JOC Featured Article

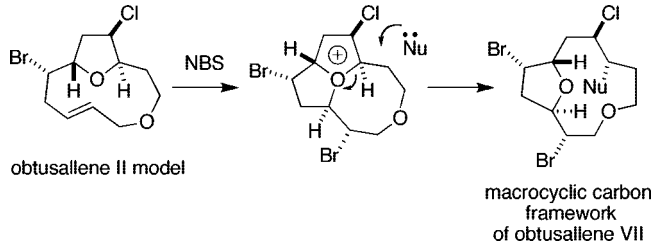
Bromonium Ion Induced Transannular Oxonium Ion Formation−Fragmentation in Model Obtusallene Systems and Structural Reassignment of Obtusallenes V−VII

D. Christopher Braddock,*,† David S. Millan,‡ Yolanda Pérez-Fuertes,† Rebecca H. Pouwer,† Richard N. Sheppard,† Savade Solanki,† and Andrew J. P. White†

Department of Chemistry, Imperial College London, South Kensington, London SW7 2AZ, U.K., and Sandwich Laboratories, Pfizer Global Research and Development, Ramsgate Road, Sandwich, Kent CT13 9NJ, U.K.

c.braddock@imperial.ac.uk

Received December 3, 2008



Ring-closing metathesis was used to construct the strained 11-membered ring of obtusallenes II (and IV). Bromonium ion induced transannular oxonium ion formation−fragmentation gave the macrocyclic carbon skeleton of obtusallene VII with a bromine atom at C-13, in line with a previously published hypothesis. An additional brominated [5.5.1]bicyclotridecane adduct that must arise from a bromonium ion induced transannular oxonium ion formation−fragmentation could also be isolated, suggesting that this adduct represents the core of an as yet undiscovered natural product. An authentic sample of obtusallene V was studied by NMR spectroscopy, and the position of the halogens at C-7 and C-13 was reassigned on the basis of a ^{13}C NMR chlorine induced isotopic shift. This revised structure was subsequently confirmed by X-ray crystallography. These findings allow us to confidently conclude that the structures of obtusallenes VII and VI should also be reassigned.

Introduction

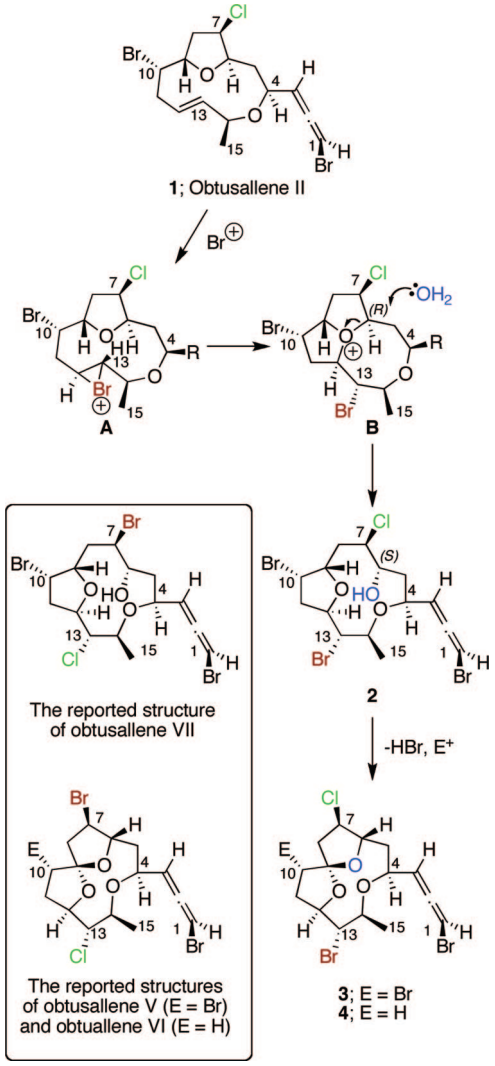
Recently, one of us proposed an internally self-consistent hypothesis concerning the biosynthesis of the obtusallene family—complex halogenated C_{15}-acetogenic marine natural products isolated from *Laurencia* species. Multiple electrophilic bromination events are invoked.[1−3] The hypothesis correctly predicts the macrocyclic carbon frameworks and all relative and absolute stereochemistries of obtusallene I,[4,5] obtusallenes II and III,[6] and obtusallene IV,[7,8] whose structures have all been unambiguously solved by X-ray crystallography. It also correctly predicts the macrocyclic carbon frameworks and the absolute and relative stereochemistries of all the stereocenters for obtusallenes V−VII.[9,10] Interestingly, while the reported structures of obtusallenes V−VII, as solved by NMR spectroscopy,

† Imperial College London.
‡ Pfizer Global Research and Development.

(1) Braddock, D. C. *Org. Lett.* **2006**, *8*, 6055–6058.
(2) For a synthesis of the core of obtusallene II and IV by bromoetherification, see: Braddock, D. C.; Bhuva, R.; Millan, D. S.; Pérez-Fuertes, Y.; Roberts, C. A.; Sheppard, R. N.; Solanki, S.; Stokes, E. S. E.; White, A. J. P. *Org. Lett.* **2007**, *9*, 445–448.
(3) For the stereochemical course of bromoetherification of enynes to form bromoallenes, see: Braddock, D. C.; Bhuva, R.; Pérez-Fuertes, Y.; Pouwer, R.; Roberts, C. A.; Ruggiero, A.; Stokes, E. S. E.; White, A. J. P. *Chem. Commun.* **2008**, 1419–1421.
(4) Cox, P. J.; Imre, S.; Islimyeli, S.; Thomson, R. H. *Tetrahedron Lett.* **1982**, *23*, 579–580.
(5) 10-Bromoobtusallene has also been reported: Öztunç, A.; Imre, S.; Wagner, H.; Norte, M.; Fernández, J. J.; González, R. *Tetrahedron* **1991**, *47*, 2273–2276.
(6) Öztunç, A.; Imre, S.; Lotter, H.; Wagner, H. *Phytochemistry* **1991**, *30*, 255–257.
(7) Guella, G.; Chiasera, G.; Mancini, I.; Öztunç, A.; Pietra, F. *Chem.—Eur. J.* **1997**, *3*, 1223–1231.
(8) Ciavatta, M. L.; Gavagnin, M.; Puliti, R.; Cimino, G.; Martínez, E.; Ortea, J.; Mattia, C. A. *Tetrahedron* **1997**, *53*, 17343–17350.
(9) Guella, G.; Mancini, I.; Öztunç, A.; Pietra, F. *Helv. Chim. Acta* **2000**, *83*, 336–348.
(10) For obtusallenes VIII and IX, the predicted constitution is correct but the stereochemistry at C_{13} is inverted. See ref 1.

