133834-31-8; (±)-38, 133834-32-9; (±)-39, 133834-33-0; (±)-40, 133834-34-1; 41, 133834-35-2; (±)-42, 133834-36-3; (±)-44, 133834-38-5; 45, 133834-39-6; (±)-46, 133834-40-9; 47 (isomer 1), 133834-41-0; 47 (isomer 2), 133834-73-8; 48, 133834-42-1; (±)-49, 133834-43-2; (±)-*exo*-50, 133834-44-3; (±)-*endo*-50, 133834-70-5; (±)-51, 60478-96-8; (±)-52a, 67928-92-1; (±)-53 (isomer 1), 133834-45-4; (±)-53 (isomer 2), 133834-69-2; 54, 81925-56-6; (±)-55, 133834-46-5; (±)-*exo*-56, 133906-54-4; (±)-*endo*-56, 133834-47-6; 57, 72081-22-2; (±)-58, 133834-48-7; (±)-*exo*-59, 133834-49-8; (±)-*endo*-59, 133906-56-6; (±)-60, 133834-50-1; 62, 64391-30-6; (±)-63, 133834-51-2; (±)-*exo*-64, 133906-55-5; (±)-*endo*-64, 133834-52-3; (±)-65, 133834-53-4; CH_2=$C(CH_3)C(CH_3)$=CH_2, 513-81-5; CH_2=CHSPh, 1822-73-7; CH_2=CHOEt, 109-92-2; HC≡$CNEt_2$, 4231-38-3; HC≡COEt, 927-80-0; HC≡$CSiMe_3$, 1066-54-2; CH_2=$C(CH_3)_2$, 115-11-7; furan, 110-00-9; 1,3-dioxolane, 646-06-0; tetrahydrofuran, 109-99-9; cyclopentadiene, 542-92-7; 1,3-cyclohexadiene, 592-57-4; anthracene, 120-12-7; 2-isopropylidene-1,3-dithiane, 36998-38-6; 2,3-dihydrofuran, 1191-99-7; 4,5-dihydro-2-furancarbonitrile, 108734-03-8; 2-methylenetetrahydrofuran, 18137-88-7; 3,4-dihydro-2*H*-pyran, 110-87-2; indene, 95-13-6; 2,5-norbornadiene, 121-46-0; 2-norbornene, 498-66-8; (−)-β-pinene, 18172-67-3.

Supplementary Material Available: ^1H spectra for **3a, 3f, 3g, 3h, 6a, 6c, 9, 11, 24, 26a, 27a/27b, 34, 35, 36, 40, 42, 44, 45/46, 47, 48, 55,** *endo*-**56**/*exo*-**56, 60, 63, 65.** ^{13}C NMR spectra for **34-36, 40** (29 pages). Ordering information is given on any current masthead page.

A Facile Synthesis of Bicyclo[*m*.*n*.1]alkan-1-ols. Evidence for Organosamarium Intermediates in the Samarium(II) Iodide Promoted Intramolecular Barbier-Type Reaction

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Samarium(II) iodide (SmI_2) has been successfully employed as a reductive coupling agent for the intramolecular Barbier-type synthesis of bicyclo[*m*.*n*.1]alkan-1-ols. Thus, a variety of 3-(ω-iodoalkyl)cycloalkanones, upon treatment with SmI_2 and a catalytic quantity of iron complex in tetrahydrofuran (THF), provide the title compounds in excellent yields. The reaction is quite general for the construction of diverse bicyclic ring systems, including the highly strained bicyclo[2.1.1]hexan-1-ol. In addition to exploring the synthetic utility of this reaction, studies have been performed which provide insight on the mechanistic details of the SmI_2-promoted intramolecular Barbier-type synthesis. Compelling evidence for the intermediacy of organosamarium species has thus been gathered.

Bridgehead bicyclic alcohols and their derivatives have played an integral role in the development of organic chemistry. Such compounds have been instrumental tools for the elucidation of fundamental reaction mechanisms,[2] and the rigid carbon skeletons which characterize these molecules have also provided ideal templates on which to examine the structural requirements and thermodynamic features of reactive intermediates (carbocations, radicals, and carbanions).[3] Synthetic chemists have also taken advantage of the inherent features of bridgehead-functionalized bicyclic systems for the construction of complex natural products and theoretically interesting molecules.[4]

Conventional syntheses of even the simplest bridgehead bicyclic alcohols are often long, involved sequences that lead to mixtures of products.[5] In fact, no unified, efficient strategy for the synthesis of bridgehead bicyclic alcohols exists. An intramolecular Barbier-type synthesis, utilizing appropriately substituted halo ketone precursors, would provide one such approach to this important class of compounds. The SmI_2-promoted version of the intramolecular Barbier reaction has already proven to be a convenient method for the synthesis of monocyclic[6] and fused bicyclic or polycyclic alcohols,[7] comprising an impressive range of substitution patterns. A single example of bridged

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bicyclic alcohol synthesis using this procedure currently graces the literature.[8] Herein we report a systematic study of the SmI_2-promoted intramolecular Barbier synthesis applied to the construction of bridged bicyclic alcohols. This investigation has led to a facile, general synthesis of bicyclo[*m.n.*1]alkan-1-ols and has also revealed important new mechanistic information on the nature of the SmI_2-promoted intramolecular Barbier-type reaction itself.

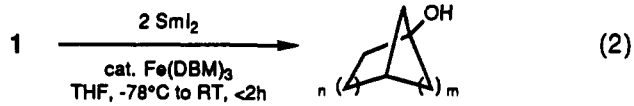
Results and Discussion

In order to test the broad outlines of the intramolecular Barbier strategy for bridgehead bicyclic alcohol construction, several representative iodo ketones were synthesized as potential substrates. These compounds (**1**, m = 2–4) were prepared by a three-step process involving initial conjugate addition of appropriate organocopper or organosilicon reagents to α,β-unsaturated ketones, followed by photochemically induced hydrobromination and finally Finkelstein reaction with NaI in acetone. The 3-(iodomethyl)cycloalkanones (**1**, m = 1) were most conveniently prepared by cyclopropanation of α,β-unsaturated enones with dimethyl sulfoxonium methylide,[9] followed by ring opening of the cyclopropane with HI[10] or TMSI[11] (eq 1).

(1)

1

Optimization of the SmI_2-promoted cyclization procedure was achieved by performing the reaction at fairly high dilution (0.015 M) in THF, with initiation of the reaction at −78 °C. Iron complexes serve as effective catalysts for the process,[7a,b,12] allowing the reaction to be carried out under extremely mild conditions (eq 2). Any number of



(2)

2

iron complexes appear to catalyze these reactions quite effectively, including $FeCl_3$, $FeCl_2$,[13] $Fe(acac)_3$, and tris(dibenzoylmethido)iron(III) [$Fe(DBM)_3$].[14] The latter is an air-stable, THF-soluble, nonhygroscopic complex that can be very easily prepared in gram quantities. Utilizing these protocols, high yields of the desired products can be achieved in nearly all cases.

As outlined in Table I, the method is quite general for the synthesis of a variety of bicyclo[*m.n.*1]alkan-1-ols. Cyclopentanone through cyclooctanone substrates can all be accommodated with little, if any, differentiation in reactivity or yields. In addition, the halo alkyl side chain length can be varied satisfactorily from one to three carbons. Particularly impressive is the fact that the bicyclo[2.1.1]hexane skeleton can be constructed by this process (entry 1), in spite of the considerable ring strain (41 kcal mol^{-1}) that is engendered in the carbocyclic backbone of this system[15] and the high energy of activation that must be surmounted in leading to it. 3-(4-Iodobutyl)cycloalkanones define the practical limit of side-chain extension that can be tolerated (**1**, m = 4, entries 4 and 8). Apparently entropic factors begin to limit the process at this point.

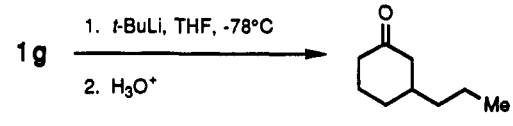
Table I. Samarium(II) Iodide Promoted Cyclization of Halo Ketones 1 To Provide Bridgehead Bicyclic Alcohols 2 (eq 2)

entry	substrate	product	n	m	% isoltd yield
1	**1a**	**2a**	1	1	66
2	**1b**	**2b**	1	2	71
3	**1c**	**2c**	1	3	54
4	**1d**	**2d**	1	4	22
5	**1e**	**2e**	2	1	77
6	**1f**	**2f**	2	2	69
7	**1g**	**2g**	2	3	73 (58)[a]
8	**1h**	**2h**	2	4	15
9	**1i**	**2i**	3	2	73
10	**1j**	**2j**	3	3	76
11	**1k**	**2k**	4	2	86
12	**1l**	**2l**	4	3	87

[a] The yield in parentheses is for the corresponding bromo ketone, which required 12 h to react completely as compared to <1 h for the iodo ketone.

Although bromo ketones can be utilized for the reaction (entry 7), they react much more slowly than the corresponding iodides under similar conditions (12 h for complete reaction of the bromide versus 1 h for the iodide). The yields of products derived from bromo ketone precursors also tend to be lower when compared to those of the iodide counterparts (58% versus 73% for the iodide). Chloro ketones were not utilized in the study, but on the basis of the results acquired with the bromo ketone above and previous reports of intermolecular Barbier-type reactions promoted by SmI_2,[12] it can be assumed that they would be quite unreactive.

