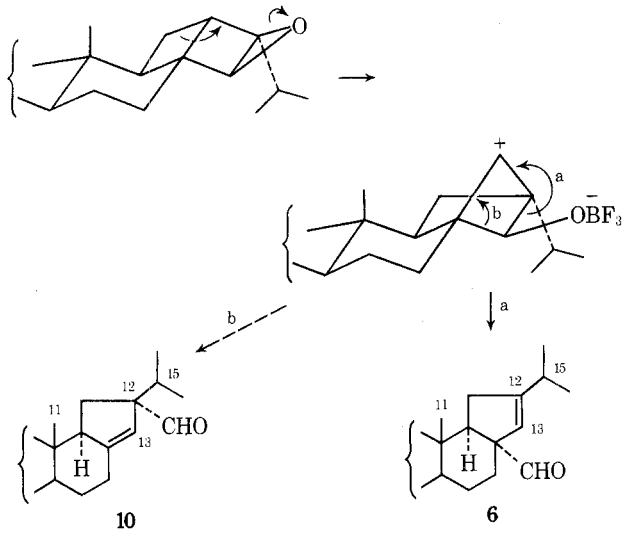


the isolation procedure resulted in an improved yield (67%) of alcohol **7a**, whose stereochemical assignment was based not only on the assumption that cis addition of the reagent takes place from the least hindered, β face of **3c**, but also on the appearance of the H-14 resonance (doublet, J = 7 Hz, at 4.06 ppm in **7a** and at 5.16 ppm in **7b**) which indicated that H-13 and H-14 were trans. Contrary to the literature report,[7] however, there was also formed an appreciable

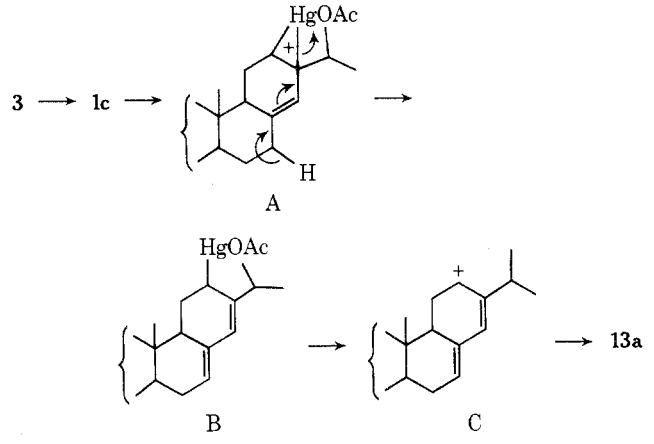
Scheme II



Scheme III



Scheme IV



amount (27%) of a tertiary alcohol **12a,** whose structure was confirmed by $LiAlH_4$ reduction to **12b,** the same substance being formed by $LiAlH_4$ reduction of **5.**

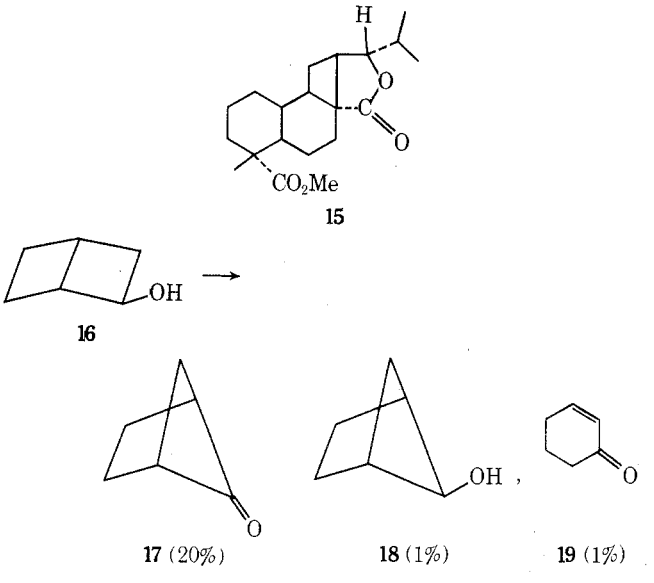
The surprising formation of a tertiary alcohol in appreciable quantity during the normally much more regioselective hydroboration reaction may be attributed to the high reactivity of the bicyclo[2.2.0]hexene system of **3c** as the result of excessive strain which "decreases the activation energy of the addition process, thereby making the transition state more reactant-like and, hence, less sensitive to steric and polar factors" as has been claimed[10] in a somewhat similar situation, i.e., the hydroboration of bicyclo[3.3.1]nonene, which also furnishes a mixture of isomeric alcohols.

An attempt to prepare **12a** independently from **3c** by the oxymercuration–demercuration reaction did not result in the formation of the expected alcohol, but gave a mixture of **13** (62%)[11] and methyl levopimarate (**1c,** 22%). Since omission of $NaBH_4$ or treatment of methyl levopimarate with mercuric acetate gave the same mixture of **1c** and **13,** the reaction probably proceeds as outlined in Scheme IV. Such a scheme was proposed earlier[12] to account for the products obtained on treatment of cholesta-6,8(9)-dien-3-ol *p*-nitrobenzoate with mercuric acetate.

Repetition of the literature oxidation of **7** to **8** with Jones reagent gave a single substance in 90% yield which had properties identical with those described by Dauben and Coates[7] and whose previously unreported ^1H NMR spectrum was, on the whole, consonant with structure **8** assigned by them (Scheme II) except for an inexplicable upfield shift of the C-10 methyl resonance (from 1.02 ppm in **7** to 0.78 ppm in **8**). Hydride reduction of the ketone led to a new alcohol which was initially presumed to be alcohol **9.**

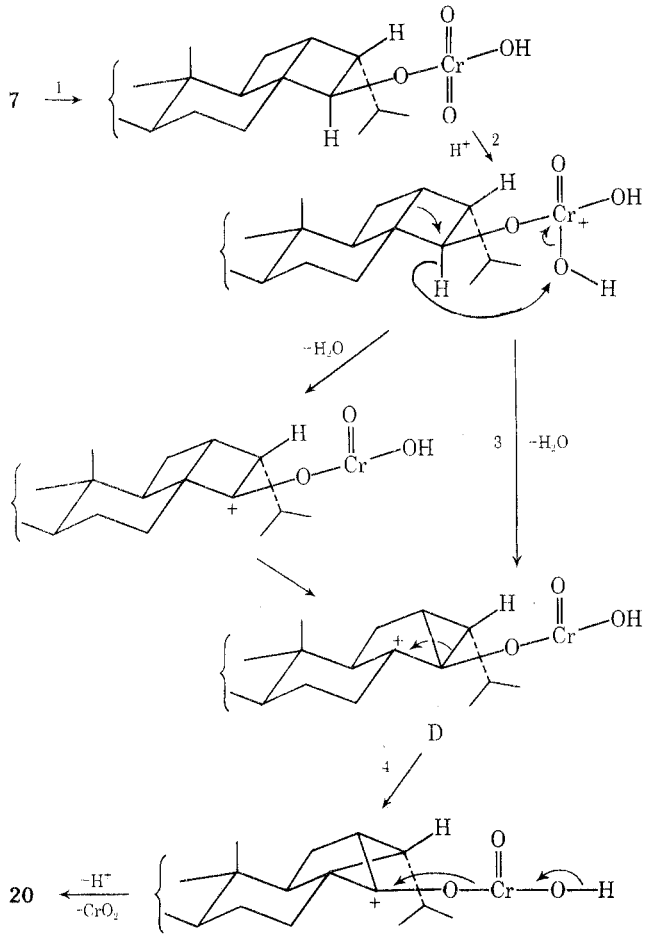
Subsequent transformations of these two substances, however, did not yield products to be expected on the basis of the postulated structures. Of special importance was the observation that the lactone obtained by Baeyer–Villiger oxidation of the ketone was not identical with either of the authentic lactones **14a** and **14b** (vide infra) nor was the ^1H NMR spectrum of this lactone compatible with formula **15.** Moreover, conversion of the ketone to a thioketal followed by nickel desulfurization gave a gummy but homogeneous saturated ester different in all respects from authentic crystalline methyl dihydrophotolevopimarate (**4a**). It was clear, therefore, that the structures of **8** and **9** required revision and that an entirely unexpected rearrangement had taken place during the oxidation of **7.**

A clue to the situation was provided by a recent observation[13] that *exo*-bicyclo[2.2.0]hexan-2-ol (**16**) undergoes oxidative rearrangement under Oppenauer conditions, albeit in low yield, to a mixture of **17, 18,** and **19,** the driving force

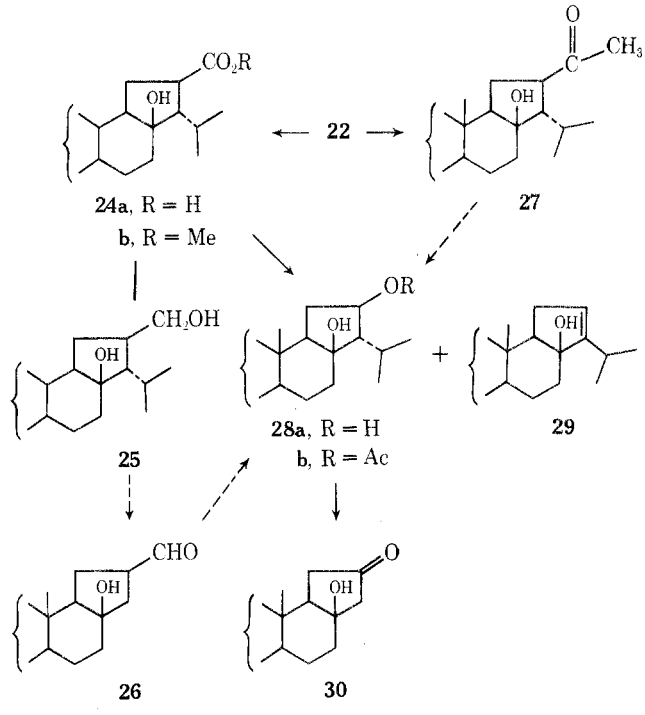


of the rearrangement being attributed to the greater strain in the bicyclo[2.2.0] system as compared with the strain in the bicyclo[2.1.1] system. If **7** undergoes a similar oxidative rearrangement under the influence of the Jones reagent, the structure of the resulting ketone reagent should be **20.** The thioketal desulfurization product would be **21,** the Baeyer–Villiger product would be **22,** and the alcohol produced by hydride reduction of the ketone would be **23** be-

Scheme V



Scheme VI



cause approach of the reagent from the side of the C-10 methyl group would be severely hindered.