10.1021/jo8026577 CCC: $40.75 © 2009 American Chemical Society
Published on Web 01/26/2009

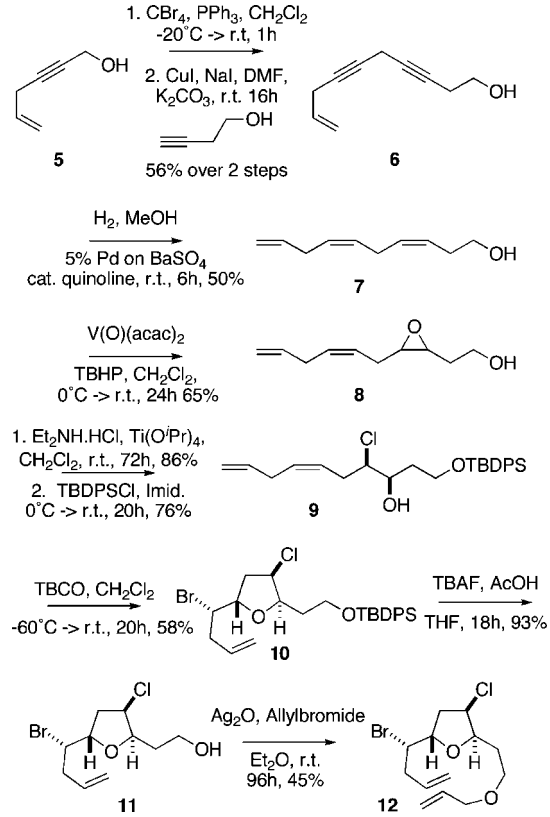
SCHEME 1. Proposed Bromonium Ion Driven Rearrangement from Obtusallene II (R = (*R*)-Bromoallene)



show a bromine atom at C-7 and a chlorine atom at C-13, the hypothesis predicts that obtusallenes V−VII should bear a bromine atom at C-13 and a chlorine atom at C-7.[1,11] This prediction arises from invoking an electrophilic bromination of the C12−13 *trans*-double bond in obtusallene II (**1**) to give bromonium ion **A** (Scheme 1), followed by transannular attack of the THF oxygen at C-12 to generate tricyclic oxonium ion **B**. This intermediate would subsequently undergo nucleophilic attack at C-6 by water with the signature inversion of stereochemistry.[1] Thus, the hypothesis predicts that the actual structure of obtusallene VII is represented by compound **2**. Subsequently, invoking HBr elimination across C9−10 and spiroketalization via electrophilic bromination or protonation of the resulting enol ether leads to the conclusion that obtusallene V and obtusallene VI may be represented by structures **3** and **4**, respectively. Therefore, there is a need to investigate the viability of this bromonium ion induced transannular oxonium ion formation−fragmentation experimentally in order to validate the proposed biosynthetic pathway and, as a consequence, confirm or correct the reported structures of obtusallenes V−VII.

(11) For the structural reassignment of obtusallenes V, VI, and VII by GIAO-based density functional prediction, see: Braddock, D. C.; Rzepa, H. S. *J. Nat. Prod.* **2008**, *71*, 728–730.

SCHEME 2. Preparation of Ring-Closing Metathesis Substrate 12



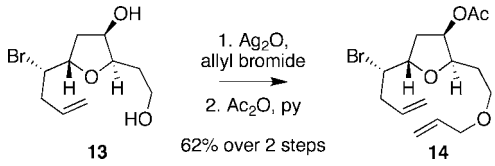
In this paper, we show that (i) strained macrocycles corresponding to obtusallene II can be prepared by ring-closing metathesis to give the desired *E*-olefin in an 11-membered ring; (ii) bromonium ion induced transannular oxonium ion formation−fragmentations occur as predicted to give macrocyclic carbon frameworks corresponding to obtusallene VII with a bromine atom at C-13. The results of these studies strongly support our biosynthetic hypothesis for the obtusallene family. In addition, the isolation of a brominated [5.5.1]bicyclotridecane adduct that must also arise from a bromonium ion induced transannular oxonium ion formation−fragmentation suggests that this represents the core of an as yet undiscovered natural product. Furthermore, the observation of a chlorine induced isotopic shift at C-7 in the ^{13}C NMR spectrum of an authentic sample of obtusallene V and an X-ray crystallographic determination of its structure allow for the definitive reassignment[11] of obtusallene V as structure **3** and thence obtusallenes VI and VII as structures **4** and **2**, respectively.

Results and Discussion

In order to synthesize a macrocyclic model substrate for our studies by ring-closing metathesis, alcohol **5**[12] was activated by conversion to the bromide and immediate coupling[13,14] with but-3-yn-1-ol to give diynene **6** (Scheme 2). *cis*-Selective partial hydrogenation[14] and directed epoxidation[15] of the resulting (*Z*,*Z*)-triene alcohol **7** gave epoxide **8**. Regioselective chloride

(12) Vilavi-Servin, N. P.; Laurent, A.; Fallis, A. G. *Can. J. Chem.* **2004**, *82*, 227–239.
(13) Jeffery, T.; Gueugnot, S.; Linstrumelle, G. *Tetrahedron Lett.* **1992**, *33*, 5757–5760.
(14) Miyaoka, H.; Tamura, M.; Yamada, Y. *Tetrahedron* **2000**, *56*, 8083–8094.

SCHEME 3. Preparation of Ring-Closing Metathesis Substrate 14



ring opening[16] and protection of the primary alcohol gave chlorohydrin **9**. Biosynthetically inspired electrophilic bromoetherification[1,2] gave chlorobromotetrahydrofuran **10** as a single diastereoisomer in excellent yield with all the relative stereochemistry correctly set for the THF core of obtusallene II. Deprotection to alcohol **11** and allylation[17] gave acyclic diene **12** ready for attempted ring-closing metathesis.

A second acyclic diene metathesis substrate with an acetate group rather than a chloride at the equivalent C-7 position of obtusallene II position was also prepared. Allylation[17] of enantiopure diol **13**[2] followed by acetylation gave diene **14** ready for ring-closing metathesis (Scheme 3). The acetate group was purposefully introduced to act as a neighboring group participant in the oxonium ion fragmentation (vide infra).