It is important to note that other potential reductants for this process (e.g., activated magnesium, n-BuLi, or t-BuLi[16]) failed completely in identical reactions. For example, addition of t-BuLi to **1g** provided none of the desired bicyclic alcohol. The major product isolated was 3-propylcyclohexanone (eq 3). Activated magnesium and n-BuLi provided intractable mixtures, in which again the bicyclic alcohol could not be detected.



(3)

41%

Further demonstration of the method's generality can be appreciated by the examples displayed in Table II. Thus, the SmI_2-promoted intramolecular Barbier approach can be applied to a variety of elaborated substrates and is expected to be tolerant of a wide range of sensitive functional groups (entry 2). The ability to generate highly strained ring systems is once again clearly in evidence (entry 3), and even the most highly hindered ketones react with no attenuation of yield (entry 6). Neopentyl iodides have been found to react quite effectively (entry 7), but allylic iodides are surprisingly capricious in their reactivity (entries 8–10). The latter is particularly puzzling because allylic halides are more reactive than alkyl halides in

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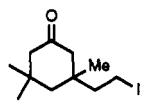
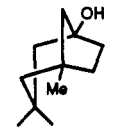
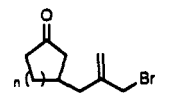
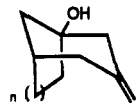
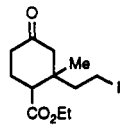
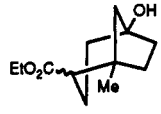
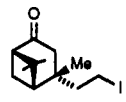
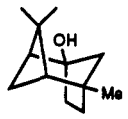
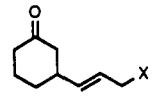
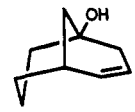
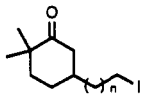
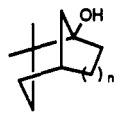
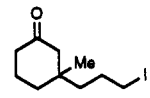
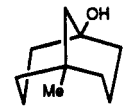
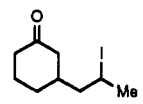
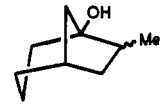
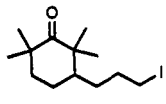
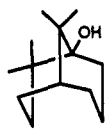
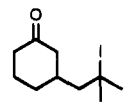
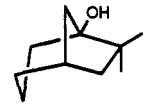
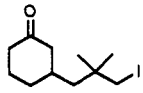
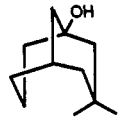
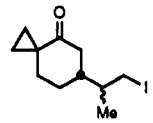
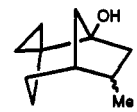
(16) See refs 6a and 7b and references cited therein.

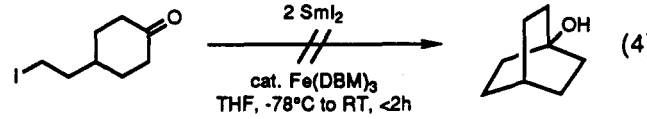
Table II. Samarium(II) Iodide Promoted Cyclization of Substituted Cycloalkanone Derivatives To Provide Bicyclo[*m*.*n*.1]alkan-1-ols

entry	substrate	product	% isoltd yield	entry	substrate	product	% isoltd yield
1	 3a	 4a	88	8	 3h (n=1)	 4h	54
2	 3b	 4b	83[a]	9	3i (n=2)	4i	0
3	 3c	 4c	75	10	 3j X = Cl, Br, I, OMs	 4j	0
4	 3d (n=1)	 4d	84	11	 3k	 4k	71
5	3e (n=2)	4e	77	12	 3l	 4l	79[c]
6	 3f	 4f	74[b]	13	 3m	 4m	57[d]
7	 3g	 4g	65	14	 3n	 4n	75[e]

[a] A single (undefined) diastereomeric substrate was utilized for the reaction, resulting in the generation of a single diastereomeric product. [b] In addition, a 12% yield of a 1:1 mixture of 3-(2-propenyl)-2,2,6,6-tetramethylcyclohexanone and 3-propyl-2,2,6,6-tetramethylcyclohexanone was isolated. [c] A 3:1 mixture of exo:endo isomers was generated. See: Belotti, D.; Cossy, J.; Pete, J. P.; Portella, C. *J. Org. Chem.* **1986**, *51*, 4196. [d] 3-(2-Methylpropyl)cyclohexanone and 3-(2-methyl-2-propenyl)cyclohexanone were also isolated as a 1:1 mixture in 30% yield. A trace of 3-(2-methyl-1-propenyl)cyclohexanone was also detected. [e] A 3:1 mixture of endo:exo isomers was isolated, using a 3:1 mixture of diastereomeric substrates **3n**.

Barbier-type reactions, and have provided excellent yields of coupled product in related reactions.[6a] Secondary alkyl iodides react smoothly and efficiently in the cyclization process (entry 12). As expected, a mixture of diastereomers results from this transformation. Cyclic ketones with pendant tertiary alkyl iodide side chains are also suitable substrates for the reaction (entry 13). In the single such example that was examined, the desired bicyclic alcohol was isolated in 57% yield. In addition, 3-(2-methylpropyl)cyclohexanone and 3-(2-methyl-2-propenyl)cyclohexanone were isolated as a 1:1 mixture in 30% yield. A trace of 3-(2-methyl-1-propenyl)cyclohexanone was also detected. These products may arise from disproportionation of the tertiary radical generated as the initial intermediate in the process.[17] Alternatively, the disproportionation products could result from decomposition of intermediate organoiron species. The latter process is known to provide 1:1 mixtures of alkenes and alkanes in iron-catalyzed reactions of organomagnesium reagents.[18]

Although the intramolecular Barbier approach to bicyclo[*m*.*n*.1]alkan-1-ols proved to be extraordinarily general, it has thus far not been possible to extend the method to the construction of bicyclo[*m*.*n*.2]alkan-1-ols. Subjection of 4-(2-iodoethyl)cyclohexanone to the standard reaction conditions led to a mixture of products in which the desired bicyclo[2.2.2]octan-1-ol was not detected (eq 4).



(4)

The mechanism of the SmI_2-promoted Barbier reaction has been the object of much study and speculation. Kagan's initial studies on the *intermolecular* process led to the conclusion that organosamarium species were probably not involved in the coupling between organic halides and carbonyl substrates.[19] Instead, alkyl radicals were pro-

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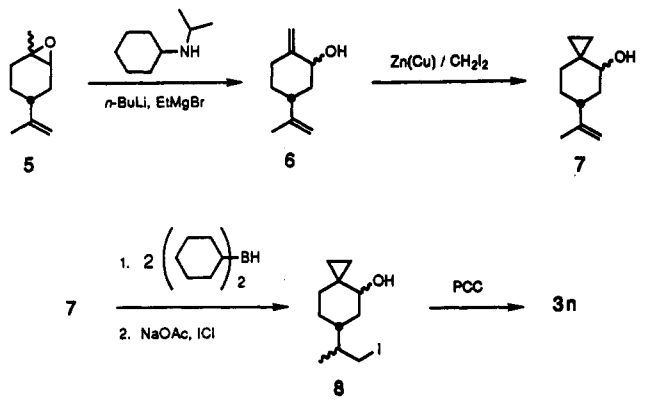
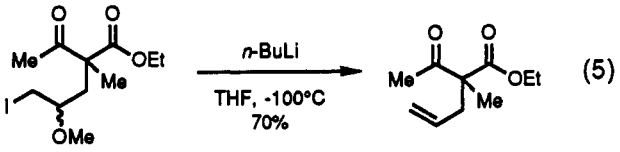
(18) Kochi, J. K. *Organometallic Mechanisms and Catalysis*; Academic: New York, 1978; pp 374–381.

Scheme I



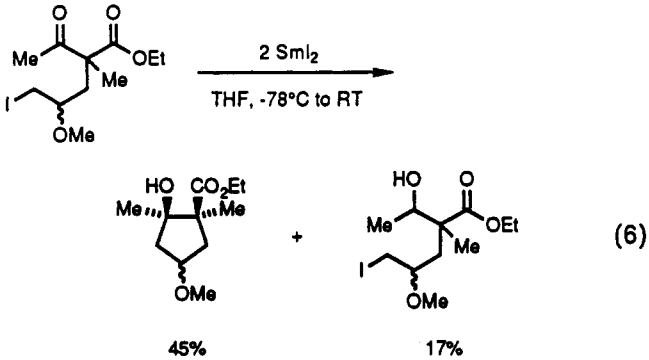
posed as the key intermediates in the process. Left open was the question of whether the crucial carbon–carbon bond-forming step in the reaction was the result of alkyl radical/ketyl coupling, or whether an alkyl radical addition to a samarium(III)-activated carbonyl was perhaps responsible for formation of the desired alcohol.[20]

Subsequent studies on SmI_2-induced *intramolecular* processes with β-dicarbonyl substrates seemed to reinforce these conclusions.[21] For example, treatment of an appropriately functionalized β-methoxy organic halide with *n*-BuLi led (as expected) to the olefin through a well-established β-elimination process (eq 5).[22] No cyclized



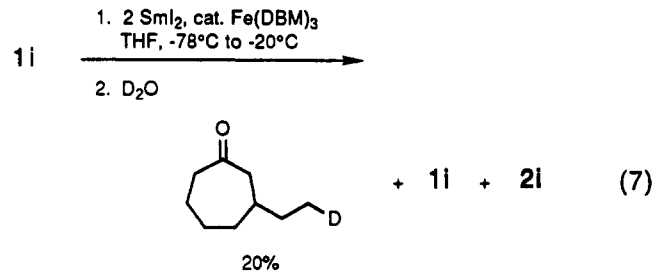
(5)

material was detected. On the other hand, treatment of the same substrate with SmI_2 led largely to cyclized product and a small amount of reduced alcohol, with none of the olefin detected by gas chromatographic analysis of the crude reaction mixture (eq 6).[21] This latter result demonstrated that an organosamarium species was not involved in the cyclization reaction and implied that some type of radical process was responsible.