A possible mechanism for the formation of **20** (Scheme V) involves transfer of hydride ion to reagent accompanied, for stereoelectronic reasons, by migration of the 8,12, not the 8,9, bond, the driving force for this being the formation of the more stable bicyclo[3.1.0]hexyl cation D.[14] Concomitant or subsequent migration of the 13,14 bond, necessarily from the bottom face of the molecule, would give **20.** Alternatively, initial transfer of hydride ion without 8,12-bond migration might first lead to the bicyclo[2.2.0]hexyl cation E, which could undergo a series of Wagner–Meerwein shifts; however, even here some degree of participation by the 8,12 σ bond to maintain maximum overlap with the developing p orbital on C-8 will probably have to be invoked.[19]

Formula **20** also provides a ready explanation for the upfield shift of the C-10 methyl group to which allusion has been made earlier, since it is now shielded by a one-carbon bridge.[20] Oxidation to **22** produces a downfield shift to 0.90 ppm and reduction to **23** a downfield shift to 1.08 ppm, both understandable if lactone and hydroxyl groups were situated on the β face as required by the formulas.

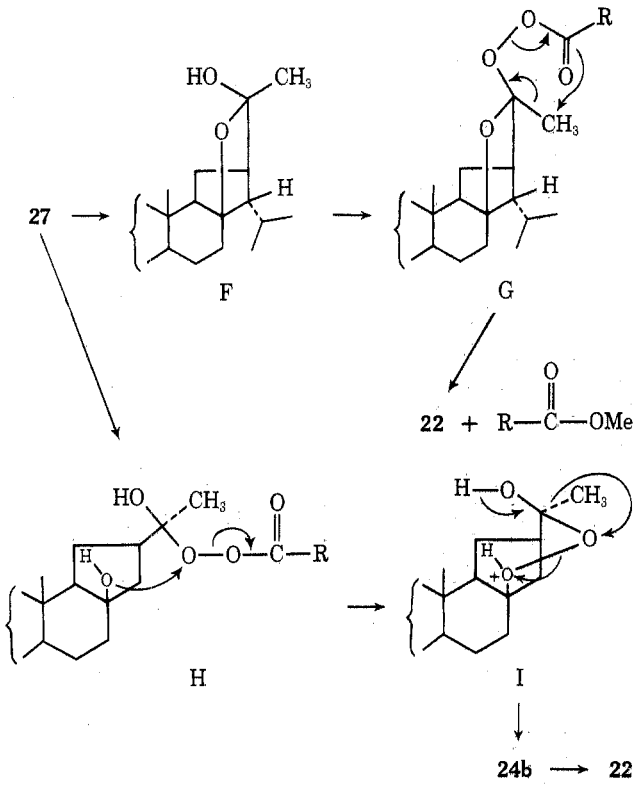
Structure Proof of Bicyclo[2.1.1]hexanone 20. To confirm the presence of a bicyclo[2.1.1]hexanone system in **20,** degradation of lactone **22** to a product exhibiting the spectral characteristics of a cyclopentanone was undertaken as outlined in Scheme VI. Reduction of **24a** with B_2H_6–THF complex[21] gave diol **25** in 72% yield, but treatment of the latter with various oxidizing agents merely resulted in regeneration of **22** instead of formation of the hoped-for **26,** possibly by way of a transitory hemiacetal (but see discussion in the next paragraph).

In exploration of an alternative route to **28b,** reaction of **22** with 1.5 equiv of methyllithium gave the methyl ketone **27** (56%).[22a] However, exposure of the latter to *m*-chloroperbenzoic acid resulted, very surprisingly, again in isolation of lactone **22.** This might conceivably be rationalized by assuming that **27** is in equilibrium with the hemiketal F (Scheme VII) and that esterification of the latter by peracid to G and decomposition by way of a cyclic transition state leads to the observed product. However, the ir spectrum shows that **27** is entirely in the ketone form as might be expected, since molecular models indicate that in the preferred conformation of **24b** and **27** the hydroxyl group at C-8 and the substituent at C-12 are oriented away from each other. "Flipping" of the five-membered ring to a less stable conformation which brings the substituents at C-8 and C-12 closer would not be expected to occur except at higher temperatures or in a situation where the equilibrium **27** $\rightleftarrows$ F, normally unfavorable to F, is displaced toward the right by further reaction.[22b]

A situation somewhat more favorable to participation by the hydroxyl group is pictured in the second row of Scheme VII. Approach of the bulky peracid molecule to the carbonyl group from the least hindered side of **27** would give rise to intermediate H. The tertiary hydroxyl group may now participate in decomposition of H to give species I. Molecular models of I indicate that the bond linking the methyl group to C-14 is trans-antiparallel to the –O–O– bond; thus collapse of I with preferential methyl migration, rather than 12,14 σ bond migration, could occur to give **24b.** The latter might undergo transesterification to give lactone **22,** although this would again require prior "flipping" to an unfavorable conformation. That this is a possibility is shown by the formation of **22** from **24b** at elevated temperatures.

Finally, oxidative decarboxylation of **24a** with lead tetraacetate in benzene afforded a mixture of **22** (27%), **29** (10%), and **28b** (3%), the acetate group in **28b** being assigned the β orientation because of the coupling constants exhibited by the H-12 signal at 5.01 ppm.[22] Repeated recycling of lactone **22** permitted accumulation of a sufficient quantity of **28b** for hydrolysis to **28a** (H-12 signal at 4.21 ppm) and subsequent oxidation ($CrO_3 \cdot 2Py$) to hydroxycy-

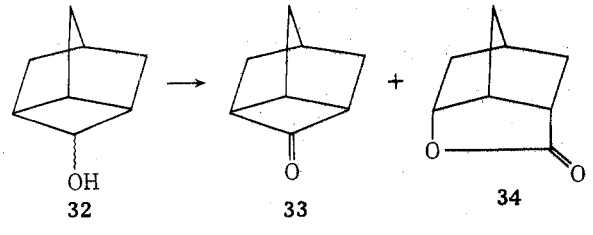
Scheme VII



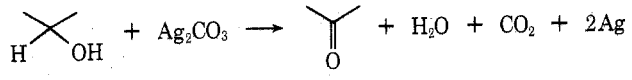
clopentanone **30**, which had ir bands at 3615 (hydroxyl), 1739 (cyclopentanone), and 1728 cm^{-1} (carbomethoxy group). Thus, the structure of ketone **20** was securely established.

To avoid the rearrangement encountered during the chromic acid oxidation of **7a**, the action on **7a** of dimethyl sulfoxide in combination with various other reagents[23] was also investigated; however, this invariably led to recovery of starting material. Treatment of **7a** with silver carbonate on Celite[24] again did not yield the desired **8** but resulted in formation of a lactone **14a** (Scheme I, 73% yield, new ir band at 1772 cm^{-1}), which was converted to an epimer **14b** on treatment with base. This is in accord with stability relationships deduced from Dreiding models. These indicate that **14a** contains an interaction between H-11α and one of the methyls of the isopropyl group which is relieved in **14b**. The isomeric lactones were reduced to the triols **31a** and **31c**, which were characterized as the isomeric diacetates **31b** and **31d**.

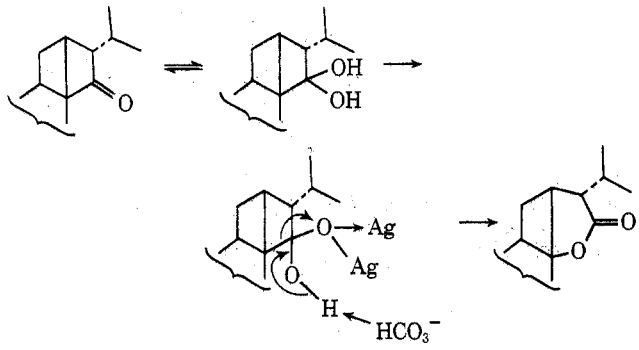
The unusual oxidation of a secondary alcohol to a γ-lactone with silver carbonate–Celite has one precedent.[25] Oxidation of the *exo*- and *endo*-tricyclo[3.2.1.0^{36}]octan-4-ols **32** with this reagent under anhydrous conditions afforded a mixture of ketone **33** and lactone **34** in yields of 69 and 31%,



respectively. It was proposed that lactone **25** was formed via the hydrated form of ketone **33**, since treatment of the ketone with moist reagent gave an 11% yield of the lactone. Presumably, the water required for the hydration of **33** under anhydrous conditions was that liberated in the overall equation[26] below.