The ring-closing metatheses of dienes **12** and **14** were then explored. Although some spectacular macrocyclic ring-closing metatheses have been performed in recent years,[18] the optimum catalyst and conditions tend to be highly substrate dependent.[19] Inspection of the X-ray crystal structure of obtusallene II[6] shows its double bond to be distorted away from planarity, indicative of strain in the macrocycle. In addition, we required only the *E*-olefin, whereas macrocyclic ring-closing metathesis typically provides mixtures of *E*- and *Z*-olefins. Notwithstanding all these issues, we were confident that the desired macrocycles could be constructed in this manner. After much optimization, both substrates **12** and **14** underwent ring-closing metathesis using a Hoveyda modified Grubbs catalyst[20] to provide the macrocyclic *E*-olefins **15** and **16**, respectively (Scheme 4).[21] These macrocyclic alkenes lack only the methyl and bromoallene substituents of obtusallene II (**1**) and should make excellent model systems to explore the proposed bromonium ion induced transannular oxonium ion formation−fragmentation.[22]

Macrocyclic alkenes **15** and **16** proved to be crystalline and their X-ray crystal structures (Figures 1 and 2) were determined, confirming the presence of the *E*-double bond in both cases. A

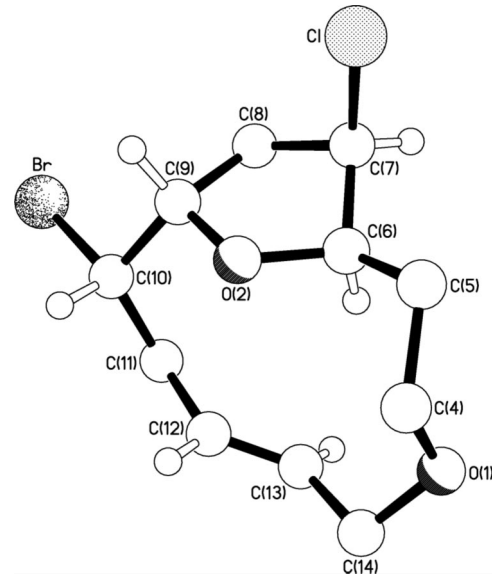


FIGURE 1. Molecular structure of **15-A**, one of the three crystallographically independent molecules present in the crystals of **15**.

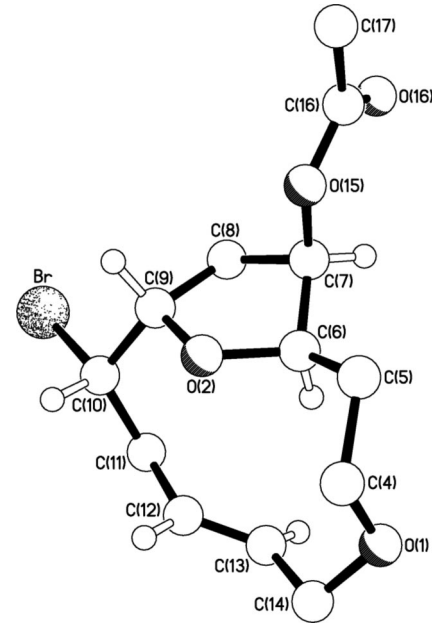
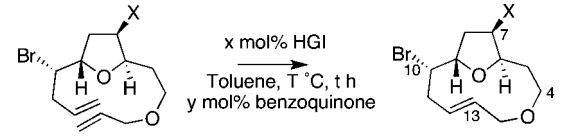


FIGURE 2. Molecular structure of **16**.

SCHEME 4. Ring-Closing Metatheses to Provide Macrocycles 15 and 16



(±)-**12**; X = Cl; x = 10 ; T = 110; t = 18; y = 0
14; X= OAc; x = 12; T = 110; t = 21; y = 46

(±)-**15**; X = Cl; 34%
16; X = OAc; 33%

HGI = $Ru(Cl)_2(PCy_3)(=CH\text{-}2\text{-}(2\text{-}PrO)C_6H_4)$; Cy = cyclohexyl

distortion of ca. 10° of the double bond away from planarity in each case reveals significant strain and underscores further the utility and versatility of the ring-closing metathesis reaction. Macrocycles **15** and **16** have essentially identical conformations (Figure 3), and a comparison with the known X-ray crystal structure of obtusallene II revealed them to be essentially identical outside of a local change in conformation at

(15) Mihelich, E. D.; Daniels, K.; Eickhoff, D. J. *J. Am. Chem. Soc.* **1981**, *103*, 7690–7692.

(16) Fujiwara, K.; Awakura, D.; Tsunashima, M.; Nakamura, A.; Honma, T.; Murai, A. *J. Org. Chem.* **1999**, *64*, 2616–2617.

(17) Schmidt, B.; Wildemann, H. *J. Org. Chem.* **2000**, *65*, 5817–5822.

(18) For recent representative examples, see: (a) Fyvie, W. S.; Peczuh, M. W. *J. Org. Chem.* **2008**, *73*, 3626–3629. (b) Nicolaou, K. C.; Sun, Y.-P.; Guduru, R.; Banerji, B.; Chen, D. Y.-K. *J. Am. Chem. Soc.* **2008**, *130*, 3633–3644.

(19) For a review, see: Gradillas, A.; Pérez-Castells, J. *Angew. Chem., Int. Ed.* **2006**, *45*, 6086–6101.

(20) (a) Kingsbury, J. S.; Harrity, J. P. A.; Bonitatebus, P. J., Jr.; Hoveyda, A. H. *J. Am. Chem. Soc.* **1999**, *121*, 791–799. (b) For the use of benzoquinone to prevent undesirable isomerization during olefin metathesis, see: Hong, S. H.; Sanders, D. P.; Lee, C. W.; Grubbs, R. H. *J. Am. Chem. Soc.* **2005**, *127*, 17160–17161.

(21) No *Z*-alkenes were observed from these reactions. In Scheme 4, the mass balance is tentatively assigned to homo-dimerization products. With *N*-heterocyclic bearing ruthenium benzylidene catalysts (not shown), the desired products were observed in minor quantities (5−10%) in the ^{1}H NMR spectra of the crude mixtures, but extensive decomposition of the substrate had occurred.

(22) For the formation of an oxonium ion by the intramolecular attack of an epoxide on an iodonium ion, see: (a) Alvares, E.; Manta, E.; Martin, J. D.; Rodriguez, M. L.; Ruiz-Perez, C. *Tetrahedron Lett.* **1988**, *29*, 2093–2096. For an epoxide on a bromonium ion, see: (b) Davies, S. G.; Polywka, M. E. C.; Thomas, S. E. *J. Chem. Soc., Perkin Trans. 1* **1986**, 1277–1282.