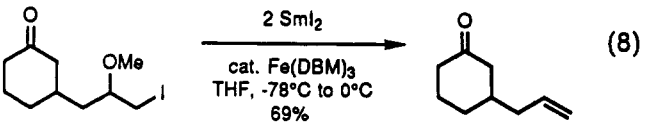
(6)

Somewhat surprisingly, studies completed on the mechanism of the SmI_2-induced intramolecular Barbier reaction applied to the synthesis of bridgehead bicyclic alcohols have revealed that organosamarium compounds undoubtedly *are* involved in these transformations. For example, allowing the reaction of 3-(2-iodoethyl)cycloheptanone with SmI_2 to proceed to partial completion (using shorter reaction times at lower temperatures) and then quenching the reaction with D_2O leads to the generation of 3-ethylcycloheptanone in about 20% isolated yield, with >90% deuterium incorporation in the ethyl group as determined by ^1H NMR, ^{13}C NMR, and mass spectral analysis (eq 7). Further evidence for the inter-



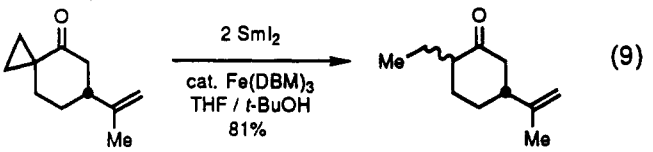
(7)

mediacy of an organosamarium species was derived from subjection of 3-(3-iodo-2-methoxypropyl)cyclohexanone to the standard reductive cyclization reaction conditions. In this case, 3-allylcyclohexanone was isolated from the reaction mixture in 69% yield (eq 8). There was no evidence for the formation of any bridgehead bicyclic alcohol. Again, these results appear consistent only with the intermediacy of an organosamarium species, which in this case undergoes a rapid β-elimination process prior to cyclization onto the carbonyl.



(8)

A final study was conducted to indicate whether ketyls were involved in the reaction. Recognizing the propensity of cyclopropyl carbinyl ketyls to undergo facile ring opening,[23] substrate **3n** was designed and synthesized as a test substrate for the existence of these intermediates. As indicated in Table II (entry 14), this substrate underwent an efficient cyclization to provide the expected bridgehead bicyclic alcohol, with no evidence for the ketyl-induced fragmentation. To insure that the cyclopropyl ring cleavage can indeed occur in the event of ketyl anion generation, a model substrate that did not possess the iodide was subjected to similar reaction conditions. As anticipated, in the absence of the more reactive alkyl iodide functional group, a ketyl was generated, leading to isolation of the fragmentation product in excellent yield (eq 9). One



(9)

caveat in this analysis is the revelation that some aryl cyclopropyl ketyl anions undergo reversible ring opening.[24]

(19) Kagan, H. B.; Namy, J. L.; Girard, P. *Tetrahedron* **1981**, *37*, 175, Supplement No. 1.

(20) (a) Kagan, H. B. *Inorg. Chim. Acta* **1987**, *140*, 3. (b) Kagan, H. B.; Sasaki, M.; Collin, J. *Pure Appl. Chem.* **1988**, *60*, 1725. (c) Kagan, H. B.; Collin, J. In *Paramagnetic Organometallic Species in Activation/Selectivity, Catalysis*; Chanon, M., Julliar, M., Poite, J. C., Eds.; Kluwer Academic Publishers: Dordrecht, 1989. (d) Kagan, H. B. *New J. Chem.* **1990**, *14*, 453.

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(22) Cooke, M. P., Jr.; Houpis, I. N. *Tetrahedron Lett.* **1985**, *26*, 4987.

(23) (a) Norin, T. *Acta Chem. Scand.* **1965**, *19*, 1289. (b) House, H. O.; Boots, S. G.; Jones, V. K. *J. Org. Chem.* **1965**, *30*, 2519. (c) Dauben, W. G.; Deviny, E. J. *Ibid.* **1966**, *31*, 3794. (d) Fraisse-Jullien, R.; Frejaville, C. *Bull. Soc. Chim. Fr.* **1968**, 4449. (e) Dauben, W. G.; Wolf, R. E. *J. Org. Chem.* **1970**, *35*, 374. (f) Dauben, W. G.; Wolf, R. E. *Ibid.* **1970**, *35*, 2361. (g) White, J. D.; Torii, S.; Nogami, J. *Tetrahedron Lett.* **1974**, 2879. (h) Murphy, W. S.; Wattanasin, S. *Ibid.* **1981**, *22*, 695. (i) Nelson, K. A.; Mash, E. A. *J. Org. Chem.* **1986**, *51*, 2721.

Because the question of reversibility has not been addressed for alkyl cyclopropyl ketyl anions, due caution is required in the interpretation of experiments like those described above which were designed to demonstrate the intermediacy (or absence) of ketyl anions along the major reaction pathway.[25]

These mechanistic studies have provided the first irrefutable evidence that an organometallic species *can* be involved in the SmI_2-promoted intramolecular Barbier-type synthesis.[26] Because several other SmI_2-induced Barbier reactions quite clearly do *not* proceed via discrete organometallic species, it is obvious that even rather subtle changes in the nature of the reaction (e.g., intermolecular versus intramolecular reactions, as well as the presence or absence of an iron catalyst) or in the structure of the substrates themselves (e.g., isolated ketone substrates versus β-dicarbonyl precursors) have the potential to tip the balance quite dramatically from one mechanistic manifold to another.

Conclusions

Samarium(II) iodide has been successfully applied as a reductive coupling agent for the intramolecular Barbier-type synthesis of bicyclo[*m.n.*1]alkan-1-ols. This protocol provides, for the first time, an efficient, convenient, and general synthesis of this important class of compounds. In addition, evidence has been presented for the intermediacy of organosamarium species in these processes.

Experimental Section

Reagents. Tetrahydrofuran (THF) was distilled immediately prior to use from benzophenone ketyl under Ar. Samarium metal was purchased from Rhône-Poulenc Inc., Phoenix, AZ, and was weighed and stored under an inert atmosphere. CH_2I_2 was purchased from Fluka Chemicals and was distilled prior to use. Standard benchtop techniques were employed for handling air-sensitive reagents,[27] and all reactions were carried out under Ar.

General Procedure for Preparation of 3-(Iodomethyl)-cycloalkanones. To a suspension of NaH (10 mmol) in 20 mL of DMF was added trimethyl sulfoxonium iodide in several portions over 10 min. The resulting mixture was allowed to stir at rt for 30 min, after which the enone (10 mmol) in 3 mL of DMF was added. After being stirred for an additional 2 h the reaction mixture was poured into ice cold aqueous HCl (2%). Extractive workup (Et_2O) followed by flash chromatography afforded the desired cyclopropyl ketone.

Aqueous HI (47%, 5.5 mmol) in 1 mL of HOAc was added to a solution of the cyclopropyl ketone (4 mmol) in 15 mL of benzene at 0 °C. Upon complete reaction (ca. 30 min) and normal workup, the title compounds were isolated via flash chromatography.

Bicyclo[3.1.0]hexan-2-one (1e Precursor). Following the general procedure described above, the title compound was isolated in 72% yield: ^1H NMR (300 MHz, $CDCl_3$) δ 2.22 (ddd, *J* = 18.6, 5.4, 3.9 Hz, 1 H), 2.25–1.78 (m, 3 H), 1.72–1.48 (m, 4 H), 1.18–1.12 (m, 1 H), 1.06–0.98 (m, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 209.28, 36.59, 25.64, 21.07, 17.56, 17.24, 10.01.

3-(Iodomethyl)cyclohexan-1-one (1e). Following the general procedure described above, 1e was isolated in 66% yield: ^1H NMR (200 MHz, $CDCl_3$) δ 3.17–3.14 (m, 2 H), 2.47–1.37 (m, 9 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 209.85, 47.91, 40.62, 40.00, 31.47, 24.15, 13.61.

General Procedure for Preparation of 3-(2-Iodoethyl)-cycloalkanones.[28] To a suspension of CuCN[29] (21 mmol) in 20 mL of THF was added 1 equiv of TMEDA. The mixture was allowed to stir at rt for 10 min prior to being cooled to −78 °C. Vinylmagnesium bromide (20 mmol, 1 M THF) was added dropwise over 5 min, and the resulting light yellow suspension continued to stir for an additional 20 min. TMSCl (18 mmol) was added followed by a precooled solution of the enone (15 mmol) in 10 mL of THF. Upon complete reaction (ca. 30 min), the reaction mixture was quenched with aqueous NH_4Cl/NH_4OH (10:1). Extractive workup (Et_2O) afforded the TMS enol ether that was hydrolyzed in 1 M HCl. The 3-ethenylcycloalkanone was purified by flash chromatography for use in the next step.

A solution of the olefinic ketone (8 mmol) in 100 mL of hexanes was added to a 110-mL quartz tube, and the resulting solution was purged with Ar for 5 min. The vessel was irradiated (254 nm) in a Rayonet reactor while HBr gas was slowly bubbled into the solution.[30] Reaction progress was monitored by TLC, and complete reaction times were generally <15 min. Workup involved purging the reaction mixture with Ar for 5 min and then washing the solution with aqueous $Na_2S_2O_3$, $NaHCO_3$, and brine. Purification of the resulting 3-(2-bromoethyl)cycloalkanone was accomplished via flash chromatography for use in the final step.

