Titanocene-Catalyzed Reduction of Lactones to Lactols

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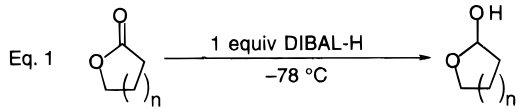
A convenient method for the conversion of lactones to lactols is described. The hydrosilylation to lactols is carried out *via* air-stable titanocene difluoride or a titanocene diphenoxide precatalyst using inexpensive polymethylhydrosiloxane (PMHS) as the stoichiometric reductant. These procedures have been demonstrated with a variety of substrates and proceed in good to excellent yield.

Introduction

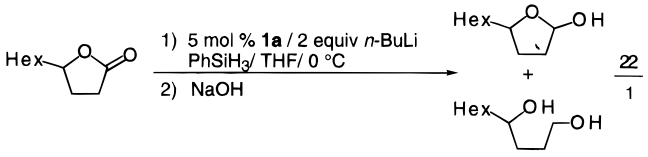
During recent decades, the development of catalytic processes in organic synthesis has become a research area of great importance. While the metal-catalyzed hydrogenation[1,2] and hydrosilylation[3] of ketones are well-established processes, in the related reduction of lactones to the corresponding lactols (eq 1) the use of a stoichiometric amount of a metal hydride has remained mandatory. Several modified aluminum hydrides have been



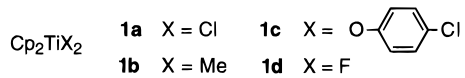
reported to accomplish the partial reduction of lactones and esters,[4] and diisobutylaluminum hydride (DIBAL-H) is currently the reagent of choice.[5] However, a disadvantage with the standard reaction conditions is the low temperature required, usually −78 °C (eq 1). In addition, DIBAL-H is a pyrophoric and air-sensitive reagent that requires special handling, particularly on a large scale.

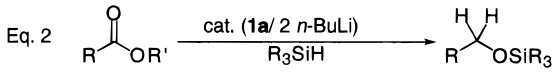
In recent years, our group has studied the titanocene-catalyzed reduction of esters[6] and other functional groups.[7] As shown in eq 2, the reaction of 2 equiv of *n*-BuLi with titanocene dichloride (**1a**) generates an active catalyst for the hydrosilylation of esters to their corresponding silylated primary alcohols. While unable to achieve the partial reduction of straight-chain esters, we envisioned this protocol could be applicable to the partial reduction of lactones. Our initial efforts in developing a convenient catalytic system for such transformations have been

Scheme 1



described previously.[8] Herein we describe full results of our previous work, along with details of a new precatalyst, control experiments, and further study of the scope of this process.





Results and Discussion

When γ-decanolactone was subjected to the titanocene-catalyzed hydrosilylation protocol using **1a** with 2 equiv of *n*-BuLi and triethoxysilane, the silylated lactol was formed as a major product in the final reaction mixture.[9] To maximize the lactol:diol ratio, use of phenylsilane, a more reactive silylating agent, was investigated. Under the conditions shown in Scheme 1, a 22:1 ratio of lactol:diol resulted. Although this was a promising result, the need to use *n*-BuLi for catalyst activation and the high cost of phenylsilane as a stoichiometric reducing agent prompted us to search for an improved protocol. We focused our efforts toward developing a practical system in which the catalyst could be activated by the hydrosilylating agent itself and in which a less expensive silane could be utilized as the stoichiometric reductant.

Catalyst Generation. Brintzinger[10] and Martin[11] studied the reaction of titanocene dichloride **1a** with 2 equiv of RMgX or RLi (R = Et or *i*-Pr) and proposed that the reactive species obtained in this process was consistent with a titanocene(III) hydride in either a monomeric or dimeric form. Similarly, Harrod and co-workers were able to isolate and characterize two binuclear titanium(III) silyl hydride complexes (Figure 1) from the reaction of dimethyltitanocene (**1b**) with phenylsilane, which are

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(1) Rylander, P. N. *Hydrogenation Methods*; Academic Press: New York, 1985.

(2) Chaloner, P. A.; Esteruelas, M. A.; Jou, F.; Oro, L. A. *Homogeneous Hydrogenation*; Kluwer Academic: Boston, 1994.

(3) Ojima, I. In *The Chemistry of Organic Silicon Compounds*, Part 2; Wiley: New York, 1989; pp 1479−1526.