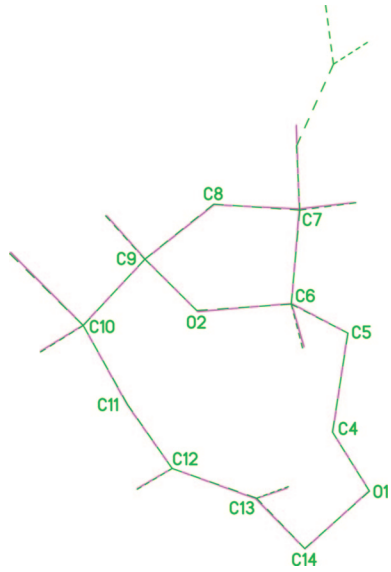


FIGURE 3. Overlay of molecules **15-A** (magenta) and **16** (green) showing the essentially identical conformations for the 5- and 11-membered ring system.

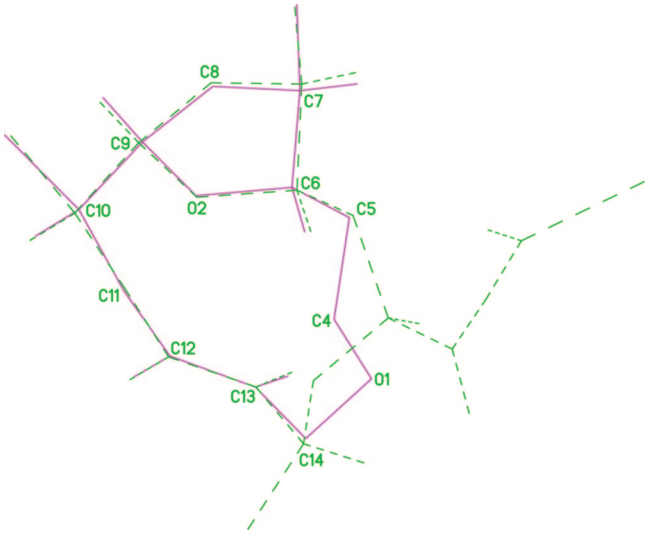
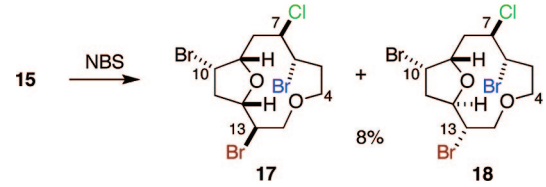


FIGURE 4. Overlay of molecules **15-A** (magenta) and **1** (green) showing the different conformations for the C14−O1−C4−C5 linkages.

C14−O−C4−C5 (Figure 4). Of particular note, the transannular separations between the THF oxygen and C-12 are ca. 2.78 and 2.780(2) Å in **15**[23] and **16**, respectively, distances considerably shorter than the sum of their van der Waal's radii (ca. 3.22 Å), and serve to position the THF oxygen perfectly to trap any bromonium ion formed at C12−13. Interestingly, bromonium ion formation on the exposed *exo* face of the alkene, as seen in the X-ray crystal structures for **1**, **15**, and **16**, would lead to a product with the opposite configurations at C-12 and C-13 compared to obtusallene VII. The requisite stereochemistry for obtusallene VII implies bromonium ion formation on the buried *endo* face. This dichotomy can be rationalized by consideration of Guella's careful NMR studies on the obtusallenes. According to these studies, in solution, obtusallenes bearing a *trans*-olefin

(23) The structure of **15** contains three independent molecules with nearly identical conformations (see the Supporting Information). The THF oxygen···C_{12} distances are 2.761(4), 2.800(4), and 2.770(3) Å in molecules **15-A**, **15-B**, and **15-C**, respectively.

SCHEME 5. Products Isolated after Bromonium Ion Induced Transannular Oxonium Ion Formation−Fragmentation of 15



in the macrocycle are characterized by conformational motion involving 180° flipping of the olefinic bond.[7] Clearly, this would expose the other face of the alkene for bromonium ion formation.

The reaction of macrocycle **15** with NBS was performed in chlorinated solvents saturated with water to encourage progression along the obtusallene VII manifold. After 20 days at rt, approximately 50% of the NBS had been consumed and a complex mixture of products had been formed. Extensive column chromatography led to the isolation of a mixture of two components in an approximate 3:2 ratio (8% yield). It was evident by ^{1}H NMR that there was no double bond, and mass spectrometry gave a molecular ion with a characteristic isotopic pattern indicating the presence of three bromine atoms and one chlorine atom. The structures of the two components were solved by X-ray crystallography (see Figure S9 in Supporting Information), showing that they were the two diastereoisomers **17** and **18** (Scheme 5).[24]

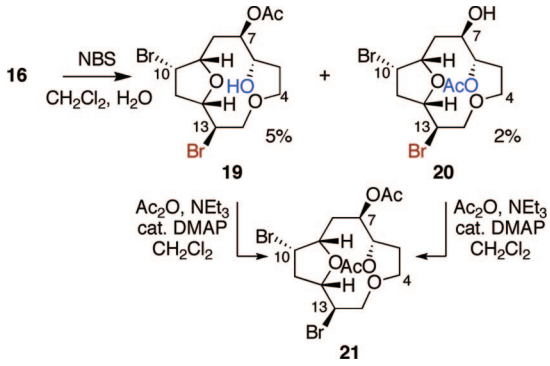
These must have resulted from the predicted bromonium ion induced transannular oxonium ion formation−fragmentation (cf. Scheme 1), where bromide, rather than water, is functioning as the nucleophile at C-6 with the signature inversion of stereochemistry. In this instance, bromide anion presumably arises from the well-known tendency of NBS to produce molecular bromine. It is also evident, by comparison of their stereochemistries at C-12 and C-13, that initial bromonium ion formation occurs on both faces of the double bond of macrocycle **15**.[25] Most significantly, diastereomer **18** represents the complete macrocyclic carbon framework, with the correct relative stereochemistries of the C-6, C-7, C-9, C-10, C-12, and C-13 stereocenters for obtusallene VII, all of which derive from the initial stereocenters of chlorohydrin **9** and two subsequent electrophilic bromination events. Despite the long reaction time and low isolated yield, this result shows that the proposed chemical pathway is perfectly feasible and is therefore completely consistent with our original hypothesis and further supports the reassignment of the structures of obtusallenes V−VII.

Macrocycle **16** was also treated with NBS to give macrocycles **19** and **20** (Scheme 6). The desired bromonium ion induced

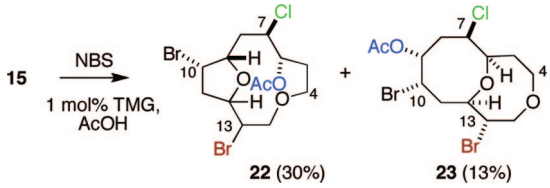
(24) Diastereoisomers **17** and **18** were found to have co-crystallized in the same crystal in a ca. 69:31 ratio. Hence the structure is referred to as **17**/**18**. See the Supporting Information for more details.