Finkelstein reactions to provide the title compounds were performed by heating the bromo ketones (5 mmol) with NaI (20 mmol) in 15 mL of acetone at reflux for 12 h.

(1*S*,2*R*,5*S*)-2-Ethenyl-4-oxopinane (3c Precursor). Via the general procedure described above, the title compound was prepared in 92% yield from (1*S*)-(−)-verbenone (Aldrich): ^1H NMR (300 MHz, $CDCl_3$) δ 5.74 (dd, *J* = 17.6, 10.7 Hz, 1 H), 4.95 (d, *J* = 10.7 Hz, 1 H), 4.88 (d, *J* = 17.6 Hz, 1 H), 2.72 (d, *J* = 20.0 Hz, 1 H), 2.52–2.39 (m, 2 H), 2.31 (d, *J* = 20.0 Hz, 1 H), 1.99 (t, *J* = 5.6 Hz, 1 H), 1.52 (d, *J* = 10.7 Hz, 1 H), 1.34 (s, 3 H), 1.20 (s, 3 H), 1.03 (s, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 213.57, 148.29, 110.62, 57.56, 51.23, 44.79, 40.60, 38.30, 27.50, 27.29, 25.75, 25.50; LRMS (EI) *m/e* 178 (8), 124 (44), 109 (71), 95 (67), 93 (75), 83 (100).

(1*S*,2*R*,5*S*)-2-(2-Bromoethyl)-4-oxopinane (3c Precursor). Via the general procedure described above for photochemical hydrobromination, the title compound was prepared in 84% yield: ^1H NMR (200 MHz, $CDCl_3$) δ 3.36–3.28 (m, 2 H), 2.55–2.52 (m, 2 H), 2.35–2.32 (m, 2 H), 2.03–1.95 (m, 3 H), 1.63 (d, *J* = 9.4 Hz, 1 H), 1.35 (s, 3 H), 1.17 (s, 3 H), 0.99 (s, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 213.00, 57.90, 51.35, 47.58, 47.36, 40.92, 35.83, 28.00, 27.41, 25.80, 25.25, 24.78.

(1*S*,2*R*,5*S*)-2-(2-Iodoethyl)-4-oxopinane (3c). Via the general Finkelstein procedure described above, 3c was isolated in 89% yield: ^1H NMR (300 MHz, $CDCl_3$) δ 3.09–3.03 (m, 2 H), 2.50–2.48 (m, 2 H), 2.35–2.24 (m, 2 H), 2.05–1.94 (m, 3 H), 1.58 (d, *J* = 10.5 Hz, 1 H), 1.32 (s, 3 H), 1.12 (s, 3 H), 0.96 (s, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 212.62, 57.92, 51.14, 49.09, 47.33, 40.84, 37.12, 27.37, 25.72, 24.87, 24.73, −0.99; LRMS (EI) *m/e* 306 (0.2), 179 (14), 151 (51), 109 (37), 95 (31), 83 (100).

General Procedure for the Preparation of 3-(3-Iodopropyl)cycloalkanones. Sakurai reaction[31] of the corresponding 2-cycloalkenone with allyltrimethylsilane and $TiCl_4$ yielded 3-(2-propenyl)cycloalkan-1-one. Subjection of this compound to anti-Markovnikov hydrobromination followed by Finkelstein reaction of the resulting bromide, as previously described, yielded the title compounds.

3-(2-Propenyl)cyclooctan-1-one (11 Precursor). To a solution of the enone (3.5 mmol) in 5 mL of CH_2Cl_2 cooled to −78 °C was added $TiCl_4$ (4 mmol). The resulting solution was allowed to stir at −78 °C for 5 min, after which allyltrimethylsilane (4.2 mmol) in 5 mL of CH_2Cl_2 was added. After stirring for 1 h, TLC indicated that the starting material was consumed. The reaction was quenched with 15 mL of H_2O. Extractive workup (Et_2O) followed by flash chromatography yielded 511 mg (88%) of a colorless oil: ^1H NMR (300 MHz, $CDCl_3$) δ 5.82–5.67 (m, 1 H), 5.08–4.94 (m, 2 H), 2.47–2.23 (m, 4 H), 2.08–1.18 (m, 11 H); ^{13}C

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(26) There is now strong evidence for stable organosamarium species in several other reductive coupling reactions as well. (a) Molander, G. A.; Kenny, C. *J. Am. Chem. Soc.* **1989**, *111*, 8236. (b) Molander, G. A.; Harring, L. S. *J. Org. Chem.* **1990**, *55*, 6171. (c) Molander, G. A.; Kenny, C. *J. Org. Chem.* **1991**, *56*, 1439.
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NMR (75 MHz, $CDCl_3$) δ 217.40, 136.64, 116.79, 46.88, 42.92, 41.72, 37.85, 33.22, 27.61, 24.66, 23.76.

3-(3-Bromopropyl)cyclooctan-1-one (1l Precursor). Via the general procedure for photochemical hydrobromination, the title compound was prepared in 63% yield: ^1H NMR (200 MHz, $CDCl_3$) δ 3.42 (t, J = 7.1 Hz, 2 H), 2.48–2.21 (m, 4 H), 1.98–1.11 (m, 13 H).

3-(3-Iodopropyl)cyclooctan-1-one (1l). Via the general procedure for Finkelstein reaction, 1l was isolated in 95% yield: ^1H NMR (300 MHz, $CDCl_3$) δ 3.16 (t, J = 7.1 Hz, 2 H), 2.41–2.28 (m, 4 H), 1.95–1.79 (m, 5 H), 1.67–1.60 (m, 2 H), 1.46–1.25 (m, 6 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 216.70, 46.84, 43.07, 37.91, 37.36, 33.08, 31.11, 27.67, 24.34, 23.57, 6.81.

General Procedure for the Preparation of 3-(4-Iodobutyl)cycloalkanones. Conjugate addition of the organocopper species derived from 3-butenylmagnesium bromide with the corresponding 2-cycloalken-1-one, as previously described for vinylmagnesium bromide, afforded 3-(3-butenyl)cycloalkanone.[28] The title compounds were synthesized by the hydrobromination/Finkelstein sequence outlined above.

An alternative procedure involved the one-step synthesis of 3-(4-chlorobutyl)cycloalkan-1-one[32] followed by Finkelstein reaction.

3-(4-Chlorobutyl)cyclohexan-1-one (1h Precursor). The known title compound was prepared in 68% yield:[32] ^1H NMR (200 MHz, $CDCl_3$) δ 3.50 (t, J = 6.5 Hz, 2 H), 2.42–1.34 (m, 15 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 1.72, 48.05, 44.87, 41.43, 38.87, 35.72, 32.50, 31.14, 25.18, 23.93.

3-(4-Iodobutyl)cyclohexan-1-one (1h). Via the general procedure for Finkelstein reaction, 1h was isolated in 89% yield: ^1H NMR (200 MHz, $CDCl_3$) δ 3.14 (t, J = 7.1 Hz, 2 H), 2.41–2.15 (m, 4 H), 2.02–1.72 (m, 7 H), 1.42–1.25 (m, 4 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 211.60, 48.02, 41.44, 38.81, 35.20, 33.22, 31.13, 27.54, 25.11, 6.93.

The following were prepared by analogous routes and were judged to be >98% pure by fused silica capillary GC analysis and/or ^1H NMR spectroscopy.

3-(Iodomethyl)cyclopentan-1-one (1a): ^1H NMR (300 MHz, $CDCl_3$) δ 3.25–3.21 (m, 2 H), 2.42–2.11 (m, 5 H), 1.93–1.86 (m, 1 H), 1.58–1.52 (m, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 217.08, 45.55, 39.00, 38.78, 29.82, 11.31.

3-(2-Iodoethyl)cyclopentan-1-one (1b): ^1H NMR (200 MHz, $CDCl_3$) δ 3.21–3.24 (m, 2 H), 2.42–1.52 (m, 11 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 218.23, 44.03, 39.05, 38.28, 37.69, 28.58, 3.88.

3-(3-Iodopropyl)cyclopentan-1-one (1c): ^1H NMR (200 MHz, $CDCl_3$) δ 3.15 (t, J = 7.1 Hz, 2 H), 2.48–2.11 (m, 5 H), 1.90–1.72 (m, 3 H), 1.63–1.49 (m, 3 H).

3-(4-Iodobutyl)cyclopentan-1-one (1d): ^1H NMR (200 MHz, $CDCl_3$) δ 3.12 (t, J = 7.1 Hz, 2 H), 2.49–2.12 (m, 4 H), 1.81–1.62 (m, 3 H), 1.57–1.45 (m, 6 H).

3-(Iodomethyl)cyclohexan-1-one (1e) (see general procedure above).

3-(2-Iodoethyl)cyclohexan-1-one (1f): ^1H NMR (300 MHz, $CDCl_3$) δ 3.18–3.05 (m, 2 H), 2.41–2.16 (m, 4 H), 2.02–1.22 (m, 7 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 211.84, 47.53, 41.78, 39.25, 38.89, 30.42, 24.92, 3.73.

3-(3-Iodopropyl)cyclohexan-1-one (1g): ^1H NMR (200 MHz, $CDCl_3$) δ 3.14 (t, J = 7.1 Hz, 2 H), 2.41–1.30 (m, 13 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 211.35, 47.94, 41.35, 38.17, 37.29, 31.14, 30.59, 25.10, 6.59.

3-(4-Iodobutyl)cyclohexan-1-one (1h) (see general procedure above).

3-(2-Iodoethyl)cycloheptan-1-one (1i): ^1H NMR (200 MHz, $CDCl_3$) δ 3.22–3.15 (m, 2 H), 2.40–2.25 (m, 4 H), 1.84–1.35 (m, 9 H).