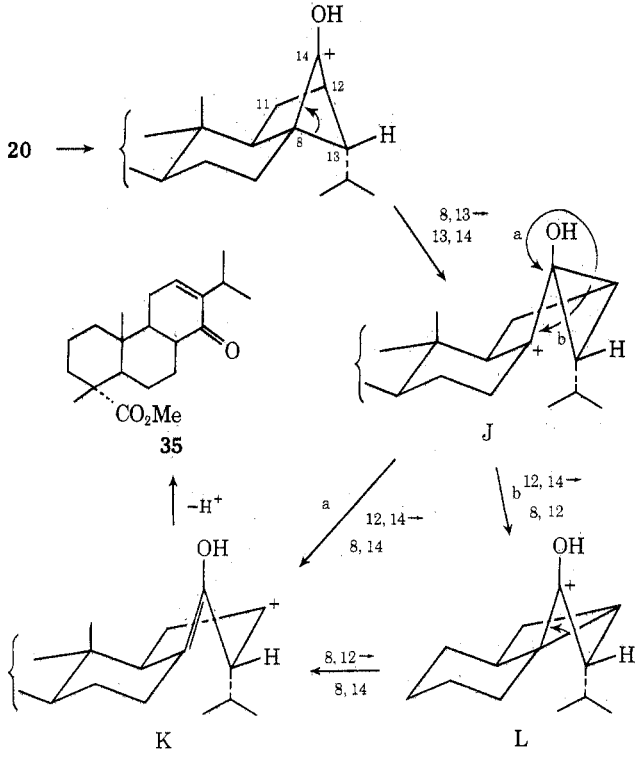


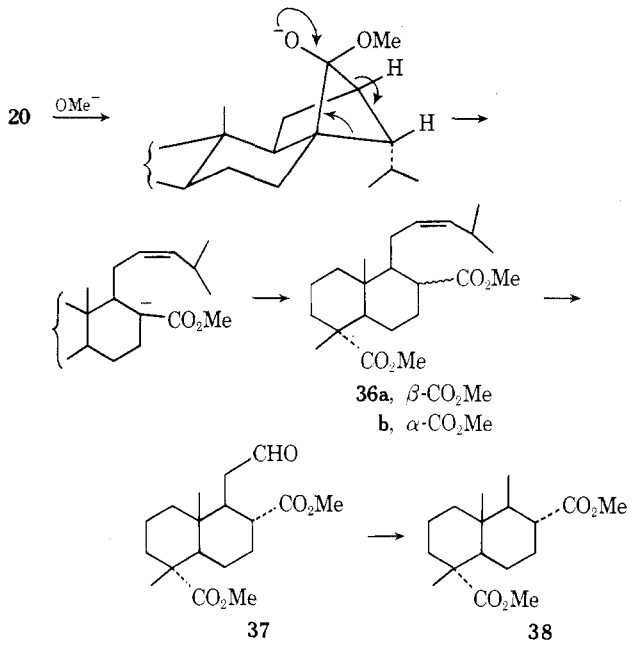
In the present instance, the complete conversion of **7a** to lactone **14a** may perhaps be due to the high reactivity of the intermediate bicyclo[2.2.0]hexanone **8**, which is in equilibrium with its hydrated form and undergoes further oxidation as illustrated.[26]



Rearrangement of Bicyclo[2.1.1]hexanone 20. Additional reactions of ketone **20** which are in agreement with its formulation as a bicyclo[2.1.1]hexan-5-one will now be described. Solution of **20** in chloroform saturated with HCl resulted in formation of an α,β-unsaturated ketone which was identified as **35**, a substance previously prepared in our laboratory.[27] Its formation from **20** can be rationalized in terms of a series of Wagner–Meerwein shifts (Scheme VIII) similar to those postulated for the acid-induced rearrangement of some simpler cyclobutanones.[28] The cyclopropyl carbinyl cation J, formed by initial migration of the 8,13 bond, could be converted to homoallylic ion K, and thence to **35**, either directly (path a) or by way of the protonated bicyclo[2.2.0]hexanone L which, because of its high reactivity (vide supra), undergoes further rearrangement (path b).

Scheme VIII





Treatment of the nonenolizable ketone **20** with sodium methoxide resulted in cleavage to a mixture of epimeric unsaturated esters **36a** and **36b** which could be separated by preparative TLC. Hydrogenation of the mixture afforded a mixture of two saturated esters, an observation which demonstrated that the two products were not cis–trans or double-bond isomers. Equilibration with base converted **36a** (carbomethoxy group axial) quantitatively to **36b** (carbomethoxy group equatorial).

Haller–Bauer cleavage of a nonenolizable ketone normally results in cleavage of one of the bonds adjacent to the carbonyl group, the resultant carbanion being discharged by reaction with a proton donor.[29] In the present instance, the driving force leading to formation of **36** may be attributed to stabilization of the final anion by the carbomethoxy group after additional cleavage of the five-membered ring, the composition of the final product being due at least partially to kinetic control.[30]

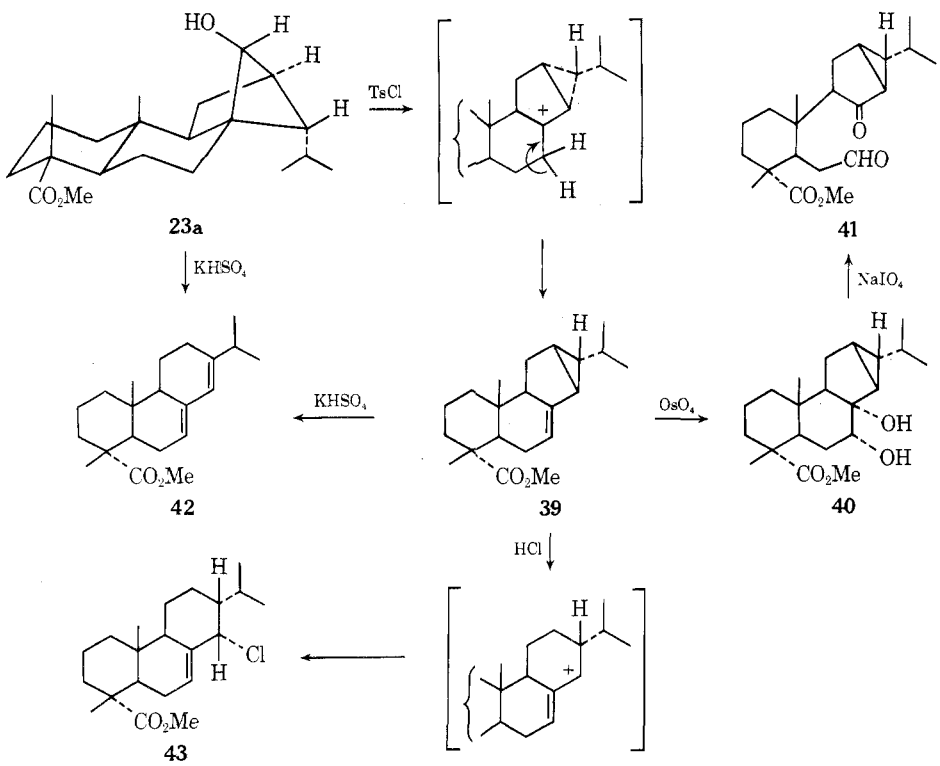
Proof for the nature of the unsaturated side chain was obtained by further degradation. Ozonolysis of **36b** gave a saturated aldehyde **37** containing the partial structure $-CH_2CHO$ (aldehyde triplet at 9.4 ppm). Decarbonylation of this substance with tris(triphenylphosphine)rhodium chloride yielded the drimane derivative **38** whose ^1H NMR spectrum, in addition to the C-4 and C-10 methyl resonances, exhibited a doublet at 1.21 ppm (J = 6 Hz) for the methyl group attached to C-9.[30] Thus, the double bond of **36b** is two carbon atoms removed from ring B, a situation which requires attachment of a five-membered ring to C-8 and C-9 of the precursor ketone **20.**

Solvolytic Rearrangement of Bicyclo[2.1.1]hexanol 23. The endo configuration of alcohol **23a** was deduced on steric grounds and is supported by analysis of the ^1H NMR spectrum of **23a** and its derived acetate. The appearance of the H-14 signal (sharp doublet, J = 3 Hz) is in accordance with the H-12, H-14 dihedral angle measured on models (45–50°) as is the absence of long-range coupling to H-13 which would be expected in an endo alcohol. Additional chemical evidence was provided by its solvolysis.

Treatment of **23a** with *p*-toluenesulfonyl chloride–pyridine did not result in formation of a tosylate; instead, there was isolated a new isomer **39** of methyl photolevopimarate which was named methyl isophotolevopimarate. The presence of a double bond in **39** was evident from the ^1H NMR spectrum, which exhibited a broadened singlet at 5.3 ppm, different from that of H-14 in the ^1H NMR spectrum of **3b** and similar in appearance and chemical shift to the H-7 signal of 7-abietenes, hence obviously coupled to two other protons. The isopropyl signals had remained unaffected by this transformation; thus, an obvious possibility for the new compound was the cyclopropane derivative **39,** a more complex relative of the bicyclo[3.1.0]hexane derivatives which are found among the solvolysis products of *endo*-bicyclo[2.1.1]hexyl 5-tosylate.[31]

Further spectroscopic evidence for formula **39** was diffi-

Scheme IX



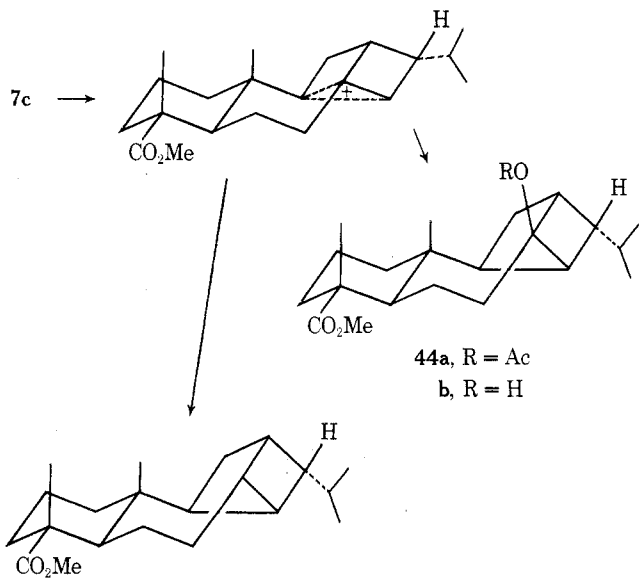
cult to adduce, since signals of the cyclopropyl protons were obscured by the methylene envelope and the uv spectrum displayed only end absorption. However, the transformations outlined in Scheme IX provided adequate proof.

Osmylation of **39** furnished a diol which was assigned stereochemistry **40**. Earlier work on osmylation of abietenes[32-34] resulted in osmylation from the α or the β face depending on the conformation of starting material; models of **39** suggested that α-osmylation would be preferred. This was borne out by the ^{1}H NMR spectrum, which displayed the H-7 signal as a triplet (J = 8 Hz), compatible only with α orientation of the 7-hydroxyl, and the C-10 methyl signal at 0.86 ppm, appropriate for an α-oriented 8-hydroxyl group.[34] Periodate cleavage of **40** gave **41** (aldehyde triplet at 9.6 ppm); unfortunately, no firm conclusions could be drawn from the uv spectrum, which exhibited little evidence of conjugation.