(25) Guella demonstrated that obtusallene II displayed temperature-dependent NMR spectra, existing as a mixture of equilibrating conformers, including a slow 180° flipping process of its *trans*-olefin through the macrocyclic ring, giving rise to broad NMR resonances at room temperature (see ref 7). In contrast, macrocycle **15** (and, indeed **16**) shows sharp resonances in its ^{1}H NMR and ^{13}C NMR spectra (see Supporting Information). Taken together with the experimental result that both faces of the olefin in **15** evidently undergo bromination may indicate that this macrocycle enjoys comparable conformation motion at the fast exchange limit at room temperature. Alternatively, room temperature may represent the slow exchange limit for the aforementioned molecular motion, where the major solution conformation is expected to resemble that of the solid state (cf. Figure 1), and a minor, unobserved conformer undergoes competitive reaction by the Curtin−Hammett principle.

SCHEME 6. Products Isolated after Bromonium Ion Induced Transannular Oxonium Ion Formation−Fragmentation of 16



SCHEME 7. Bromonium Ion Induced Transannular Oxonium Ion Formation−Fragmentation of 15 Using NBS and AcOH Catalyzed by TMG



transannular oxonium ion formation−fragmentation (cf. Scheme 1) has evidently occurred with neighboring group participation of the acetate followed by hydrolysis of the Woodward-type intermediate with adventitious water. The structure of **19** was confirmed by X-ray crystallography (see Figure S10 in Supporting Information), and the identity of **20** was confirmed by transforming them both into their bisacetates, which proved to be identical to **21**. Although the bromonium ion induced oxonium ion formation−fragmentation has occurred, the stereochemistry at C-12 and C-13 in **19** and **20** is the opposite to that observed in macrocycle **18** and in obtusallene VII. This illustrates the delicate balance between conformers and reactivity that are clearly in operation here. Again, however, despite the poor yield and long reaction time, a bromonium ion induced transannular oxonium ion formation−fragmentation is clearly a viable chemical pathway.

In an effort to reduce the long reaction times, to increase the yield of these bromonium ion induced transannular oxonium ion formation−fragmentation reactions, and to introduce an oxygen substituent at C-6, we made two key modifications to our reaction conditions on chloride-containing macrocycle **15**. We elected to catalyze the transfer of electrophilic bromine from NBS by the use of catalytic quantities of tetramethylguanidine.[26] Second, we used organic soluble acetic acid as our oxygen-based nucleophile. Much to our delight, the desired bromonium ion induced transannular oxonium ion formation−fragmentation (cf. Scheme 1) occurred rapidly (<1 h) with incorporation of acetate at C-6 to give bromoacetate **22** (stereochemistry unassigned at C-12 and C-13) in a much improved yield of 30% (Scheme 7). This is highly significant since the requisite oxygen and halide functionalities have now been installed at C-6 and C-13, respectively, as hypothesized for obtusallene VII. Interestingly, bromoacetate [5.5.1]bicyclotridecane **23** was also isolated in 13% yield from this reaction and characterized by X-ray

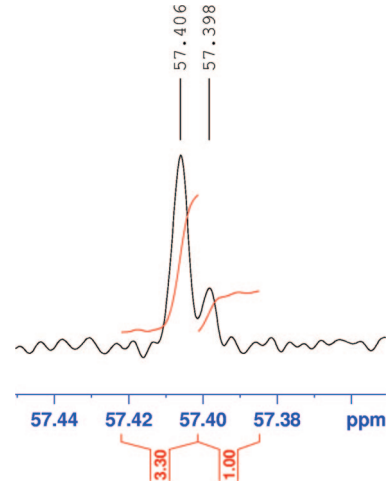


FIGURE 5. Chlorine isotope splitting of the ^{13}C resonance of obtusallene V at 57.4 ppm; the data were zero-filled to give a digital resolution of 0.031 Hz per point.

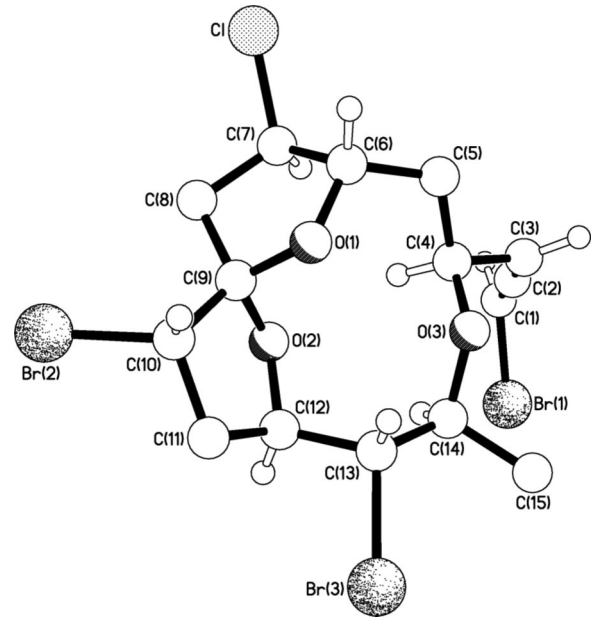


FIGURE 6. Molecular structure of **3**.

crystallography (see Figure S11 in Supporting Information). Evidently, **23** must also have been formed via bromonium ion induced transannular oxonium ion formation (cf. Scheme 1) but followed instead by nucleophilic attack of acetate at C-9, as witnessed by the inversion of (relative) stereochemistry at that position. It is interesting to speculate on the significance of adduct **23**, whereby since the pathway leading to it is apparently competitive with that leading to the obtusallene VII framework **22**, it may represent the core of an as yet undiscovered natural product from *Laurencia* species.

Finally, extensive NMR experiments on an authentic sample of obtusallene V led to an identical interpretation to that of Guella.[9] Thus, ^{13}C NMR analysis showed a resonance with a chemical shift of 57 ppm corresponding to C-7, and the carbon at C-13 showed a resonance at 61 ppm, where one must bear a chlorine atom and one must bear a bromine atom. Using the chlorine induced isotopic shift method[27,28] at 323 K in C_6D_6,

(26) Ahmad, S. M.; Braddock, D. C.; Cansell, G.; Hermitage, S. A. *Tetrahedron Lett.* **2007**, *48*, 915–918.