3-(3-Iodopropyl)cycloheptan-1-one (1j): ^1H NMR (300 MHz, $CDCl_3$) δ 3.13 (t, J = 7.1 Hz, 2 H), 2.46–2.38 (m, 4 H), 1.86–1.35 (m, 11 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 214.15, 49.60, 43.81, 37.83, 36.69, 35.20, 30.83, 29.64, 28.25, 24.18, 6.59.

3-(2-Iodoethyl)cyclooctan-1-one (1k): ^1H NMR (200 MHz, $CDCl_3$) δ 3.19–3.13 (m, 2 H), 2.47–2.24 (m, 4 H), 1.85–1.14 (m, 11 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 216.10, 46.25, 42.62, 40.02, 37.84, 32.54, 27.37, 25.15, 23.44, 4.35.

(32) Yeh, M. C. P.; Knochel, P.; Butler, W. M.; Berk, S. C. *Tetrahedron Lett.* **1988**, *29*, 6693.

3-(3-Iodopropyl)cyclooctan-1-one (1l) (see general procedure above).

3-(2-Iodoethyl)-3,5,5-trimethylcyclohexan-1-one (3a): ^1H NMR (200 MHz, $CDCl_3$) δ 3.16–3.05 (m, 2 H), 2.24–2.03 (m, 4 H), 1.84–1.42 (m, 4 H), 1.04 (s, 3 H), 1.02 (s, 3 H), 1.00 (s, 3 H).

Ethyl 2-(2-iodoethyl)-2-methyl-4-oxocyclohexanecarboxylate (3b): ^1H NMR (200 MHz, $CDCl_3$) δ 4.20–4.14 (m, 2 H), 3.31–3.10 (m, 2 H), 2.71–1.89 (m, 9 H), 1.29 (t, J = 7.0 Hz, 3 H), 1.00 (s, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 209.16, 172.93, 60.68, 50.98, 47.36, 46.51, 42.71, 38.87, 24.48, 21.08, 14.31, -2.24.

(1*S*,2*R*,5*S*)-2-(2-Iodoethyl)-4-oxopinane (3c) (see general procedure above).

5-(2-Iodoethyl)-2,2-dimethylcyclohexan-1-one (3d): ^1H NMR (300 MHz, $CDCl_3$) δ 3.16 (t, J = 7.1 Hz, 2 H), 2.25–2.21 (m, 2 H), 1.87–1.54 (m, 7 H), 1.12 (s, 3 H), 1.05 (s, 3 H).

5-(3-Iodopropyl)-2,2-dimethylcyclohexan-1-one (3e): ^1H NMR (200 MHz, $CDCl_3$) δ 3.14 (t, J = 7.1 Hz, 2 H), 2.28–2.21 (m, 2 H), 1.88–1.37 (m, 9 H), 1.11 (s, 3 H), 1.03 (s, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 215.49, 44.65, 44.36, 39.45, 38.83, 37.29, 30.67, 27.70, 25.05, 25.15, 6.70.

3-(3-Iodopropyl)-2,2,6,6-tetramethylcyclohexan-1-one (3f): ^1H NMR (200 MHz, $CDCl_3$) δ 3.19–3.08 (m, 2 H), 1.93–1.14 (m, 9 H), 1.07 (s, 6 H), 1.01 (s, 3 H), 0.95 (s, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 219.99, 48.27, 45.75, 43.81, 37.95, 32.02, 31.25, 27.85, 27.19, 24.67, 22.84, 21.74, 6.92.

3-(3-Iodo-2,2-dimethylpropyl)cyclohexan-1-one (3g). To a solution of 3-(3-hydroxy-2,2-dimethylpropyl)cyclohexan-1-one[33] (10 mmol) in 40 mL of CH_2Cl_2 at 0 °C was added Et_3N (15 mmol) and $MeSO_2Cl$ (11 mmol). The reaction mixture was allowed to stir at 0 °C for 3 h and was then quenched with aqueous $NaHCO_3$. Extractive workup (Et_2O) afforded the crude methanesulfonate, which was used without further purification.

To a solution of the crude methanesulfonate in 30 mL of DMF was added NaI (30 mmol). The resulting mixture was heated to 90 °C for 14 h. The reaction mixture was cooled to rt, and 100 mL of H_2O was added. Extractive workup (Et_2O) followed by flash chromatography afforded **3g** in 81% yield: ^1H NMR (200 MHz, $CDCl_3$) δ 3.12 (s, 2 H), 2.38–1.22 (m, 11 H), 1.01 (s, 6 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 211.50, 50.10, 47.21, 41.06, 35.39, 34.11, 33.56, 27.34, 27.04, 25.25, 24.41.

Preparation of Allylic Bromides 3h and 3i. Sakurai reaction employing 2-[(trimethylsiloxy)methyl]-3-(trimethylsilyl)prop-1-ene[34] yielded the corresponding allylic alcohol upon aqueous workup. Preparation of the methanesulfonate ester ($MsCl/NEt_3$) followed by nucleophilic displacement of the methanesulfonate with NaBr in DMF at rt afforded the desired allylic bromide:

3-[2-(Bromomethyl)-2-propenyl]cyclopentan-1-one (3h). In the case of cyclopentenone, yields were maximized using inverse addition (i.e., $TiCl_4$ was added last). To a solution of the enone (15 mmol) in 45 mL of CH_2Cl_2 at -78 °C was added 2-[(trimethylsiloxy)methyl]-3-(trimethylsilyl)prop-1-ene (19 mmol) followed by the slow addition of $TiCl_4$ (17 mmol). The reaction was determined to be complete by TLC after 45 min, at which time it was quenched with H_2O. Extractive workup (Et_2O) followed by flash chromatography yielded 61% of 3-[2-(hydroxymethyl)-2-propen-1-yl]cyclopentan-1-one.

To a solution of the allylic alcohol (8 mmol) in 35 mL of CH_2Cl_2 at 0 °C was added Et_3N (12 mmol) followed by CH_3SO_2Cl (9 mmol). The resulting solution was allowed to stir for 3 h. The reaction mixture was then quenched with aqueous $NaHCO_3$. Usual workup afforded the crude methanesulfonate that was used without purification in the next step.

To a solution of the methanesulfonate (ca. 8 mmol) in 25 mL of DMF was added NaBr (30 mmol). The resulting suspension was allowed to stir at rt for 12 h. Usual workup followed by flash chromatography yielded **3h** in 95% yield: ^1H NMR (200 MHz, $CDCl_3$) δ 5.17 (s, 1 H), 4.93 (s, 1 H), 3.90 (s, 2 H), 2.37–1.50 (m, 9 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 218.67, 143.17, 116.42, 44.65, 39.16, 38.02, 36.30, 34.47, 29.02.

3-[2-(Bromomethyl)-2-propenyl]cyclohexan-1-one (3i). Following the general procedure described above, **3i** was isolated in 74% overall yield from 2-cyclohexen-1-one: ^1H NMR (200 MHz,

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(34) Heathcock, C. H.; Smith, K. M.; Blumenkopf, T. A. *J. Am. Chem. Soc.* **1986**, *108*, 5022.

$CDCl_3$) δ 5.22 (s, 1 H), 4.94 (s, 1 H), 3.91 (s, 2 H), 2.32–1.55 (m, 11 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 211.24, 142.40, 117.30, 47.69, 41.32, 40.51, 36.60, 36.23, 31.14, 24.99.

(*E*)-3-(3-Bromo-1-propenyl)cyclohexan-1-one (3j).[35] To a solution of Cp_2ZrHCl (3 mmol) in 6 mL of benzene at rt was added 1-(*tert*-butyldimethylsiloxy)-2-propyne (3.15 mmol). The resulting solution was allowed to stir for 4 h. Solvent was removed in vacuo to yield an orange-red viscous oil.

To the above organozirconium compound was added a solution of 2-cyclohexen-1-one in 25 mL of THF. The resulting solution was transferred via cannula to a solution of $Ni(acac)_2$ (0.43 mmol) and DIBAH (0.41 mmol) in 6 mL of THF at 0 °C. After being stirred for 4 h the reaction mixture was quenched (saturated aqueous NH_4Cl). Extractive workup (Et_2O) followed by deprotection of the TBDMS ether (Bu_4NF/THF) and flash chromatography afforded a 70% yield of the expected allylic alcohol.

Preparation of the methanesulfonate ($MsCl/NEt_3$) followed by displacement of the methanesulfonate with NaBr in DMF, as previously described, afforded **3j** in 85% yield: ^1H NMR (200 MHz, $CDCl_3$) δ 5.69–5.64 (m, 2 H), 3.97–3.88 (m, 2 H), 2.44–1.45 (m, 9 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 210.37, 138.19, 125.79, 46.73, 41.13, 40.84, 32.68, 30.74, 24.78.

3-(3-Iodopropyl)-3-methylcyclohexan-1-one (3k): ^1H NMR (200 MHz, $CDCl_3$) δ 3.10 (t, J = 7.1 Hz, 2 H), 2.44–2.13 (m, 4 H), 1.87–1.39 (m, 8 H), 0.93 (s, 3 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 211.79, 53.69, 42.42, 40.99, 38.35, 35.83, 27.89, 25.07, 22.07, 7.06.