(4) (a) Kanazawa, R.; Tokoroyama, T. *Synthesis* **1976**, 526. (b) Cha, J. S.; Min, S. J.; Lee, J. C.; Lee, H. S.; Lee, S. E. *Org. Prep. Proced. Int.* **1992**, *24*, 335.

(5) (a) Winterfeldt, E. *Synthesis* **1975**, 617. (b) Takacs, J. M.; Helle, M. A.; Seely, F. L. *Tetrahedron Lett.* **1986**, *27*, 1257.

(6) (a) Berk, S. C.; Kreutzer, K. A.; Buchwald, S. L. *J. Am. Chem. Soc.* **1991**, *113*, 3, 5093. (b) Barr, K. J.; Berk, S. C.; Buchwald, S. L. *J. Org. Chem.* **1994**, *59*, 4323.

(7) (a) Verdaguer, X.; Lange, U. E. W.; Reding, M. T.; Buchwald, S. L. *J. Am. Chem. Soc.* **1996**, *118*, 6784. (b) Broene, R. D.; Buchwald, S. L. *J. Am. Chem. Soc.* **1993**, *115*, 12569. (c) Lee, N. E.; Buchwald, S. L. *J. Am. Chem. Soc.* **1994**, *116*, 5985.

(8) Verdaguer, X.; Berk, S. C.; Buchwald, S. L. *J. Am. Chem. Soc.* **1995**, *117*, 12641.

(9) Berk, S. C. Ph.D. Thesis, Massachusetts Institute of Technology, 1994.

(10) Brintzinger, H. H. *J. Am. Chem. Soc.* **1967**, *89*, 6871.

(11) Martin, H. A.; Jellinek, F. *J. Organomet. Chem.* **1968**, *12*, 149.

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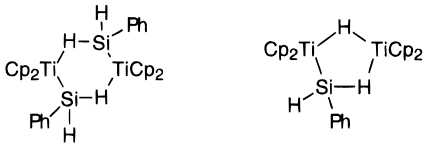
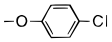
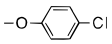


Figure 1. Harrod's binuclear titanium(III) silyl hydride complexes.

Table 1. Activation Conditions for Various Cp_2TiX_2 Derivatives

Entry	–X	Activation Conditions
1	–Cl	1) 2 equiv *n*-BuLi /–78 °C / THF 2) silane / 0 °C → r.t.
2		$PhSiH_3$ / neat
3		PMHS / 0.5 equiv Bu_4NF / r.t. toluene or THF
4	–F	$PhSiH_3$ / r.t. / THF
5	–F	PMHS / 50–60 °C / THF

proposed to be intermediates in the polymerization of primary silanes.[12] Since a titanium hydride catalyst is implicated in the catalytic cycle of our ester reduction system,[6a] we speculated that **1b** could be used as a precatalyst in the hydrosilylation of lactones. However, dimethyltitanocene is not a practical precursor because it is an air-sensitive complex that must be handled and stored under an inert atmosphere.

Recently, Moreau and co-workers reported that titanocene diphenoxides react with phenylsilane at or below 50 °C to yield an active system for silane polymerization.[13] Unlike Cp_2TiMe_2, titanocene diphenoxides are crystalline, air-stable complexes and can be readily prepared from the reaction of Cp_2TiCl_2 with the corresponding phenoxide anion.[14] Among several titanocene diphenoxides studied by Moreau, $Cp_2Ti(O\text{-}p\text{-}ClC_6H_4)_2$ (**1c**) required the shortest induction period for the generation of an active catalyst. Hence, we proceeded to evaluate **1c** as a precatalyst in our hydrosilylation system.

Reaction of the orange solid **1c** with neat phenylsilane afforded a dark blue solution that, after addition of THF, proved to be effective in hydrosilylating lactones (Table 1, entry 2). However, even upon heating, **1c** could not be activated with polymethylhydrosiloxane (PMHS), a polymeric inexpensive hydride source. We later discovered the requirement for phenylsilane could be circumvented by using tetrabutylammonium fluoride (TBAF) supported on alumina (0.5 equiv/equiv of catalyst). Addition of PMHS to a THF slurry of **1c** and TBAF/Al_2O_3[15] resulted in rapid activation of the catalyst at room temperature; the color of the reaction mixture changed from orange to dark blue (Table 1, entry 3). We reasoned that displacement of one of the phenoxide ligands by a fluoride ion facilitated the activation process. To test this hypothesis, we examined whether the reaction of a titanocene fluoride with a silane could generate an active catalyst. Thus, titanocene difluoride (**1d**) was prepared according to a literature procedure by the reaction of Cp_2TiCl_2 with NaF in water; **1d** is an air-stable yellow crystalline solid slightly soluble in THF at room temperature.[16] Indeed, the reaction of **1d** with phenylsilane in THF at room temperature afforded a dark blue solution, indicating the successful generation of the desired catalyst (Table 1, entry 4). Most importantly, the active catalyst could also be formed by briefly heating **1d** with PMHS at 50−60 °C (Table 1, entry 5).