(27) Sergeyev, N. M.; Sergeyeva, N. D.; Raynes, W. T. *J. Magn. Reson., Ser. A* **1995**, *115*, 174–182.

the resonance at 57 ppm resolved into two signals in a 3:1 ratio separated by 8 ppb (Figure 5). This definitively locates the chlorine atom at C-7 and the bromine atom at C-13 in obtusallene V, directly in line with our hypothesis. This previously liquid sample proved to be crystalline in our hands, and the resulting X-ray crystal structure of obtusallene V (Figure 6) confirms these repositionings of the halogens, confirms all other relative and absolute stereochemistries, and confirms the structure of obtusallene V is that of compound **3**. In light of this finding, and also our experimentally observed bromonium ion induced rearrangements of obtusallene II models to give obtusallene VII macrocyclic frameworks with a bromide at C-13 and a signature inversion of stereochemistry at C-6 in accordance with our hypothesis (cf. Scheme 1), we now also reassign the structure of obtusallene VII as compound **2**. It follows also that obtusallene VI is reassigned as compound **4**.

Experimental Section

(1*R,6*E*,9*S**,10*S**,12*R**)-9-Bromo-12-chloro-4,13-dioxabicyclo[8.2.1]tridec-6-ene (15).** Tetrahydrofuran **12** (65 mg, 0.20 mmol) was dissolved in toluene (88 mL) and Hoveyda−Grubbs first generation catalyst $Ru(Cl)_2(PCy_3)(=CH\text{-}2\text{-}(2\text{-}PrO)C_6H_4)$ [Cy = cyclohexyl] (15 mg, 0.02 mmol) was added in one portion. The yellow solution was heated to reflux for 18 h. The solvent was evaporated in vacuo, and the resulting brown residue was purified by flash column chromatography (3:1 petroleum ether/EtOAc) to give macrocycle **15** (20 mg, 34%) as a white solid: mp 96−98 °C (recrystallized from hexane); IR (neat) 2928, 2871, 1447 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 5.75 (ddd, J = 15.2, 10.7, 2.4 Hz, 1H), 5.60−5.52 (m, 1H), 4.76 (ddd, J = 9.2, 7.2, 5.6 Hz, 1H), 4.52 (ddd, J = 12.5, 5.3, 4.0 Hz, 1H), 4.42 (app. dd, J = 4.0, 2.1 Hz, 1H), 4.26 (app. ddd, J = 12.3, 4.3, 1.8 Hz, 1H), 4.06−4.01 (m, 2H), 3.44 (dd, J = 12.1, 10.6 Hz, 1H), 3.24 (dt, J = 12.0, 1.7 Hz, 1H), 2.93−2.86 (m, 1H), 2.57−2.36 (m, 3H), 1.73−1.55 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 133.6, 125.0, 78.2, 76.6, 73.0, 67.5, 63.0, 50.1, 38.6, 37.5, 32.8; MS (CI^+, NH_3) m/z 299, 297, and 295 $(M + H)^+$; HRMS (CI^+, NH_3) m/z calcd for $C_{11}H_{17}O_2{}^{35}Cl^{79}Br$ $(M + H)^+$ 295.0100, found 295.0107.

(1*R*,6*E*,9*S*,10*S*,12*R*)-12-Acetoxy-9-bromo-4,13-dioxabicyclo[8.2.1]tridec-6-ene (16). Five identical simultaneous reactions were carried out according to the following protocol. Tetrahydrofuran **14** (0.055 g, 0.16 mmol) was dissolved in anhydrous toluene (10 mL). Aliquots of this solution (2 mL) were added to each of five reaction tubes, and toluene (8 mL) was added to each tube. Benzylidene $Ru(Cl)_2(PCy_3)(=CH\text{-}2\text{-}(2\text{-}PrO)C_6H_4)$ [Cy = cyclohexyl] (0.0115 g, 0.02 mmol) was dissolved in anhydrous toluene (10 mL) and 2 mL of this solution added to each of the five sealed tubes. Finally, 1,4-benzoquinone (0.0079 g, 2.3 mmol) was dissolved in toluene (10 mL) and 2 mL of this solution added to each of the five tubes. The five reaction mixtures where then heated at reflux for 21 h. The reaction mixtures were allowed to warm to rt and combined, and the solvent was evaporated in vacuo. The residue was chromatographed (70:30 petroleum ether/Et_2O to 30:70 petroleum ether/Et_2O) to give macrocycle **16** (0.017 g, 33%) as a white solid: mp 145−147 °C (recrystallized from hexane); R_f 0.53 (petroleum ether/Et_2O 30:70); $[\alpha]_D$ −16.5 (c 0.9, $CHCl_3$); IR (neat) 1736 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 5.73 (ddd, J = 15.2, 10.4, 2.4 Hz, 1H), 5.59−5.51 (m, 1H), 5.27−5.26 (br m, 1H), 4.65−4.60 (m, 1H), 4.51−4.46 (m, 1H), 4.26−4.22 (m, 1H), 3.99 (dt, J = 12.0, 3.0 Hz, 1H), 3.93 (app. br d, J = 11.6 Hz, 1H), 3.41 (dd, J = 12.0, 10.8 Hz, 1H), 3.20 (app. t, J = 12.2 Hz, 1H), 2.89−2.83 (m, 1H), 2.56−2.47 (m, 1H), 2.28−2.15 (m, 2H), 2.08 (s, 3H), 1.70−1.62 (m, 1H), 1.42−1.35 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 170.6, 133.4, 124.9, 78.4, 76.0, 75.7, 73.0, 67.5, 50.6, 37.2, 34.9, 31.1, 21.0; MS (CI^+, NH_3) m/z 338 and 336 $(M + NH_4)^+$, 321 and 319 $(M + H)^+$; HRMS (CI^+, NH_3) m/z calcd for $C_{13}H_{19}{}^{79}BrO_4$ $(M + H)^+$ 319.0545, found 319.0554. Anal. Calcd for $C_{13}H_{19}BrO_4$: C, 48.92, H, 6.00. Found: C, 49.03; H, 6.07.

(1*S,2*R**,7*S**,8*R**,10*S**,11*S**)-8-Chloro-4,13-dioxa-2,7,11-tribromobicyclo[8.2.1]tridecane (17) and (1*R**,2*S**,7*S**,8*R**,10*S**,11*S**)-8-Chloro-4,13-dioxa-2,7,11-tribromobicyclo[8.2.1]tridecane (18).** Macrocyclic alkene **15** (34 mg, 0.12 mmol) was dissolved in $CDCl_3$ in an NMR tube and NBS (14 mg, 0.12 mmol) added. The mixture was shaken and left covered in foil for a period of 20 days. To the mixture was added CH_2Cl_2 (30 mL), and the solution was washed with sodium bisulfite solution (20% w/w) (30 mL). The aqueous layer was extracted with CH_2Cl_2 (3 × 20 mL); the combined organic layers were washed with water (20 mL) and brine (20 mL), dried over anhydrous $MgSO_4$, filtered, and concentrated in vacuo. The residue was purified by successive rounds of flash column chromatography (10:1 petroleum ether/EtOAc) to give the title compounds **17** and **18** as an inseparable mixture in a ca. 3:2 ratio (4 mg, 8%) as a white solid: ^1H NMR (400 MHz, $CDCl_3$) δ 5.04 (br s, 1H **18**), 4.92−4.86 (m, 1H **17** + 1H **18**), 4.54−4.44 (m, 1H **17** + 1H **18**), 4.26 (d, J = 11.0 Hz, 1H **17**), 4.16−3.86 (m, 4H **17** + 4H **18**), 3.70−3.47 (m, 3H **17** + 3H **18**), 3.10−2.98 (m, 1H **17**), 2.92−2.74 (m, 1H **17** + 1H **18**), 2.60−2.37 (m, 2H **17** + 3H **18**), 2.30−1.93 (m, 2H **17** + 2H **18**); MS (CI^+, NH_3) m/z 459, 457, 455, 453 $(M + H)^+$; 476, 474, 472, 470 $(M + NH_4)^+$ HRMS (CI^+, NH_3) m/z calcd for $C_{11}H_{17}{}^{79}Br_3{}^{35}ClO_2$ $(M + H)^+$ 452.8467, found 452.8469.