3-(2-Iodopropyl)cyclohexan-1-one (3l).[36] To 1.5 mL of H_3PO_4 (85%) was added KI (15 mmol) in several portions, and the resulting mixture was allowed to stir at rt for 10 min. 3-(2-Propen-1-yl)cyclohexan-1-one[31] was added slowly over 5 min, and the solution was heated to 70 °C for 2 h. The reaction was quenched (H_2O), and usual workup followed by flash chromatography afforded **3l** in 25% yield. Capillary GC indicated a 1:1 mixture of diastereomers >99% pure: ^1H NMR (200 MHz, $CDCl_3$) δ 4.17–4.02 (m, 4 H), 2.48–2.17 (m, 8 H), 2.04–1.38 (m, 24 H).

3-(2-Iodo-2-methylpropyl)cyclohexan-1-one (3m). To a solution of 1-bromo-2-methylpropene (10 mmol) in 30 mL of THF at −78 °C was added 1.1 equiv of *t*-BuLi. The resulting mixture was allowed to stir for 30 min. To a suspension of CuCN (10 mmol) in 20 mL of THF at −78 °C was added 1 equiv of MeLi. The resulting mixture was allowed to stir for 15 min, and the previously prepared alkenyllithium was then added. After the mixture was stirred for an additional 30 min, a solution of 2-cyclohexen-1-one (9 mmol) in 15 mL of THF was added. The reaction was determined to be complete after 1 h at −78 °C and was quenched with aqueous NH_4Cl/NH_4OH (10:1). Extractive workup followed by flash chromatography afforded 3-(2-methyl-1-propen-1-yl)cyclohexan-1-one in 73% yield.

To a solution of the above keto olefin (3 mmol) in 10 mL of CH_2Cl_2 was added 50 mg of Bu_4NI and 1.5 mL of aqueous HI (47%).[37] The resulting mixture was allowed to stir at rt for 3 h. The reaction was quenched by pouring into ice-cold aqueous $NaHCO_3$ and extracted with Et_2O. Passage of the crude product through a short column of neutral alumina protected from light afforded **3m** in 43% yield: ^1H NMR (300 MHz, $CDCl_3$) δ 2.56–1.45 (m, 11 H), 1.91 (s, 3 H), 1.89 (s, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 211.21, 55.99, 50.45, 49.33, 41.05, 38.79, 38.53, 38.07, 32.79, 24.94.

(6*R*)-6-(1-Methyl-2-iodoethyl)spiro[2.5]octan-4-one (3n) (Scheme I). **6** was synthesized in 87% yield from (+)-limonene oxide (**5**, Aldrich) via the literature procedure.[38]

Subjecting **6** to Simmons–Smith conditions[39] afforded **7** as a separable mixture of diastereomers. The combined yield was 75%. However, the final product was contaminated with 8% of the dicyclopropanated adduct.

To a solution of dicyclohexylborane (5.06 mmol) in 5 mL of THF at 0 °C was added a solution of **7** (ca. 2.4 mmol, enriched in the higher R_f diastereomer) in 10 mL of THF. The reaction mixture was allowed to stir at 0 °C for 1 h and rt for 2 h. Five milliliters of a 1 M solution of NaOAc in MeOH was added followed by ICl (2 equiv) in THF.[40] The resulting solution was allowed to stir at rt for 45 min then quenched with saturated aqueous $Na_2S_2O_3$. Extractive workup (Et_2O) followed by flash chromatography afforded **8** as a mixture of diastereomers in 64% yield.

To a suspension of **8** (1 mmol), NaOAc (5 mmol), and 600 mg of 4-Å molecular sieves in 20 mL of CH_2Cl_2 was added PCC (4 mmol).[41] The resulting mixture was allowed to stir at rt for 3 h followed by the usual workup. Flash chromatography afforded **3n** (62%) as a ca. 3:1 mixture of diastereomers: ^1H NMR (300 MHz, $CDCl_3$) δ 3.27–3.13 (m, 4 H), 2.48–2.43 (m, 2 H), 2.12–1.83 (m, 8 H), 1.53–1.38 (m, 8 H), 1.01 (d, J = 6.6 Hz, 6 H), 0.88–0.85 (m, 2 H), 0.63–0.54 (m, 4 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 210.80, 210.70, 43.85, 41.85, 40.41, 40.38, 39.18, 39.09, 32.68, 28.25, 28.22, 27.84, 25.65, 21.34, 17.27, 17.04, 14.51, 14.19, 14.14; LRMS (EI) *m/e* 292 (7), 165 (63), 123 (100), 95 (80), 81 (93), 67 (65), 55 (61).

3-(3-Iodo-2-methoxypropyl)cyclohexan-1-one. To a solution of $Hg(OAc)_2$ (4.65 mmol) in 20 mL of MeOH at 0 °C was added 3-(2-propenyl)cyclohexan-1-one (4.43 mmol) in 10 mL of MeOH.[42] After the mixture was stirred for 2 h, TLC indicated that the starting material had been consumed. A solution of KI (5 mmol) and $KHCO_3$ (5 mmol) in 15 mL of H_2O was added to the reaction mixture, and the resulting suspension was allowed to stir at 0 °C for an additional 30 min. Addition of KI (5 mmol) in H_2O followed by I_2 (5 mmol) in 20 mL of MeOH resulted in a deep brown mixture that faded to pink over 1.5 h. Saturated aqueous NaCl was added followed by extractive workup (Et_2O). The combined organic layers were washed with aqueous $NaHSO_3$, H_2O, and brine. Concentration of the organic extracts followed by flash chromatography afforded the title compound in 58% yield. Capillary GC and ^{13}C NMR indicated a 1:1 mixture of diastereomers of purity >99%: ^1H NMR (200 MHz, $CDCl_3$) δ 3.32 (s, 3 H), 3.29–3.20 (m, 2 H), 3.18–3.02 (m, 1 H), 2.48–2.14 (m, 4 H), 2.04–1.51 (m, 7 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 211.30, 211.27, 77.30, 76.74, 56.91, 56.77, 48.30, 46.61, 41.74, 41.41, 41.31, 41.26, 35.51, 35.16, 31.85, 30.98, 25.07, 24.96, 9.54, 9.41.

Preparation of Tris(dibenzoylmethido)iron(III) [Fe(DBM)$_3$].[14] To a solution of $FeCl_3 \cdot (H_2O)_6$ (1.20 g, 4.40 mmol) in 10 mL of H_2O was added a solution of dibenzoylmethane (3.70 g, 16.5 mmol) in 35 mL of EtOH, with warming until a homogeneous solution was obtained. Aqueous NH_4OH (30%) was added until the solution was basic, resulting in the formation of a dark red precipitate that was collected by filtration. When dry, the precipitate [$Fe(DBM)_3$] was recrystallized from benzene/hexane as purple crystals (2.8 g, 88%).

Preparation of SmI_2 Solution. Samarium metal (0.15 g, 1.0 mmol) was added under a flow of Ar to an oven-dried round bottomed flask containing a magnetic stirring bar and septum inlet. The flask and samarium were gently flame-dried and cooled under Ar. To the samarium was added 10 mL of THF followed by CH_2I_2 (0.241 g, 0.90 mmol) and the mixture was allowed to stir at rt for 1 h. The resulting deep blue solution was used directly to effect the following reductive cyclizations.

General Procedure for Preparation of Bridgehead Bicyclic Alcohols. To the SmI_2 (1.00 mmol) in 10 mL of THF was added the $Fe(DBM)_3$ (0.007 g, 0.01 mmol) in 15 mL of THF. The resulting solution was cooled to −78 °C. A precooled solution of the iodo ketone (0.45 mmol) in 5 mL of THF was added via a dry ice cooled cannula over 5 min, and the reaction mixture was allowed to warm to 0 °C. The reaction was stirred for 2 h at 0 °C prior to being quenched with 5 mL of saturated aqueous $NaHCO_3$. The aqueous layer was extracted with Et_2O. The combined organic layers were washed with brine, dried ($MgSO_4$), and concentrated at atmospheric pressure. Purification of the final product involved flash chromatography (pentane–Et_2O) followed by sublimation. In each case below, the structure number and amounts of the starting iodo ketone are given, followed by the product yield.

Bicyclo[2.1.1]hexan-1-ol (2a): **1a** (0.220 g, 0.982 mmol); yield 0.064 g (66%); mp 93–95 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 2.27

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(s, 1 H), 2.14 (s, 1 H), 1.66–1.57 (m, 4 H), 1.44–1.42 (m, 4 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 79.21, 45.06, 30.08, 29.31, 28.76; IR (CCl_4) 3319, 2954, 2860, 1290 cm^{-1}. LRMS (EI) *m/e* 98 (8), 97 (46), 83 (100), 79 (31), 70 (71), 56 (62), 55 (70). Anal. Calcd for $C_6H_{10}O$: C, 73.43; H, 10.27. Found: C, 73.32; H, 9.93.

Bicyclo[2.2.1]heptan-1-ol (2b): **1b** (0.148 g, 0.622 mmol); yield 0.050 g (71%); mp 151–154 °C (lit. mp 155–158 °C,[5e] 152–154 °C,[5a] 151–153 °C);[43] ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.06–2.03 (m, 1 H), 1.81–1.72 (m, 3 H), 1.64–1.48 (m, 4 H), 1.41–1.36 (m, 4 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 82.90, 43.83, 35.26, 34.67, 30.19; IR (CCl_4) 3630, 3325, 2957, 1451, 1089 cm^{-1}; HRMS calcd for $C_7H_{12}O$ 112.0888, found 112.0902; LRMS (EI) *m/e* 112 (5), 97 (13), 83 (100), 70 (37), 55 (24).