Acid-catalyzed cleavage, however, provided conclusive proof for the presence of a cyclopropane ring. Treatment with HCl gave a substance $C_{21}H_{33}O_2Cl$ (**43**) (mass spectrum) which displayed a one-proton peak in the vinyl region similar to that of **39** itself and a broadened one-proton singlet at 4.46 ppm ($W_{1/2}$ = 6 Hz) assignable to H-14. This is the result of cyclopropane ring cleavage in such a manner so as to form the most stable carbonium ion, in this instance an allylic carbonium ion. Inversion at the point of attack of the nucleophile should result in α orientation of the halogen, a supposition confirmed by the half-height width of the H-14 signal characteristic of an equatorial proton. Lastly, the negative Cotton effect exhibited by **43** is typical of 7-abietenes.[35]

Dehydration of **23** with $KHSO_4$ in refluxing dioxane resulted in conversion to methyl abietate (**42**). It is probable that methyl isophotolevopimarate is an intermediate, since it is also transformed into **42** under these conditions.

Solvolytic Rearrangements of Bicyclo[2.2.0]hexanol 7c. The observation that hydride abstraction during the chromic acid oxidation of **7a** resulted in rearrangement due to migration of the 8,12 σ bond made it of interest to study the solvolysis of **7c** since, in analogy with earlier work[36] on the solvolysis of simpler bicyclo[2.2.0]hexan-2-ol tosylates,



45

1

Experimental Section[a,1]

Methyl Photolevopimarate (3c).--Modification of the procedure of Dauben and Coates[7] resulted in improvement of the yield to 70%. A solution of 10 g of levopimaric acid in 200 ml of methanol was irradiated in a quartz cell with unfiltered light from a Hanovia high pressure mercury vapor arc lamp for 7 hr under a slow stream of nitrogen. Part of the solvent was evaporated; the crystals of 3a which separated were recrystallized from methanol, yield 7.0 g, mp 115-116°, $[\alpha]_D^{25}$ + 79.2°, pmr signals at 5.50br (H-14), 1.25 (C-4 methyl), 1.08 (C-10 methyl), 1.00d (J=7, C-15 methyls). Esterification with diazomethane and purification of the product by passage through an alumina column (activity III) gave the gummy ester 3c, $[\alpha]_D^{25}$ + 57°.

Anal. Calcd. for $C_{21}H_{32}O_2$: C, 79.70; H, 10.19; O, 10.11. Found: C, 79.71; H, 10.01; O, 9.84.

One g of 3c was pyrolyzed by heating in a nitrogen atmosphere at 120° for 6 hr. The crude product was recrystallized from methanol, yield 0.78 g (78%) of 1c, identical in all respects with an authentic sample.

Preparation of 4a and 4b.--Methyl dihydrophotolevopimarate (4a) was prepared by the literature method.[7] The previously unreported pmr spectrum exhibited signals at 1.22 (C-4 methyl), 1.05 (C-10 methyl), 0.74d and 0.63d (J=7, C-15 methyls).

To a stirred suspension of 0.1 g of $LiAlH_4$ in 15 ml of tetrahydrofuran was added a solution of 0.1 g of 4a in 6 ml of tetrahydrofuran. Stirring was continued for 4 hr, at which time excess reagent was decomposed by wet ether. Dilution with water, filtration and evaporation of the ether layer gave (4b) which was recrystallized from methanol and then melted at 64-65°, yield quantitative, pmr signals at 3.23 (center of AB system of -CH$_2$OH), 1.11 (C-4 methyl), 0.87 (C-10 methyl), 0.81d and 0.70d (J=7, C-15 methyls).

Anal. Calcd. for $C_{20}H_{34}O$: C, 82.69; H, 11.80; O, 5.51. Found: C, 82.29; H, 11.90; O, 5.30.

Epoxidation of Methyl Photolevopimarate.--To a solution of 2.0 g of m-chloroperbenzoic acid in 25 ml of $CHCl_3$ was added dropwise 2.0 g of 3c in 10 ml of $CHCl_3$. The reaction was followed by tlc and was complete after 2 hr. The mixture was evaporated at reduced pressure and taken up in ether. Washing with aqueous Na_2CO_3, KI and sodium thiosulfate solution and evaporation furnished 2 g of gum which crystallized on addition of methanol. Recrystallization from hexane gave 1.7 g (87%) of 5, mp 111-112°, pmr signals at 3.72d (J=3, H-14), 1.20 (C-4 methyl), 1.02 (C-10 methyl), 1.01d and 0.78d (J=7, C-15 methyls).

Anal. Calcd. for $C_{21}H_{32}O$: C, 75.86; H, 9.70; O, 14.44. Found: C, 75.61; H, 9.92; O, 14.70.

The substance was not affected by treatment with silver perchlorate or lithium diethylamide.

Rearrangement of Methyl 13β,14β-epoxydihydrophotolevopimarate to 6.--To a solution of 1 g of 5 in 10 ml of ether was added 0.5 ml of BF_3-etherate, the progress of the reaction which was complete after 15 min being monitored by tlc. Addition of water, separation of the organic layer, washing, drying and evaporation gave a gum which was recrystallized from hexane, yield of 6 0.64 g, mp 62-63°,

2

ir bands at 2780 (aldehyde C-H), 1735 (aldehyde C=O), 1721 cm^{-1} (ester), pmr signals at 5.83br ($W_{1/2}$=6.5 Hz, H-14), 3.73 (methoxyl), 1.20 (C-4 methyl), 1.10d and 0.95d (J=7 Hz, C-15 methyls), 0.81 (C-10 methyl).

Anal. Calcd. for $C_{21}H_{32}O_3$: C, 75.86; H, 9.70; O, 14.44. Found: C, 75.70; H, 9.40; O, 14.14.

The dinitrophenylhydrazone was prepared in the usual fashion, mp 132-133° after recrystallization from methanol.

Anal. Calcd. for $C_{27}H_{36}O_6N_4$: C, 63.26; H, 7.08; O, 18.73. Found: C, 63.56; H, 7.00; O, 19.12.

Hydroboration-Oxidation of Methyl Photolevopimarate.--To a solution of 4.3 g of 3c in 45 ml of dimethoxyethane was added 1 g of $NaBH_4$ at 0° with stirring, followed by dropwise addition of 3.75 g of freshly distilled BF_3-etherate. The solution was allowed to warm up to room temperature, stirring being continued for 4.5 hr. Two drops of water were added followed by cautious addition of 25 ml of 10% NaOH solution and 30 ml of 30% H_2O_2. The mixture was stirred overnight and thoroughly extracted with ether. The ether extracts were washed, dried and evaporated to give 4.0 g of gum from which alcohol 7a crystallized on addition of methanol, yield 3.0 g (70%), mp 126-130°, lit.[7] 129-131°, pmr signals at 4.06d (J=7, H-14), 3.70 (methoxyl), 1.20 (C-4 methyl), 1.02 (C-10 methyl), 0.96d and 0.78d (J=7, C-15 methyls).

The mother liquor was evaporated and the residue chromatographed over alumina (activity III). Elution with benzene gave 0.8 g (26%) of 12a, mp 171°, ir bands at 3610 (-OH), 1723 cm^{-1} (ester), pmr signals 1.23 (C-4 methyl), 1.10 (C-10 methyl), 0.92d and 0.80d (J=7.0, C-15 methyls). This substance was prepared independently as described in the next section.

Anal. Calcd. for $C_{21}H_{34}O_3$: C, 75.41; H, 10.25; O, 14.35. Found: C, 75.40, H, 9.89; O, 14.69.

Acetylation of 0.1 g of 7a with pyridine-acetic anhydride and recrystallization from hexane gave 0.09 g of 7b, mp 118-119°, ir bands at 1730 (acetate) and 1723 (ester), pmr signals identical to those of 7a except for a shift of the H-14 signal to 5.16d (J=7) and an acetate resonance at 2.00 ppm.

Anal. Calcd. for $C_{23}H_{36}O_4$: C, 73.37; H, 9.64; O, 17.00. Found: C, 73.19; H, 9.44; O, 16.86.

LiAlH$_4$ Reduction of Methyl 13β,14β-epoxydihydrolevopimarate.--Reduction of 1.0 g of 5 in 6 ml of THF with 0.6 g of $LiAlH_4$ in 20 ml of THF at reflux temperature followed by the usual work-up and recrystallization from methanol gave 0.8 g of 12b, mp 140-142°, pmr signals at 3.7 (center of AB system of -CH$_2$OH), 1.06 (C-4 methyl), 0.81 (C-10 methyl), 0.78d and 0.70d (J=7, C-15 methyls).

Anal. Calcd. for $C_{20}H_{36}O_2$: C, 77.87; H, 11.76; O, 10.37. Found: C, 77.59; H, 11.46; O, 10.27.

Acetylation of 0.100 g of acetic anhydride-pyridine at room temperature for 16 hr followed by the usual work-up gave 0.098 g of 12c, mp 132-133° (from hexane), ir bands at 3615 and 1723 cm^{-1}, pmr signals similar to those of 12b except for a shift of -CH$_2$O- to 4.7 and an acetate resonance at 2.00 ppm.

3

Anal. Calcd. for $C_{22}H_{36}O_3$: C, 75.38; H, 10.93; O, 13.69. Found: C, 75.45; H, 10.43; O, 14.00.

To a solution of 0.2 g of 12b in 10 ml of acetone at 0° was added 3 ml of Jones reagent dropwise with stirring. After 1 hr, acetone was removed at reduced pressure. The remaining mixture was diluted with water and extracted with ether. The washed and dried ether extracts were evaporated and the residue was esterfied with diazomethane. After recrystallization from hexane, the product melted at 170-171° and was identical in all respects with 12a from the hydroboration reaction.