(1*S*,2*R*,7*S*,8*R*,10*S*,11*S*)-8-Acetoxy-2,11-dibromo-4,13-dioxa-7-hydroxybicyclo[8.2.1]tridecane (19) and (1*S*,2*R*,7*S*,8*R*,10*S*,11*S*)-7-Acetoxy-2,11-dibromo-4,13-dioxa-8-hydroxybicyclo[8.2.1]tridecane (20). Macrocyclic alkene **16** (129 mg, 0.40 mmol) was dissolved in CH_2Cl_2 (13 mL) and NBS (72 mg, 0.40 mmol) added. Periodically, the reaction mixture was worked up as for the conversion of **15** into **18** and **19**. After ^1H NMR analysis to monitor conversion, the crude mixture was redissolved in CH_2Cl_2 (4 mL, 4 mL) and fresh NBS (72 mg, 144 mg) was added. After the third cycle and a total of ca. 100 h reaction time, the mixture was worked up as usual and column chromatography (10:90 petroleum ether/Et_2O and then 30:70 petroleum ether/CH_2Cl_2) gave first isohydroxydibromide **20** (3 mg, 2%) as a colorless oil: $[\alpha]^{25}_D$ −8.7 (c 0.16, CH_2Cl_2); IR (KBr) 3550−3100, 1729 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 4.77 (dd, J = 10.3, 4.5 Hz, 1H), 4.60 (ddd, J = 11.4, 6.8, 1.1 Hz, 1H), 4.48−4.06 (m, 2H), 3.97 (dd, J = 11.9, 6.9 Hz, 1H), 3.83 (dd, J = 11.9, 1.8 Hz, 1H), 3.70 (ddd, J = 9.8, 3.6, 2.8 Hz, 1H), 3.58 (app. t, J = 9.8 Hz, 1H), 2.78 (app. quint., J = 5.6 Hz, 1H), 2.45−2.34 (m, 2H), 2.24 (ddd, J = 13.2, 9.8, 8.2 Hz, 1H), 2.09 (s, 3H), 1.84 (dt, J = 14.7, 4.4 Hz, 1H), 1.47 (ddd, J = 14.5, 11.2, 11.2 Hz, 1H), OH peak not observed; ^{13}C NMR (125 MHz, $CDCl_3$) δ 170.8, 81.7, 79.0, 77.7, 72.2, 71.5, 66.7, 50.1, 45.6, 39.9, 34.5, 29.0, 21.4; MS (CI^+, NH_3) m/z 436, 434, 432 $(M + NH_4)^+$, 419, 417, 415 $(M + H)^+$; HRMS (CI^+, NH_3) m/z calcd for $C_{13}H_{21}O_5{}^{79}Br_2$ $(M + H)^+$ 414.9756, found 414.9757. Second hydroxydibromide (**19**) (9 mg, 5%) as a white solid: mp 128−129 °C; $[\alpha]^{25}_D$ −6.5 (c 0.47, CH_2Cl_2); IR (KBr) 3550−3200, 1727 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 5.30 (br s, 1H), 4.61 (m, 2H), 4.43 (br s, 1H), 4.34 (br s, 1H), 4.03−3.87 (m, 3H), 3.73−3.68 (m, 2H), 2.92 (app. quint., J = 6.1 Hz, 1H), 2.77 (br d, J = 11.2 Hz, 1H), 2.36−2.21 (m, 2H), 2.19−2.09 (m, 1H), 2.10 (s, 3H), 1.61−1.50 (m, 1H), OH peak not observed; ^{13}C NMR (125 MHz, $CDCl_3$) δ 170.5, 83.4, 77.7, 74.6, 74 (broad), 71.1, 66.8, 51.0, 49.0, 42.0, 35.1, 31.9, 21.3; MS (CI^+, NH_3) m/z 436, 434, 432 $(M + NH_4)^+$, 419, 417, 415 $(M + H)^+$; HRMS (CI^+, NH_3) m/z calcd for $C_{13}H_{21}O_5{}^{79}Br_2$ $(M + H)^+$ 414.9756, found 414.9764.

Chemical Correlation of 19 and 20 by Conversion into (1*S*,2*R*,7*S*, 8*R*,10*S*,11*S*)-7,8-Diacetoxy-2,11-dibromo-4,13-dioxabicyclo[8.2.1]tridecane (21). To a stirred solution of alcohol **19** (4.7 mg, 0.011 mmol) in dichloromethane (0.4 mL) at 0 °C was added DMAP (1 mg), followed by a solution of acetic anhydride (4.5 μL, 0.047 mmol) and triethylamine (6.6 μL, 0.047 mmol) in dichloromethane (0.1 mL). The mixture was allowed to warm to rt and stirred for 8 h. The mixture was quenched with water and