Bicyclo[3.2.1]octan-1-ol (2c): **1c** (0.133 g, 0.50 mmol); yield 0.034 g (54%); mp 147–149 °C; ^{1}H NMR (200 MHz, $CDCl_3$) δ 2.36–2.22 (bs, 1 H), 1.92–1.17 (m, 13 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 79.30, 46.17, 40.23, 36.83, 35.39, 31.41, 27.97, 20.31; IR (CCl_4) 3366, 2919, 1455, 1079 cm^{-1}; LRMS (EI) *m/e* 126 (8), 97 (98), 83 (100), 55 (30). Anal. Calcd for $C_8H_{14}O$: C, 76.14; H, 11.18. Found: C, 76.51; H, 11.30.

Bicyclo[4.2.1]nonan-1-ol (2d): **1d** (0.180 g, 0.677 mmol); yield 0.021 g (22%), identical in every respect with **2i** below.

Bicyclo[3.1.1]heptan-1-ol (2e): **1e** (0.215 g, 0.903 mmol); yield 0.078 g (77%); mp 113–115 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.19–2.14 (m, 1 H), 1.86–1.54 (m, 11 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 74.03, 41.60, 35.87, 26.87, 25.33, 17.39; IR (CCl_4) 3331, 2943, 1149 cm^{-1}; HRMS calcd for $C_7H_{12}O$ 112.0888, found 112.0880; LRMS (EI) *m/e* 112 (4), 97 (31), 84 (55), 58 (100).

Bicyclo[3.2.1]octan-1-ol (2f). **1f** (0.098 g, 0.39 mmol); yield 0.034 g (69%), identical in every respect with **2c** above.

Bicyclo[3.3.1]nonan-1-ol (2g): **1g** (0.149 g, 0.560 mmol); yield 0.057 g (73%); mp 180–182 °C (lit. mp 182–184 °C),[5b,m] ^{1}H NMR (200 MHz, $CDCl_3$) δ 2.20–2.10 (bs, 1 H), 2.02–1.71 (m, 4 H), 1.68–1.50 (m, 11 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 69.64, 44.75, 39.73, 32.14, 30.35, 23.10; IR (CCl_4) 3240, 2925, 1468, 1025 cm^{-1}; LRMS (EI) *m/e* 140 (10), 97 (100), 55 (26). Anal. Calcd for $C_9H_{16}O$: C, 77.09; H, 11.50. Found: C, 76.90; H, 11.58.

Bicyclo[4.3.1]decan-1-ol (2h): **1h** (0.198 g, 0.709 mmol); yield 0.016 g (15%), identical in every respect with **2j** below.

Bicyclo[4.2.1]nonan-1-ol (2i): **1i** (0.282 g, 1.06 mmol); yield 0.112 g (73%); mp 132–134 °C; ^{1}H NMR (200 MHz, $CDCl_3$) δ 2.38–2.29 (m, 1 H), 2.23–2.03 (m, 1 H), 1.79–1.38 (m, 14 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 82.45, 43.74, 43.13, 39.73, 34.92, 34.46, 32.45, 24.69, 23.44; IR (CCl_4) 3366, 2919, 1455, 1079 cm^{-1}; LRMS (EI) *m/e* 140 (4), 111 (86), 83 (100), 55 (32). Anal. Calcd for $C_9H_{16}O$: C, 77.09; H, 11.50. Found: C, 77.42; H, 11.61.

Bicyclo[4.3.1]decan-1-ol (2j): **1j** (0.171 g, 0.610 mmol); yield 0.072 g (76%); mp 141–142 °C (lit. mp 140 °C);[44] ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.15–2.12 (m, 1 H), 1.96 (d, *J* = 13.2 Hz, 1 H), 1.77–1.29 (m, 16 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 72.95, 42.69, 41.37, 41.07, 32.89, 31.55, 30.38, 26.10, 24.54, 20.92; IR (CCl_4) 3354, 2907, 1455, 1032 cm^{-1}; LRMS (EI) *m/e* 154 (5), 111 (95), 97 (100), 55 (35). Anal. Calcd for $C_{10}H_{18}O$: C, 77.87; H, 11.76. Found: C, 78.02; H, 11.79.

Bicyclo[5.2.1]decan-1-ol (2k): **1k** (0.241 g, 0.859 mmol); yield 0.114 g (86%); mp 120–122 °C; ^{1}H NMR (200 MHz, $CDCl_3$) δ 2.46–2.36 (m, 1 H), 2.02–1.50 (m, 17 H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 82.03, 46.25, 43.59, 39.24, 35.24, 34.94, 28.54, 26.93, 26.40, 25.66; IR (CCl_4) 3372, 2912, 1455, 1049 cm^{-1}; LRMS (EI) *m/e* 154 (2), 125 (49), 83 (100). Anal. Calcd for $C_{10}H_{18}O$: C, 77.87; H, 11.76. Found: C, 77.91; H, 11.88.

Bicyclo[5.3.1]undecan-1-ol (2l): **1l** (0.333 g, 1.13 mmol); yield 0.165 g (87%) as an inseparable 6:1 mixture of diastereomers; mp 55–57 °C; ^{1}H NMR (200 MHz, $CDCl_3$) δ 2.14–2.07 (m, 2 H), 1.83–1.17 (m, 38 H); ^{13}C NMR (50 MHz, $CDCl_3$) (major) δ 72.02, 41.07, 38.56, 36.51, 32.72, 32.16, 30.11, 30.03, 25.25, 22.39, 19.70; (minor) 75.17, 41.81, 40.29, 35.99, 29.11, 28.59, 28.45, 27.01, 25.64; IR (CCl_4) 3606, 3480, 2898, 1457, 1380 cm^{-1}; LRMS (EI) *m/e* major 168 (1), 125 (77), 112 (10), 97 (100), 83 (18), 69 (10), 55 (25), minor 168 (2), 125 (27), 112 (5), 97 (100), 83 (8), 69 (5), 55 (17). Anal. Calcd for $C_{11}H_{20}O$: C, 78.51; H, 11.98. Found: C, 78.76; H, 12.15.

3,3,5-Trimethylbicyclo[3.2.1]octan-1-ol (4a): **3a** (0.281 g, 0.956 mmol); yield 0.141 g (88%); mp 74–76 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.86–1.13 (m, 11 H), 1.10 (s, 3 H), 0.97 (s, 3 H), 0.94 (s, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 79.38, 53.06, 52.72, 52.15, 40.93, 37.11, 36.52, 34.17, 31.13, 31.06, 28.39; IR (CCl_4) 3318, 2908, 1449, 1331, 1072 cm^{-1}; LRMS (EI) *m/e* 168 (1), 153 (100), 139 (98), 97 (98). Anal. Calcd for $C_{11}H_{20}O$: C, 78.51; H, 11.98. Found: C, 78.42; H, 12.04.

Ethyl 1-hydroxy-5-methylbicyclo[3.2.1]octane-4-carboxylate (4b): **3b** (0.318 g, 0.918 mmol); yield 0.161 g (83%); mp 57–59 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.10 (dq, *J* = 14.81, 7.08 Hz, 1 H), 4.06 (dq, *J* = 14.8, 7.1 Hz, 1 H), 2.18–1.38 (m, 9 H), 1.22 (t, *J* = 7.1 Hz, 3 H), 1.04 (s, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 174.92, 79.10, 59.83, 49.43, 46.70, 42.87, 37.39, 36.60, 36.13, 26.09, 23.83, 14.22; IR (CCl_4) 3389, 2943, 1719, 1455, 1331, 1173 cm^{-1}; HRMS calcd for $C_{12}H_{20}O_3$ 212.1412, found 212.1402; LRMS (EI) *m/e* 212 (3), 183 (94), 109 (37), 97 (100). Anal. Calcd for $C_{12}H_{20}O_3$: C, 67.89; H, 9.50. Found: C, 67.43; H, 9.54.

(1*S*,2*S*,4*S*,5*S*)-3,3,5-Trimethyltricyclo[3.2.1.1^{2,4}]nonan-1-ol (4c): **3c** (0.314 g, 1.02 mmol); yield 0.139 g (75%); mp 80–82 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.61 (dt, *J* = 10.7, 3.2 Hz, 1 H), 2.18–2.12 (m, 1 H), 2.09–2.05 (m, 1 H), 1.92–1.82 (m, 1 H), 1.76 (dd, *J* = 8.4, 5.0 Hz, 1 H), 1.67–1.33 (m, 7 H), 1.43 (s, 3 H), 1.33 (s, 3 H), 1.10 (s, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 82.16, 57.44, 55.22, 49.16, 42.04, 41.24, 40.94, 40.82, 33.44, 32.86, 29.37, 26.40; IR (CCl_4) 3319, 2919, 1461, 1296, 1049 cm^{-1}; LRMS (EI) *m/e* 180 (0.3), 165 (100), 147 (51), 107 (58), 79 (48). Anal. Calcd for $C_{12}H_{20}O$: C, 79.94; H, 11.18. Found: C, 79.77; H, 11.24.

2,2-Dimethylbicyclo[3.2.1]octan-1-ol (4d). **3d** (0.288 g, 1.03 mmol); yield 0.133 g (84%); mp 78–80 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.22–2.12 (m, 1 H), 1.93–1.70 (m, 3 H), 1.44–1.25 (m, 8 H), 0.97 (s, 3 H), 0.92 (s, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 82.94, 40.73, 38.53, 35.46, 34.38, 33.28, 28.89, 27.81, 24.61, 21.56; IR (CCl_4) 3365, 2931, 1455, 1090 cm^{-1}; LRMS (EI) *m/e* 154 (8), 125 (40), 83 (100), 43 (32). Anal. Calcd for $C_{10}H_{18}O$: C, 77.87; H, 11.88. Found: C, 77.91; H, 11.76.