Reaction of Methyl Levopimarate and Methyl Photolevopimarate with Mercuric Acetate.--A solution of 1.06 g of mercuric acetate and 1 g of 3c in 30 ml of 50% aqueous THF was stirred overnight, filtered and evaporated at reduced pressure. The residue was taken up in ether. Evaporation of the washed and dried ether extract gave a gum which was chromatographed over alumina (acitivty III). Elution with hexane gave 0.22 g (22%) of methyl levopimarate (1c). Further elution with benzene gave 0.66 g (66%) of 13a, mp 88-89° (from hexane), $[\alpha]_D^{25}$ -117°; pmr signals at 5.58br (H-14), 5.50c (H-7), 4.28c (H-12), 3.76 (methoxyl), 1.24 (C-4 methyl), 1.10d and 1.07d (J=7, C-15 methyls), 0.77 (C-10 methyl).

Anal. Calcd. for $C_{21}H_{32}O_3$: C, 75.85; H, 9.71; O, 14.44. Found: C, 75.71; H, 9.59; O, 14.18.

Acetylation of 0.1 g of 13a with pyridine-acetic anhydride in the usual fashion and recrystallization of the crude product from hexane gave 0.08 g of 13b, mp 77-78°, ir bands at 1728 (acetate) and 1720 cm^{-1} (methyl ester), pmr signals at 5.58c (H-14, H-12 superimposed), 5.50c (H-7), 3.76 (methoxyl), 2.0 (acetate), 1.20 (C-4 methyl), 1.07d and 1.00d (J=7, C-15 methyls), 0.79 (C-10 methyl).

Anal. Calcd. for $C_{23}H_{34}O_4$: C, 73.36; H, 9.15; O, 17.09. Found: C, 73.19; H, 9.01; O, 16.86.

Reaction of 1.06 g of 1c with mercuric acetate in the manner described above gave the same ratio of 13a and recovered 1c.

Silver Carbonate-Celite Oxidation of Methyl 14β-hydroxydihydrophotolevopimarate.--A mixture of 1 g of 7a and 7 g of freshly prepared silver carbonate-Celite reagent was refluxed for 18 hr, filtered and evaporated. The solid residue (14a) was recrystallized from hexane, yield 0.74 g, mp 205-206°, $[\alpha]_D^{27}$ -2.5°; ir bands at 1772 (γ-lactone), 1723 cm^{-1} (ester); pmr signals at 3.72 (methoxyl), 1.23 (C-4 methyl), 1.10 (C-10 methyl), 1.16d and 0.85d (J=7, C-15 methyls).

Anal. Calcd. for $C_{21}H_{32}O_4$: C, 72.38; H, 9.26; O, 18.36; MW, 348. Found: C, 72.80; H, 9.29; O, 17.94; MW (MS), 348.

A solution of 0.075 g of 14a in 10 ml methanol was mixed with 10 ml of 5% methanolic sodium hydroxide solution, allowed to stand with stirring at room temperature for 16 hr, acidified and evaporated. The residue was taken up in ether, washed, dried and evaporated. The residual solid (14b) was recrystallized from hexane, yield 0.064 g, mp 131-132°, $[\alpha]_{Hg}^{25}$ +32.5°; ir bands at 1770 and 1723 cm^{-1}; pmr signals at 3.74 (methoxyl), 1.20 (C-4 methyl), 0.98 (C-10 methyl), 0.92d and 0.81d (J=7, C-15 methyls).

Anal. Calcd. for $C_{21}H_{32}O_4$: C, 72.38; H, 9.26; O, 18.36; MW, 348. Found: C, 72.32; H, 9.55; O, 18.43; MW (MS), 348.

5

tered and evaporated. The residual gum (21) was purified by chromatography, but could not be induced to crystallize; pmr signals at 3.76 (methoxyl), 1.11 (C-4 methyl), 0.94d and 0.73d (J=6, C-15 methyls), 0.74 (C-10 methyl).

Anal. Calcd. for $C_{21}H_{34}O_2$: C, 79.19; H, 10.76; O, 10.05. Found: C, 78.98; H, 10.66; O, 9.89.

Baeyer-Villiger Oxidation of 20.--A mixture of 1 g of 20 and 400 mg of 30% H_2O_2 and 2 ml of 9 M sodium hydroxide solution in 10 ml of methanol was stirred at room temperature for 2 hr, acidified with 25 ml of 10% HCl and extracted with ether. The washed and dried ether solution was evaporated and the residue recrystallized from hexane, yield of 22 0.65 g (65%), mp 177-178°, $[\alpha]_{Hg}^{25}$ -3.1°, ir bands at 1785 cm^{-1} (strained γ-lactone), 1723 cm^{-1} (ester), pmr signals at 2.73c (H-13), 1.20 (C-4 methyl), 0.97d and 0.90d (J=7, C-15 methyls), 0.90 (C-10 methyl).

Anal. Calcd. for $C_{21}H_{32}O_4$: C, 72.38; H, 9.26; O, 18.36; MW, 348. Found: C, 72.61; H, 9.17; O, 18.18; MW (MS), 348.

Oxidation of 20 to 22 with m-chloroperbenzoic acid was very slow at room temperature, but could be accomplished satisfactorily in about the same yield as above by refluxing the $CHCl_3$ solution.

$NaBH_4$ Reduction of 20 to 23a.--A mixture of 1 g of 20, 0.8 g of $NaBH_4$ and 15 ml of ethanol was stirred at room temperature for 3 days, evaporated at reduced pressure, diluted with water, heated on the steam bath for one half hour, cooled and extracted with ether. Evaporation of the washed and dried ether layer gave solid 23a which was recrystallized from methanol, yield 0.8 g, mp 161°, ir bands at 3615br (-OH) and 1721 cm^{-1} (ester); pmr signals at 3.71 (methoxyl), 3.0d (J=2.8, H-14), 1.21 (C-4 methyl), 1.08 (C-10 methyl), 0.88d and 0.78d (C-15 methyls).

Anal. Calcd. for $C_{21}H_{34}O_3$: C, 75.41; H, 10.25; O, 14.35. Found: C, 75.19; H, 10.21; O, 14.50.

The acetate 23b was recrystallized from methanol and melted at 119°; the pmr spectrum which contained an acetate singlet at 2.00 ppm was similar to that of 23b except for a downfield shift of the H-14 resonance to 4.2 ppm.

Anal. Calcd. for $C_{23}H_{36}O_4$: C, 73.37; H, 9.64; O, 17.00. Found: C, 72.98; H, 9.90; O, 16.88.

Degradation of 20 to 30.--A mixture of 0.2 g of 22 in 5 ml of methanol and 20 ml of 6% sodium hydroxide solution was refluxed for 2 hr, cooled, neutralized with 10% HCl and extracted with ether. The washed and dried ether extract was evaporated. The residue (24a) was recrystallized from methanol, yield 0.19 g, mp 164-165°, pmr signals at 7.21br (-COOH), 3.76 (methoxyl), 1.20 (C-4 methyl), 1.06 (C-10 methyl), 0.96d and 0.83d (J=7, C-15 methyls).

Anal. Calcd. for $C_{21}H_{34}O_5$: C, 68.82; H, 9.35; O, 20.81. Found: C, 68.87; H, 9.48; O, 21.12.

Treatment of 24a with acetic anhydride-pyridine resulted in quantitative reconversion to 22. The methyl ester 24b was obtained in quantitative yield by treatment with diazomethane and recrystallized from hexane, mp 169-170°, pmr signals similar to that of 24a except

4

Reduction of 0.2 g of 14a with 0.18 g of $LiAlH_4$ in refluxing THF solution followed by the usual work up gave the triol 31a, yield 0.17 g, mp 146-148° (from hexane).

Anal. Calcd. for $C_{20}H_{36}O_3$: C, 74.03; H, 11.18; O, 14.79. Found: C, 74.03; H, 11.10; O, 14.89.

The gummy acetate 31b exhibited pmr signals at 4.1dbr (2 protons, center of AB part of ABX system, H-14), 3.70 (center of AB system, $-CH_2OAc$), 2.00 (two acetates), 0.99 (C-4 methyl), 0.94 (C-10 methyl); 0.85d (J=7, C-15 methyls).

Anal. Calcd. for $C_{24}H_{40}O_5$: C, 70.55; H, 9.87; O, 19.58. Found: C, 70.37; H, 9.90; O, 19.52.

$LiAlH_4$ reduction of 0.2 g of 14b in refluxing THF and recrystallization of the crude product from methanol gave 0.164 g of triol 31c, mp 177-178°.

Anal. Calcd. for $C_{20}H_{36}O_3$: C, 74.03; H, 11.18; O, 14.79. Found: C, 73.76; H, 10.99; O, 15.01.

The diacetate 31d was recrystallized from hexane, mp 106-107°, pmr signals 4.0 (2 protons, center of AB system, $-CH_2OAc$), 2.00 (two acetates), 1.00 (C-4 methyl), 0.90 (C-10 methyl), 0.80d (J= 6.0, C-15 methyls).

Anal. Calcd. for $C_{24}H_{40}O_5$: C, 70.55; H, 9.87; O, 19.58. Found: C, 70.70; H, 10.00; O, 19.02.

Oxidative rearrangement of Methyl 14β-Hydroxydihydrophotolevopimarate.--To a solution of 5 g of 7a in 15 ml of acetone cooled to 0° was added dropwise with stirring 8 ml of Jones reagent. The reaction was monitored by tlc and was complete in 20 min. The solvent was evaporated and the residue taken up in ether, washed and dried. Removal of solvent gave 4.9 g of gum which crystallized on addition of hexane. Recrystallization from aqueous methanol gave 4.7 g (97%) of 20, mp 102-104° (lit. 103.5-104.5°)[7], $[\alpha]_{Hg}^{25}$ -1.2° (lit. $[\alpha]_D^{25}$ -2.6°)[7], ir bands as reported[7], pmr signals at 3.70 (methyl ester), 2.7c (H-13), 1.16 (C-4 methyl), 0.98d and 0.90d (J=7, C-15 methyls), 0.78 (C-10 methyl), CD curve (methanol, C 3 mg/5 ml) $[\theta]_{278}$ -23.40 (min).

Anal. Calcd. for $C_{21}H_{32}O_3$: C, 75.86; H, 9.70; O, 14.44. Found: C, 75.71; H, 9.60; O, 11.19.

Oxidation of 7a with excess chromic acid-pyridine reagent for two days and chromatography of the crude product resulted in a 15% yield of 20 and 82% recovery of unreacted starting material.