extracted with dichloromethane, and the combined organic phase was dried over magnesium sulfate. The solids were removed by filtration, and the solvent was evaporated. ^{1}H NMR analysis of the crude reaction mixture showed that the conversion to bisacetate **21** was quantitative. Meanwhile, to a stirred solution of alcohol **20** (1.6 mg, 0.004 mmol) in dichloromethane (0.2 mL) at 0 °C was added DMAP (1 mg), followed by a solution of acetic anhydride (1.5 μL, 0.017 mmol) and triethylamine (2.5 μL, 0.017 mmol) in dichloromethane (0.03 mL). The mixture was allowed to warm to rt and stirred for 8 h. The mixture was quenched with water, extracted with dichloromethane, and the combined organic phase was dried over magnesium sulfate. The solids were removed by filtration, and the solvent was evaporated. ^{1}H NMR analysis of the crude reaction mixture showed approximately 60% conversion to the desired bisacetate, and comparison of the ^{1}H NMR spectra of the two samples revealed them to be identical. The samples were then combined and purified by silica gel column chromatography (1:1 petroleum spirits/diethyl ether) to give bisacetate **21** (3.8 mg, 55%) as a colorless oil: $[\alpha]^{25}_D$ −47.0 (*c* 0.24, CH_2Cl_2); IR (KBr) 1731 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.31−5.25 (m, 2H), 4.46−4.41 (m, 1H), 4.15 (dd, J = 10.4, 1.2 Hz, 1H), 4.05−3.97 (m, 3H), 3.70 (dt, J = 12.4, 2.0 Hz, 1H), 3.62−3.50 (m, 3H), 2.95 (app. quint., J = 7.2 Hz, 1H), 2.48−2.33 (m, 3H), 2.08 (s, 3H), 2.06 (s, 3H), 1.37−1.31 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.1, 170.2, 82.7, 77.5, 75.8, 75.2, 74.8 (broad), 50.6, 43.7, 35.6 (broad), 29.3, 21.2, 21.0; MS (CI^+, NH_3) *m*/*z* 478, 476, 474 $(M + NH_4)^+$; HRMS (CI^+, NH_3) *m*/*z* calcd for $C_{15}H_{26}NO_6{}^{79}Br_2$ $(M + H)^+$ 474.0127, found 474.0123.

(7*S,8*R**,10*S**,11*S**)-7-Acetoxy-8-chloro-2,11-dibromo-4,13-dioxa-bicyclo[8.2.1]tridecane (22) and (1*R**,2*S**,7*R**,8*R**,10*R**,11*S**)-10-Ace-toxy-2,11-dibromo-8-chloro-4,13-dioxabicyclo[5.5.1]tridecane (23).** Macrocyclic alkene **15** (8.0 mg, 27.1 μmol) was dissolved in CD_2Cl_2. Tetramethylguanidine in CH_2Cl_2 (0.032 M, 10 μL, 0.32 μmol), AcOH in CH_2Cl_2 (2.62 M, 10 μL, 26.2 μmol), and NBS (4.8 mg, 27.1 μmol) were added sequentially at ambient temperature. The mixture was stirred for 1 h, and complete conversion of starting material was observed via TLC and ^{1}H NMR analyses. To the mixture was added CH_2Cl_2 (30 mL), and the solution was washed with sodium bisulfite solution (20% w/w) (30 mL). The aqueous layer was extracted with CH_2Cl_2 (3 × 20 mL); the combined organic layers washed with water (20 mL) and brine (20 mL), dried over anhydrous $MgSO_4$, filtered, concentrated, and purified by flash column chromatography (5:1 petroleum ether/EtOAc) to give first bromoacetate **22** (3.5 mg, 30%) as a colorless oil: R_f 0.61 (3:1 petroleum ether/EtOAc); IR (KBr) 1731 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.34 (br d, J = 7.3 Hz, 1H), 4.49 (br s, 2H), 4.22 (d, J = 11.0 Hz, 1H), 4.12 (br s, 1H), 3.95 (br s, 2H), 3.67 (br t, J = 12.3 Hz, 1H), 3.53−3.49 (m, 2H), 3.04−2.98 (m, 1H), 2.64−2.55 (m, 2H), 2.37 (br d, J = 14.5 Hz, 1H), 2.16−2.13 (m, 1H), 2.07 (s, 3H), 1.45−1.42 (m, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 171.1, 82.8, 77.2, 76.1, 76.0, 68.4, 64.5 (broad), 50.5, 49.7, 44.2, 40.6 (broad), 31.7, 21.2; MS (CI^+, NH_3) *m*/*z* 450, 452, 454, 456 $(M + NH_4)^+$; HRMS (CI^+, NH_3) *m*/*z* calcd for $C_{13}H_{23}NO_4{}^{79}Br_2{}^{35}Cl$ $(M + NH_4)^+$ 449.9682, found 449.9690. Second bromoacetate **23** (1.5 mg, 13%) as white solid: mp 134−136 °C (recrystallized from hexane); R_f 0.42 (3:1 petroleum ether/EtOAc); IR (KBr) 1733 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.66 (d, J = 8.1 Hz, 1H), 4.62 (br s, 1H), 4.25 (dd, J = 12.6, 3.4 Hz, 1H), 4.14−4.09 (m, 2H), 4.04 (ddd, J = 12.5, 5.9, 1.8 Hz, 1H), 3.92−3.88 (m, 2H), 3.83 (dd, J = 12.6, 5.3 Hz, 1H), 3.77 (td, J = 11.9, 4.6 Hz, 1H), 3.04 (ddd, J = 16.1, 8.1, 2.1 Hz, 1H), 2.64 (ddd, J = 15.0, 4.4, 1.3 Hz, 1H), 2.42 (ddd, J = 14.9, 10.9, 3.2 Hz, 1H), 2.34−2.27 (m, 1H), 2.15 (br dd, J = 16.1, 4.3 Hz, 1H), 2.08 (s, 3H), 1.53−1.45 (m, 1H); MS (CI^+, NH_3) *m*/*z* 450, 452, 454, 456 $(M + NH_4)^+$; HRMS (CI^+, NH_3) *m*/*z* calcd for $C_{13}H_{23}NO_4{}^{79}Br_2{}^{35}Cl$ $(M + NH_4)^+$ 449.9682, found 449.9681.

Acknowledgment. We thank the EPSRC for financial support (EP/C542169/1), Pfizer for an Industrial CASE award (to S.S.), and Prof. G. Guella, University of Trento, Italy, for an authentic sample of obtusallene V.

Supporting Information Available: General experimental procedures and data for **6**−**12** and **14**, copies of ^{1}H spectra for **6**−**12** and **14**−**23**, ^{13}C NMR spectra for **6**−**12**, **14**−**16**, and **19**−**22**, details of the chlorine isotope experiment on obtusallene V, and X-ray crystallographic data for **3**, **15**−**19**, and **23**. This material is available free of charge via the Internet at http://pubs.acs.org.

JO8026577

(28) For the use of the chlorine isotopic shift method for the elucidation of halogenated structures, see ref 2 and: (a) Suzuki, M.; Nakano, S.; Takahashi, Y.; Abe, T.; Masuda, M. *Phytochemistry* **1999**, *51*, 657–662. (b) Suzuki, M.; Daitoh, M.; Vairappan, C. S.; Abe, T.; Masuda, M. *J. Nat. Prod.* **2001**, *64*, 597–602. (c) Vairappan, C. S.; Daitoh, M.; Suzuki, M.; Abe, T.; Masuda, M. *Phytochemistry* **2001**, *58*, 291–297.