2,2-Dimethylbicyclo[3.3.1]nonan-1-ol (4e): **3e** (0.202 g, 0.687 mmol); yield 0.089 g (77%); mp 86–88 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.09–2.01 (m, 2 H), 1.86–1.20 (m, 12 H), 1.00 (s, 3 H), 0.93 (s, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 72.50, 39.37, 38.14, 37.96, 36.86, 32.63, 30.50, 28.13, 25.04, 23.75, 23.48; IR (CCl_4) 3601, 3460, 2919, 1454, 1073 cm^{-1}; LRMS (EI) *m/e* 168 (7), 125 (31), 97 (100), 79 (11), 55 (18), 43 (23). Anal. Calcd for $C_{11}H_{20}O$: C, 78.51; H, 11.98. Found: C, 78.67; H, 12.54.

2,2,9,9-Tetramethylbicyclo[3.3.1]nonan-1-ol (4f): **3f** (0.272 g, 0.845 mmol); yield 0.122 g (74%); mp 169–172 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.17–1.26 (m, 12 H), 1.13 (s, 6 H), 1.07 (s, 3 H), 0.97 (s, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 75.98, 42.07, 40.11, 39.02, 38.18, 32.76, 29.91, 28.10, 26.08, 25.84, 25.72, 25.28, 22.39; IR (CCl_4) 3613, 3507, 2919, 1461, 1061 cm^{-1}; LRMS (EI) *m/e* 196 (87), 126 (86), 109 (99), 97 (88), 84 (100), 69 (88), 43 (84). Anal. Calcd for $C_{13}H_{24}O$: C, 79.53; H, 12.32. Found: C, 79.76; H, 12.24.

3,3-Dimethylbicyclo[3.3.1]nonan-1-ol (4g): **3g** (0.227 g, 0.772 mmol); yield 0.084 g (65%); mp 55–56 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.28–2.24 (m, 1 H), 2.12–2.08 (m, 1 H), 1.66–1.00 (m, 12 H), 1.10 (s, 3 H), 0.93 (s, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 70.10, 50.82, 43.47, 39.65, 37.46, 34.79, 34.61, 33.34, 29.95, 28.69, 19.42; IR (CCl_4) 3354, 2919, 1461, 1067 cm^{-1}; HRMS calcd for $C_{11}H_{21}O$ (M + 1) 169.1592, found 169.1575; LRMS (EI) *m/e* 168 (1), 125 (100), 97 (65), 69 (13), 55 (13).

3-Methylenebicyclo[3.2.1]octan-1-ol (4h): **3h** (0.191 g, 0.880 mmol); yield 0.066 g (54%); mp 49–50 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.78 (s, 2 H), 2.41–2.21 (m, 3 H), 2.14–2.01 (m, 2 H), 1.85–1.42 (m, 6 H), 1.36–1.21 (m, 1 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 144.77, 111.78, 79.27, 49.85, 45.22, 41.12, 36.08, 34.70, 28.10; IR (CCl_4) 3342, 3060, 2931, 1643, 1443, 1319, 1096 cm^{-1}; HRMS calcd for $C_9H_{14}O$ 138.1045, found 138.1033; LRMS (EI) *m/e* 138 (1), 83 (100).

5-Methylbicyclo[3.3.1]nonan-1-ol (4k): **3k** (0.238 g, 0.850 mmol); yield 0.093 g (71%); mp 67–68 °C (lit. mp 72–74 °C);[5f] ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.97–1.75 (m, 4 H), 1.62–1.15 (m, 8 H), 0.86 (s, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 70.93, 50.73, 38.88, 37.34, 35.02, 32.47, 22.60; IR (CCl_4) 3354, 2907, 1455, 1131, 1008 cm^{-1}; LRMS (EI) *m/e* 154 (0.3), 111 (100), 55 (17). Anal. Calcd for $C_{10}H_{18}O$: C, 77.87; H, 11.76. Found: C, 77.45; H, 11.41.

7-Methylbicyclo[3.2.1]octan-1-ol (4l): **3l** (0.140 g, 0.526 mmol); yield 0.058 g (79%) as a 3:1 (exo:endo) mixture of C-7 epimers. The major diastereomer (exo) was isolated in 57% yield

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following flash chromatography and sublimation: mp 60–62 °C (lit. mp 61–63 °C);[45] ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.08–2.06 (m, 1 H), 1.80–1.18 (m, 12 H), 0.80 (d, J = 6.8 Hz, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 79.01, 42.69, 40.57, 38.05, 37.51, 32.87, 30.67, 19.68, 18.48; IR (CCl_4) 3401, 2931, 2860, 1455, 1120 cm^{-1}; LRMS (EI) m/e 140 (1), 97 (100), 70 (6). Anal. Calcd for $C_9H_{16}O$: C, 77.09; H, 11.50. Found: C, 77.31; H, 11.34.

7,7-Dimethylbicyclo[3.2.1]octan-1-ol (4m): 3m (0.249 g, 0.892 mmol); yield 0.078 g (57%); mp 62–64 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.09–2.06 (m, 2 H), 1.74–1.50 (m, 5 H), 1.35–1.17 (m, 5 H), 0.97 (s, 3 H), 0.95 (s, 3 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 79.78, 44.06, 42.57, 39.92, 36.48, 31.36, 30.96, 28.47, 20.86, 19.55; IR (CCl_4) 3613, 3448, 2931, 1454, 1079 cm^{-1}; LRMS (EI) m/e 154 (5), 111 (73), 97 (100), 70 (47). Anal. Calcd for $C_{10}H_{18}O$: C, 77.87; H, 11.76. Found: C, 78.01; H, 11.50.

(1′*S*,5′*R*)-6′-Methylspiro[cyclopropane-1,2′-bicyclo-[3.2.1]octan]-1′-ol (4n): 3n (0.075 g, 0.26 mmol); yield 0.032 g (75%) as an inseparable 3:1 mixture of C-6 epimers; bp 65 °C (1.0 mmHg); ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.45–2.29 (m, 1 H), 2.15 (ddd, J = 12.7, 8.7, 1.9 Hz, 1 H), 2.01–1.80 (m, 8 H), 1.62–1.40 (m, 6 H), 1.18–1.12 (m, 2 H), 1.02 (d, J = 7.1 Hz, 3 H), 0.99 (d, J = 7.3 Hz, 3 H), 0.88–0.80 (m, 2 H), 0.68–0.55 (m, 4 H), 0.17–0.02 (m, 4 H); ^{13}C NMR (75 MHz, $CDCl_3$) (major) δ 79.29, 46.37, 43.20, 42.40, 35.02, 31.57, 31.15, 27.11, 23.79, 9.74, 7.25; (minor) 78.70, 47.05, 44.16, 40.53, 34.92, 32.01, 27.73, 26.14, 15.22, 10.10, 7.28; IR (CCl_4) 3378, 3072, 3002, 2931, 2849, 1449, 1296, 1108 cm^{-1}; HRMS calcd for $C_{11}H_{18}O$ 166.1358, found 166.1372; LRMS (EI) m/e major 166 (4), 122 (100), 109 (47), 95 (93), 93 (80), 67 (49), minor 166 (3), 122 (100), 109 (38), 95 (89), 93 (67), 67 (44).

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Supplementary Material Available: ^{1}H and ^{13}C NMR data for all bridgehead bicyclic alcohols for which elemental analyses are not reported; spectra are also included for the synthetic intermediates along the pathway to the iodo ketone substrates (111 pages). Ordering information is given on any current masthead page.

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Highly Effective and Practical Enantioselective Synthesis of Half-Esters of Bicyclo[2.2.1]heptanedicarboxylic Acid

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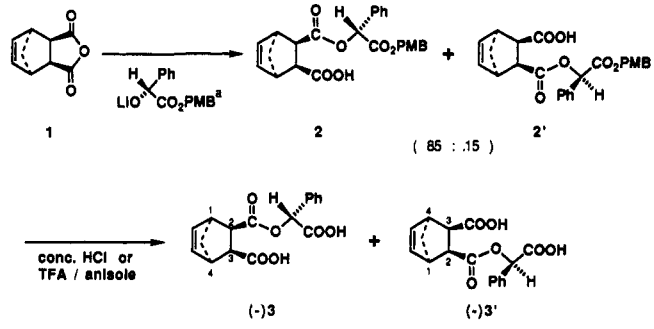
An effective and practical enantioselective synthesis of half-esters of bicyclo[2.2.1]heptane-2,3-dicarboxylic acid was developed by enantioselective fission of σ-symmetrical cyclic anhydrides with chiral mandelic acid derivatives, followed by deprotection of the mandelate moiety, crystallization, and further modification. These half-esters are very attractive chiral building blocks for numerous natural products, and this new method makes possible their synthesis via common intermediates with high optical purity.

Compounds possessing the bicyclo[2.2.1[heptane skeleton are very important compounds because they occur as natural products and serve as versatile building blocks for the synthesis of numerous compounds. They have been employed, for example in the synthesis of prostanoids,[1] alkaloids,[2] terpenes,[3] insecticides,[4] and nucleosides.[5]

Although enzymatic hydrolysis and the Diels–Alder reaction are very attractive for the asymmetric synthesis of half-esters of bicyclo[2.2.1]heptane-2,3-dicarboxylic acid, enzymatic methods have inevitable limitations[6] and the effective Diels–Alder reactions have mostly been limited to *trans*-2,3-dicarboxylic acid derivatives.[7] Moreover, some of these reactions do not offer the convenience of a simple procedure for large-scale synthesis.

Scheme I



Described herein is an enantioseletive synthesis yielding optically pure cis and trans half-esters of bicyclo[2.2.1]-heptane-2,3-dicarboxylic acid from a common intermedi-

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