Conversion of 20 to 21.--Treatment of 0.5 g of 20 with 2 ml ethanedithiol and 0.4 ml of BF_3-etherate for 18 hr at room temperature, precipitation of the crude product by addition of methanol, and chromatography over Florosil after thorough washing with methanol and drying in vacuo afforded, after elution with benzene-chloroform (1:1), a solid thioketal which was recrystallized from methanol, yield 0.24 g (49%), mp 192-193°, pmr signals at 3.70 (methoxyl), 3.20br ($W_{1/2}$=3 Hz, thioketal methylenes), 1.10 (C-4 methyl), 0.98d and 0.90d (J=7, C-15 methyls), 0.82 (C-10 methyl).

A mixture of 0.1 g of the preceding compound, 2 g of Raney nickel and 25 ml of absolute methanol was refluxed for 18 hr, fil-

6

for replacement of the carboxylic OH resonance by an additional methoxyl signal; H-13 also became visible as 2.74 dt (J=8.0, 2.4).

Anal. Calcd. for $C_{22}H_{36}O_5$: C, 69.44; H, 9.54; O, 21.02. Found: C, 69.50; H, 9.77; O, 20.97.

To a solution of 0.2 g of 24a in 40 ml of dry benzene was added 0.16 g of lead tetraacetate. The solution turned brown immediately and was refluxed under a slow stream of nitrogen, the exit gas being bubbled through a $Ca(OH)_2$ solution. After evolution of CO_2 had ceased (6 hr), the mixture was refluxed for an additional 30 min, cooled, filtered and the precipitate washed with hot benzene. The combined filtrate and washings were washed (1 M NaOH, water, and brine), dried and evaporated; recrystallization of the residue from hexane gave 54 mg (27%) of lactone 27. The mother liquor was chromatographed over Florosil. Elution with hexane-benzene (1:1) gave 20 mg of olefin 29 as a gum, pmr signals at 5.21c (H-12), 3.70 (methoxyl), 1.20 (C-10 methyl), 1.06 (C-4 methyl), 0.90d (J=7, C-15 methyls). Further elution with benzene gave 5 mg (2.5% yield) of acetate 28b, mp 156-158° (from hexane), pmr signals at 5.01dt (J= 7.5, 2.4, H-12), 2.70 (methoxyl), 2.01 (acetate), 1.15 (C-4 methyl), 1.03 (C-10 methyl), 0.90d and 0.87d (J=7, C-15 methyls).

Anal. Calcd. for $C_{22}H_{34}O_5$: C, 69.16; H, 9.25; O, 21.38. Found: C, 69.44; H, 9.54; O, 21.02.

A solution of 0.1 g of 28b in 15 ml of 2% methanolic sodium hydroxide was refluxed for one hr, concentrated at reduced pressure, diluted with water and extracted with ether. The washed and dried ether extract was evaporated; recrystallization of the residue from hexane furnished 0.08 g of 28a, mp 136-137°, pmr signals at 4.21c (H-12), 3.70 (methoxyl), 1.20 (C-10 methyl), 1.07 (C-4 methyl), 1.00d and 0.87d (J=7, C-15 methyls).

Anal. Calcd. for $C_{20}H_{34}O_4$: C, 71.48; H, 9.57; O, 19.20. Found: C, 71.27; H, 9.31; O, 18.21.

A suspension of 0.4 g of freshly prepared chromium trioxide-pyridine complex in 10 ml of CH_2Cl_2 was mixed with 0.028 g of 28a in 10 ml of CH_2Cl_2 and stirred at room temperature for 25 min. The entire mixture was added to the top of a silica gel column and eluted with benzene-$CHCl_3$ (1:1). Evaporation of solvent and recrystallization from hexane gave 18 mg of 30, mp 130-131°, $[\alpha]_{Hg}^{27}$ +78.3°, ir bands at 3615 (3° hydroxyl), 1739 (cyclopentanone) and 1728 cm^{-1} (ester); pmr signals at 3.70 (methoxyl), 1.21 (C-10 methyl), 1.06 (C-4 methyl), 1.03d and 0.85d (C-15 methyls).

Anal. Calcd for $C_{22}H_{32}O_4$: C, 70.64; H, 9.35; O, 19.38. Found: C, 70.39; H, 9.59; O, 19.02.

Diborane Reduction of 24a.--To a solution of 0.15 g of 24a in 3 ml THF kept at -16°C was added 8 drops of a 0.9 M solution of diborane over a period of 5 min. The solution was allowed to warm up to room temperature and allowed to stand until tlc indicated complete disappearance of starting material (5 hr). The mixture was cooled to 0° and hydrolyzed with 15 ml of water. After addition of 4 g of K_2CO_3 the aqueous layer was extracted thoroughly with ether. Evaporation of the washed and dried ether extracts and recrystallization of the residue from methanol furnished 0.085 g (70%) of 25, mp 141-142°; pmr signals at 3.70 (methoxyl), 3.0c (center of AB part of ABX system, H-14), 1.20 (C-4 methyl), 1.03 (C-10 methyl), 0.88d and 0.83d (J=7, C-15 methyls).

7

Anal. Calcd. for $C_{21}H_{36}O_4$: C, 71.55; H, 10.29; O, 18.15. Found: C, 71.90; H, 10.11; O, 18.50

Oxidation of the above with chromic trioxide-pyridine in methylene chloride solution gave a 90% yield of 22.

Reaction of 22 with Methyl Lithium.--Addition of 1 ml of a 1.5 M solution of methyl lithium in ether to an ice cold solution of 0.5 g of 22 in 30 ml of anhydrous ether, stirring for 4 hr was followed by addition of a saturated solution of NH_4Cl°. The washed and dried ether layer was evaporated and the residue (27) was recrystallized from hexane, yield 0.57 g, mp 144-145°, $[\alpha]_{Hg}^{25}$ -2.08°; ir bands at 3615, 1723 and 1707 cm^{-1}, pmr signals at 3.70 (methoxyl), 2.81dt (J=8.8, 2.8, H-13), 2.27 (methyl ketone), 1.20 (C-4 methyl), 1.05 (C-10 methyl), 0.89d and 0.87d (J=7, C-15 methyls).

Anal. Calcd. for $C_{22}H_{34}O_4$: C, 72.89; H, 9.45; O, 17.65. Found: C, 72.61; H, 9.80; O, 17.27.

Oxidation of 0.08 g of 27 with 0.1 g of m-chloroperbenzoic acid in refluxing $CHCl_3$ gave 54 mg (68%) of lactone 22. Under identical conditions, 24b was converted to 22 in 55% yield.

Acid-Catalyzed Cleavage of 20.--A solution of 0.2 g of 20 in 20 ml of $CHCl_3$ saturated with hydrogen chloride was stirred at room temperature for 4 hr and evaporated at reduced pressure. The residue was taken up in ether; evaporation of the washed and dried ether solution and recrystallization from hexane at -76° gave 0.174 g of 35, mp 62-63°, ir bands at 1730 (ester), 1680 and 1660 (α,β-unsaturated ketone); λ_{max} 237 nm (ε=7160); pmr signals at 6.72t (J=4, H-12), 3.66 (methoxyl), 2.85m (H-15), 1.20 (C-4 methyl), 0.98 (C-10 methyl), and 1.00d (J=7, C-15 methyls).

Anal. Calcd. for $C_{21}H_{32}O_3$: C, 75.86; H, 9.70; O, 14.44. Found: C, 75.70; H, 9.41; O, 14.30

Base-Catalyzed Cleavage of 20.--A solution of 1 g of 20 in 4% methanolic sodium methoxide was refluxed for 12 hr, cooled, evaporated at reduced pressure, diluted with water and extracted with ether. Evaporation of the washed and dried extract gave a gum which was subject to preparative tlc ($CHCl_3$-2% methanol). The less polar fraction was 36a (0.37 g) which could not be induced to crystallize, pmr signals at 5.25c (H-11 and H-12), 3.74 and 3.72 (methoxyls), 1.05 (C-4 methyl), 1.00 (C-10 methyl), 0.83d (J=6.5, C-15 methyls).

Anal. Calcd. for $C_{22}H_{36}O_4$: C, 72.49; H, 9.95; O, 17.56. Found: C, 72.88; H, 9.95; O, 16.96.

The more polar product 36b (0.37 g) was also a gum and had pmr signals at 5.10c (H-11 and H-12), 3.74 and 3.72 (methoxyls), 1.05 (C-4 methyl), 0.90d (J=7, C-15 methyls), and 0.86 (C-10 methyl).

Anal. Calcd. for $C_{22}H_{36}O_4$: C, 72.49; H, 9.95; O, 17.56. Found: C, 72.79; H, 10.09; O, 17.18.

A solution of 0.1 g of 36a in 3% methanolic sodium hydroxide was refluxed for 12 hr and acidified. The usual work-up gave 36b in almost quantitative yield.

Catalytic hydrogenation of the mixture of 36a and 36b obtained prior to separation by tlc (Pd-C, ethyl acetate solution) and work-up in the usual fashion gave a gummy residue which was a mixture of

8

two saturated diesters (tlc, pmr spectrum). No attempt was made to resolve the mixture.

A solution of 0.5 g of 36b in 25 ml of CH_2Cl_2 was ozonized at -70° until excess ozone was detected in the KI trap. The solution was flushed with dry nitrogen and decomposed by being stirred with one ml of dimethyl sulfide overnight. The solvent was removed at reduced pressure and the residue taken up in ether. Evaporation of the washed and dried ether extract, chromatography of the residue over silica gel and elution with $CHCl_3$ gave 0.25 g of 37 as a gum which could not be induced to crystallize, ir bands at 2735, 1730 (sh) and 1725 cm^{-1}, pmr signals at 9.4t (J=3, -CHO), 3.74 and 3.72 (methoxyls), 1.13 (C-4 methyl) and 0.85 (C-10 methyl).

Anal. Calcd. for $C_{18}H_{28}O_5$: C, 66.64; H, 8.70; O, 24.66. Found: C, 67.04; H, 8.79; O, 24.14.

A solution of 0.1 g of 37 in 30 ml of benzene was refluxed with 1 g of tris-triphenylphosphine rhodium chloride until the orange color of the solution had changed to yellow. Addition of 15 ml of ethanol to the cooled solution to precipitate the complex, filtration and evaporation of the filtrate gave a gum which was chromatographed over Florosil. Elution with $CHCl_3$ gave 38 (0.032 g) as a gum which could not be induced to crystallize, pmr signals at 3.74, 3.72 (methoxyls), 1.21d (J=6, C-9 methyl), 1.21 (C-4 methyl), 0.88 (C-10 methyl).

Anal. Calcd. for $C_{17}H_{26}O_4$: C, 68.89; H, 9.52; O, 21.59. Found: C, 68.60; H, 9.61; O, 21.40.

Methyl Isophotolevopimarate (39).--A mixture of 0.500 g of 23a and 0.512 g of p-toluenesulfonyl chloride in 6 ml of pyridine was kept at 0° for 20 hr, poured over crushed ice and extracted with ether. The washed and dried ether layer was evaporated at reduced pressure to give a gum which showed a major spot on tlc. Chromatography over Florosil and elution with benzene furnished 0.365 g of 39 which could not be induced to crystallize, $[\alpha]_D^{27}$ +9°, ir band at 1721 cm^{-1} (ester), pmr signals at 4.3br (H-7), 3.73 (methoxyl), 1.25 (C-4 methyl), 1.01d and 0.98d (J=7, C-15 methyls), 0.76 (C-10 methyl).

Anal. Calcd. for $C_{21}H_{32}O_2$: C, 79.70; H, 10.19; O, 10.11. Found: C, 79.84; H, 10.11; O, 10.07.

A mixture of 0.08 g of 39 in 15 ml of dioxane and 1.5 g of $KHSO_4$ was refluxed for 10 hr. The solvent was removed at reduced pressure, the residue extracted with ether and the washed and dried extract was evaporated. The residue was methyl abietate (42), yield essentially quantitative. The same result was obtained when 23a was refluxed with $KHSO_4$ in dioxane.

Cleavage of 39 to 41.--A solution of 1 g of 39 in 30 ml of benzene was oxidized with 1 g of OsO_4 in 10 ml of pyridine by stirring at room temperature for 72 hr. The osmate ester was decomposed by bubbling H_2S through the solution of 1.5 hr. The mixture was allowed to stand at room temperature for an additional 5 hr, filtered and the precipitate washed with hot $CHCl_3$. The combined filtrate and washings were washed, dried and evaporated. Chromatography of the residue over silicic acid and elution with $CHCl_3$ furnished 40 which was recrystallized from hexane, yield 0.35 g (36%), mp 105-106°, pmr signals 4.21t (J=6, H-7), 3.71 (methoxyl), 1.26 (C-4 methyl), 1.13d and 1.00d (J=7, C-15 methyls) and 0.88 (C-10 methyl).

9

Anal. Calcd. for $C_{21}H_{34}O_4$: C, 71.96; H, 9.78; O, 18.26. Found: C, 71.57; H, 9.92; O, 18.60.

A solution of 0.2 g of 40 in 10 ml of methanol and 10 drops of water was oxidized with 0.5 g of $NaIO_4$ by stirring at room temperature for 2 hr at the end of which period all starting material had been replaced by a less polar product (tlc). The solution was diluted with ether, filtered and the precipitate washed with ether. The combined solvents were washed, dried and evaporated; the residue (41) was recrystallized from hexane, yield 0.09 g, mp 136-137°, $[\alpha]_D^{25}$ +69.1°, ir bands at 2710 and 1735 sh (aldehyde), 1720 (ester) and 1700 cm^{-1} (ketone); uv λ_{max} 281 nm, pmr signals at 9.6t (J=2.5, CHO), 3.74 (methoxyl), 1.22 (C-4 methyl), 1.21 (C-10 methyl) and 1.03d (J=7, C-15 methyls).

Anal. Calcd. for $C_{21}H_{32}O_4$: C, 72.38; H, 9.26; O, 18.36. Found: C, 72.19; H, 9.42; O, 18.66.

Conversion of 39 to 43.--A solution of 0.25 g of 39 in 10 ml of $CHCl_3$ saturated with hydrogen chloride was allowed to stand at room temperature for 6 hr, evaporated and the residue was taken up in ether. The washed and dried ether extract was evaporated and the residual red gum was chromatographed over Florosil. Elution with benzene furnished 43 which was recrystallized from hexane, yield 0.187 g, mp 99°, pmr signals at 5.36br (H-7), 4.46br (H-14), 3.73 (methoxyl), 1.2 (C-4 methyl), 1.00d and 0.98d (J=6.5, C-15 methyls), and 0.81 (C-10 methyl), ord curve (hexane, C 5.6 mg/ml) Φ_{223} = -2500 (min).

Anal. Calcd. for $C_{21}H_{33}O_2Cl$: C, 71.59; H, 9.36; O, 9.09; Cl, 9.94; MW 354, 352. Found: C, 71.19; H, 9.49; O, 8.86; Cl, 9.99; MW(MS), 354 (32%), 352.

Solvolytic Rearrangements of 7c.-- a) Tosylation of 1 g of 7a with p-toluenesulfonyl chloride in pyridine in the usual fashion and

10

recrystallization of the crude product from hexane gave 0.86 g of 7c, mp 111-112°, pmr signals at 7.2-7.6c (4 aromatic protons), 4.7d (J=6.5, H-14), 3.74 (methoxyl), 3.1 (aromatic methyl), 1.16 (C-4 methyl), 0.98 (C-10 methyl), 0.81d and 0.66d (J=7, C-15 methyls).

A solution of 0.5 g of 7c and 0.3 g of sodium acetate in 25 ml of acetic acid was refluxed for 12 hr, evaporated at reduced pressure, diluted with water and extracted with ether. Evaporation of the washed and dried ether extract, chromatography of the residue over alumina (activity III) gave 44a which was recrystallized from hexane, yield 0.418 g, mp 118-119°, ir bands at 1728 and 1720 cm^{-1}, pmr signals at 3.76 (methoxyl), 2.00 (acetate), 1.13 (C-4 methyl), 0.98 (C-10 methyl), 0.79d and 0.72d (J=7, C-15 methyls).

Anal. Calcd. for $C_{23}H_{36}O_4$: C, 73.37; H, 9.64; O, 17.00. Found: C, 73.58; H, 9.70; O, 16.90.

Hydrolysis of 0.1 g of 44a with refluxing 2% methanolic sodium hydroxide, concentration to small volume, extraction with ether and evaporation of the washed and dried ether extract gave a homogeneous product (44b) which could not be induced to crystallize, ir bands at 3615 and 1720 cm^{-1}, pmr signals at 3.74 (methoxyl), 1.22 (C-4 methyl), 1.05 (C-10 methyl), 0.85d and 0.65d (J=7, C-15 methyls).

Anal. Calcd. for $C_{21}H_{34}O_3$: C, 75.41; H, 10.25; O, 14.35. Found: C, 75.50; H, 10.19; O, 14.47.

b) Reduction of 0.1 g of 7c with 0.1 g of $LiAlH_4$ in THF at room temperature for 4 hr followed by the usual work-up gave 45 in quantitative yield as a gum which could not be induced to crystallize and had pmr signals at 3.21 (center of AB system of $-CH_2OH$), 1.02 (C-4 methyl), 0.73 (C-10 methyl), 0.73d and 0.70d (J=7, C-15 methyls).

Anal. Calcd. for $C_{20}H_{34}O$: C, 82.69; H, 11.80; O, 5.51. Found: C, 82.21; H, 11.57; O, 5.31.

at least partial migration of the 8,9 bond which is trans-antiparallel to the departing tosylate was to be expected. In fact, acetolysis of **7c** yielded a single acetate in 90% yield whose ^1H NMR spectrum did not exhibit a signal characteristic of hydrogen geminal to an acetoxy group. Hydrolysis yielded an alcohol which resisted oxidation and acetylation under ordinary conditions. Consequently, the acetate and the alcohol derived from it were formulated as **44a** and **44b**. Similarly, $LiAlH_4$ reduction of **7c** gave an alcohol whose physical properties differentiated it from alcohol **4b**, obviously as the result of solvolytic rearrangement to **45**.

These rearrangements are similar in type to the biosynthetic pathway postulated for the atisane–aconane conversion[37] which has been duplicated in several diterpenoid bicyclo[2.2.2]octane model systems[38,39] and utilized in the recent synthesis of the delphinine-type alkaloid talatisamine.[40]

Registry No.—**1c**, 3513-69-7; **3a**, 5947-57-9; **3c**, 54003-59-7; **4a**, 54003-60-0; **4b**, 54003-61-1; **5**, 54003-62-2; **6**, 54003-63-3; **6** dinitrophenylhydrazone, 54003-64-4; **7a**, 54003-65-5; **7b**, 54003-66-6; **7c**, 54003-67-7; **12a**, 54003-68-8; **12b**, 54003-69-9; **12c**, 54003-70-2; **13a**, 3484-53-5; **13b**, 6821-61-0; **14a**, 54003-71-3; **14b**, 54081-34-4; **20**, 54003-72-4; **20** thioketal, 54003-73-5; **21**, 54003-74-6; **22**, 54003-75-7; **23a**, 54003-76-8; **23b**, 54003-77-9; **24a**, 54003-78-0; **24b**, 54003-

79-1; **25,** 54003-80-4; **27,** 54003-81-5; **28a,** 54003-82-6; **28b,** 54019-71-5; **29,** 54003-83-7; **30,** 54036-74-7; **31a,** 54003-84-8; **31b,** 54003-85-9; **31c,** 54081-35-5; **31d,** 54053-75-7; **35,** 54003-86-0; **36a,** 54003-87-1; **36b,** 54003-88-2; **37,** 54003-89-3; **38,** 54003-90-6; **39,** 54003-91-7; **40,** 54003-92-8; **41,** 54003-93-9; **43,** 54003-94-0; **44a,** 54003-96-2; **44b,** 54003-95-1; **45,** 54003-58-6.

Supplementary and Miniprint Material Available. The Experimental Section will appear following these pages in the microfilm edition of this volume of the journal. Photocopies of the supplementary material and full-sized photocopies of the miniprinted material from this paper only or microfiche (105 × 148 mm, 24× reduction, negatives) containing all of the miniprinted and supplementary material for the papers in this issue may be obtained from the Journals Department, American Chemical Society, 1155 16th St., N.W., Washington, D.C. 20036. Remit check or money order for $4.00 for photocopy or $2.50 for microfiche, referring to code number JOC-75-1017.

References and Notes

(1) Resin Acids. XXVIII. Previous paper: J. A. Turner, V. Iyer, R. S. McEwen, and W. Herz, *J. Org. Chem.*, **39,** 117 (1974).

(2) Supported in part by grants from the National Science Foundation (GP-12582) and the donors of the Petroleum Research Fund, administered by the American Chemical Society.

(3) W. Herz and M. G. Nair, *J. Org. Chem.*, **34,** 4016 (1969).

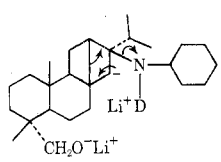
(4) W. Herz and M. G. Nair, *J. Am. Chem. Soc.*, **89,** 5474 (1967).

(5) J. A. Turner, V. Iyer, R. S. McEwen, and W. Herz, *J. Org. Chem.*, **39,** 117 (1974); J. A. Turner and R. S. McEwen, *Acta Crystallogr.*, **B30,** 2151 (1974).

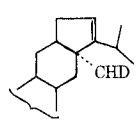
(6) W. H. Schuller, R. N. Moore, J. E. Hawkins, and R. V. Lawrence, *J. Org. Chem.*, **27,** 1178 (1962).

(7) W. G. Dauben and R. M. Coates, *J. Am. Chem. Soc.*, **86,** 2490 (1964).

(8) The reported[7] low yield (18%) of **1a** from the pyrolysis of **3a,** which would have interfered with the feasibility of the proposed scheme, could be raised to 80% by operating on **3c.** This avoids the self-induced acid-catalyzed isomerization of **1a** to abietic acid and other resin acid isomers. However, an attempt at a shortcut to **3d** through direct exchange of sp^2-bound H-14 in **3e** (to avoid complications due to reaction of butyllithium with the ester function) with lithium deuteriocyclohexylamide–*N,N*-dideuteriocyclohexylamine gave only **1d,** presumably by the mechanism depicted below. As there was no deuterium incorporation either at C-12 or C-14, the rearrangement must have taken place prior to capture of D^+ from the medium by the anion.



(9) A third possibility, **11,** resulting from formal consecutive shifts of the 8,12 and 13,14 bonds, was unlikely on mechanistic grounds in a β-oriented epoxide and is excluded by the ^1H NMR data, since H-12 should exhibit vicinal couplings of ~2 and ~6 Hz.



11

(10) J. A. Marshall and H. Faubl, *J. Am. Chem. Soc.*, **92,** 948 (1970).

(11) W. Herz, H. J. Wahlborg, W. D. Lloyd, W. H. Schuller, and G. W. Hedrick, *J. Org. Chem.*, **30,** 3190 (1965).

(12) D. H. R. Barton and W. J. Rosenfelder, *J. Chem. Soc.*, 2381 (1951).

(13) R. N. McDonald and C. E. Reinecke, *J. Org. Chem.*, **31,** 1888 (1967).

(14) Although the oxidation of secondary alcohols by Cr^{VI} has been studied extensively, some of the details are still subject to controversy. The initial formation of a chromate ester indicated in Scheme V appears to be generally accepted.[15-17] Evidence for subsequent protonation in acid solution (step 2) has been presented[18] and there seems to be widespread acceptance of the notion that hydrogen transfer involves a cyclic transition state,[18] thus leading to the possibility of Wagner–Meerwein shifts (steps 3 and 4) which are depicted discretely in Scheme V for reasons of greater clarity.

(15) R. Stewart, "Oxidation Mechanisms", W. A. Benjamin, New York, N.Y., 1964, pp 37–48.

(16) K. B. Wiberg in "Oxidation in Organic Chemistry", K. B. Wiberg, Ed., Academic Press, New York, N.Y., 1965, p 142 ff.

(17) D. Lee and R. Stewart, *J. Org. Chem.*, **32,** 2868 (1967).

(18) J. Rocek and K. Venkatasubramanian, *Proc. Indian Acad. Sci., Sect. A,* 1 (1970).

(19) Solvolysis of *endo*-bicyclo[2.2.0]hex-2-yl dinitrobenzoate which formally resembles the process adumbrated in Scheme V appears to stop at the bicyclo[3.1.0]hexane stage; R. N. McDonald and G. E. Davis, *J. Am. Chem. Soc.*, **94,** 5078 (1972).

(20) Since the C-10 methyl resonance of **21** is found at 0.74 ppm, its upfield shift in **20** cannot be due to the shielding effect of the carbonyl group.

(21) H. C. Brown, S. Krishnamoorty, T. F. Stocky, N. M. Yoon, and C. S. Pak, *J. Org. Chem.*, **38,** 2786 (1973).

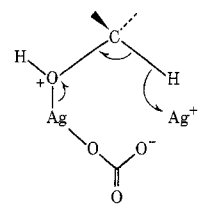
(22) (a) The ^1H NMR spectrum of **27** displayed the H-12 resonance as a doublet of triplets (J = 8.8, 8.8, 2 Hz) centered at 2.85 ppm similar to the pattern of H-12α of esters **24b** at 2.74 ppm. The observation of one small and two large coupling constants is only compatible with β orientation of the methyl ketone side chain. In the hydroxy ester **28b,** the coupling constants of H-12 were 7.5, 7.5, and 2.4 Hz. (b) As suggested by a reviewer, the genesis of **22** by way of G would also be unreasonable because it represents an intramolecular alkylation involving an endocyclic leaving group, i.e., a nonlinear SN2 type displacement; see L. Tenud, S. Farooq, S. Seibl, and A. Eschenmoser, *Helv. Chim. Acta,* **53,** 2059 (1970).

(23) H. O. House, "Modern Synthetic Reactions", W. A. Benjamin, Menlo Park, Calif., 1972, pp 415–421.

(24) M. Fétizon, M. Golfier, and J. M. Louis, *Chem. Commun.*, 1102, 1118 (1969); M. Fétizon, M. Golfier, and P. Morgues, *Tetrahedron Lett.*, 4445 (1972).

(25) M. Giesel, C. A. Grob, W. Santi, and W. Tschudi, *Helv. Chim. Acta,* **56,** 1046 (1973).

(26) F. J. Kakis, M. Fétizon, N. Douchkine, M. Golfier, P. Morgues, and T. Prange, *J. Org. Chem.*, **39,** 523 (1974). The mechanism proposed by these authors for the oxidation step of the silver carbonate–Celite reaction involves concerted irreversible homolytic shift of electrons illustrated below, a proposal which would account for the absence of rearrangement in the oxidation of **7**.



(27) W. Herz and V. Baburao, *J. Org. Chem.*, **36,** 3899 (1972).

(28) E. Wenkert, W. Erman, R. S. Triptow, and P. Bazukis, *J. Am. Chem. Soc.*, **93,** 657 (1971).

(29) P. G. Gassman, J. T. Lumb, and F. V. Zalan, *J. Am. Chem. Soc.*, **89,** 946 (1967).

(30) Because of the cis relationship of H-12 and H-13 in **20, 36a** and **36b** should be cis olefins. Superposition of the vinyl proton resonances in the ^1H NMR spectra of **36a** and **36b** interfered with verification of this deduction.

(31) K. B. Wiberg and R. Fenoglio, *Tetrahedron Lett.*, 1273 (1963); K. B. Wiberg, R. A. Fenoglio, V. Z. Williams, Jr., and R. W. Ubersax, *J. Am. Chem. Soc.*, **92,** 568 (1970).

(32) B. E. Cross and P. L. Myers, *J. Chem. Soc. C,* 471 (1968); 711 (1969).

(33) J. W. Hoffman, J. A. Alford, and R. R. Sobti, *J. Org. Chem.*, **35,** 473 (1970).

(34) W. Herz and R. C. Ligon, *J. Org. Chem.*, **37,** 1400 (1972).

(35) A. W. Burgstahler, J. M. Marx, and D. F. Zinkel, *J. Org. Chem.*, **34,** 1550 (1967).

(36) R. N. McDonald and C. E. Reineke, *J. Org. Chem.*, **32,** 1878 (1967); R. N. McDonald and G. M. Muschik, ibid., **38,** 3944 (1973).

(37) Z. Valenta and K. Wiesner, *Chem. Ind. (London)*, 354 (1956); R. C. Cookson and M. E. Trevett, *J. Chem. Soc.*, 3121 (1956).

(38) J. P. Johnston and K. Overton, *Chem. Commun.* 329 (1969); *J. Chem. Soc. C,* 1490 (1972); *J. Chem. Soc., Perkin Trans. 2,* 853 (1973).

(39) W. A. Ayer and P. D. Deshpande, *Can. J. Chem.*, **51,** 77 (1956).

(40) K. Wiesner, T. Y. R. Tsai, K. Huber, S. Bolton, and R. Vlahov, *J. Amer. Chem. Soc.*, **96,** 4990 (1974).

(41) Melting points are uncorrected. Analyses were carried out by F. Pascher, Bonn, Germany. ^1H NMR spectra were run on a Varian A-60 instrument in $CDCl_3$ with Me_4Si as internal standard. Decoupling experiments were carried out on a Bruker HFX-90 instrument. Values for line positions are expressed in parts per million. Signals are characterized in the usual way: d, doublet; t, triplet; br, broadened singlet or unresolved multiplet; c, complex signal whose center is given. Coupling constants are expressed in hertz. Ir spectra were determined on a Perkin-Elmer Model 257 spectrophotometer in $CHCl_3$ unless otherwise noted, uv spectra on a Cary 14 recording spectrophotometer in 95% ethanol, optical rotations in chloroform. ORD and CD curves were run on a Jasco Model ORD/UV-5 recording spectropolarimeter. Mass spectra were run on a MS-902 high-resolution mass spectrometer at 70 meV. Silica gel $PF_{254+366}$ (Merck) was employed for all preparative thin layer plates.