Although several titanium hydrides and titanium silyl hydrides have been reported in the literature,[12a,17] the exact nature of the active species in this system is unclear. A reasonable mechanistic model can be proposed by assuming that titanocene(III) hydride (or its equivalent) is the actual catalytic reducing agent.[18] Conversion of Cp_2TiF_2 (**1d**) into an active catalyst can be rationalized by the pathway shown in Scheme 2. First, σ-bond metathesis of a fluoride ligand with a molecule of silane, followed by disproportionation and concomitant loss of H_2, would lead to a titanocene(III) fluoride as a most likely intermediate.[19,20] A second σ-bond metathesis with another equivalent of silane would afford the titanocene hydride.

Lactone Hydrosilylation. The results described above demonstrate that PMHS can serve both as an activating agent and as the stoichiometric reducing agent[21] in the catalytic hydrosilylation of lactones. An experimentally simple protocol for the reduction of lactones is depicted in Scheme 3. The catalyst precursor is placed in a dry Schlenk flask under argon and activated according to Table 1 (entry 3 or 5). The substrate is added dropwise to the activated catalyst−silane mixture at 0 °C. The ice bath is removed, and the silylated lactol is produced as the major product in 5 min to 6 h. A subsequent aqueous workup (NaOH or TBAF) yields the free lactol in good yield. It is worth noting that in contrast to alternative procedures, this new hydrosilylation process is conducted at room temperature. While detailed mechanistic studies have not been carried out, our current view of the catalytic cycle for the lactone hydrosilylation process is presented in Scheme 4. The initially formed titanocene(III) hydride adds to the lactone carbonyl to afford titanium alkoxide **2**, in which the oxygen atom in the ring is presumably coordinated to the titanium center. A σ-bond metathesis reaction of **2** with the silane[22] regenerates the titanium hydride and yields the product silylated lactol. A competing reaction pathway involves the ring opening of **2** to form an alkoxy aldehyde complex **3**, which upon further hydrosilylation would give the fully silylated diol.[6a] This competing process can become an important alternative pathway

(12) (a) Aitken, C. T.; Harrod, J. F.; Samuel, E. *J. Am. Chem. Soc.* **1986**, *108*, 4059. (b) Harrod, J. F.; Mu, Y.; Samuel, E. *Can. J. Chem.* **1992**, *70*, 2980.

(13) Bourg, S.; Corriu, R. J. P.; Enders, M.; Moreau, J. J. E. *Organometallics* **1995**, *14*, 564.

(14) Andra, K. *J. Organomet. Chem.* **1968**, *11*, 567.

(15) 15% TBAF by weight.

(16) Druce, P. M.; Kingston, B. M.; Lappert, M. F.; Spalding, T. R.; Srivastava, R. C. *J. Chem. Soc. A* **1969**, 2106.

(17) (a) Spaltenstein, E.; Palma, P.; Kreutzer, K. A.; Willoughby, C. A.; Davis, W. A.; Buchwald, S. L. *J. Am. Chem. Soc.* **1994**, *116*, 10308. (b) Xin, S.; Harrod, J. F.; Samuel, E. *J. Am. Chem. Soc.* **1994**, *116*, 11562. (c) de Wolf, J. M.; Meetsma, A.; Teuben, J. H. *Organometallics* **1995**, *14*, 5466.

(18) Supporting this assumption are the following: (a) sharp resonances from titanium species disappear in the ^1H NMR; (b) **1a**/2 equiv of BuLi, **1c**/TBAF, and Cp_2TiF_2 systems show similar activity versus the lactone reduction; and (c) **1c**/TBAF and Cp_2TiF_2 catalyze the redistribution of polymethylhydrosiloxanes; see: Laine, R. L.; Rahn, J. A.; Youngdahl, K. A.; Babonneau, F.; Hoppe, M. L.; Zhang, Z. F.; Harrod, J. F. *Chem. Mater.* **1990**, *2*, 464. Xin, S., Aitken, C.; Harrod, J. F.; Mu, Y.; Samuel, E. *Can. J. Chem.* **1990**, *68*, 471.

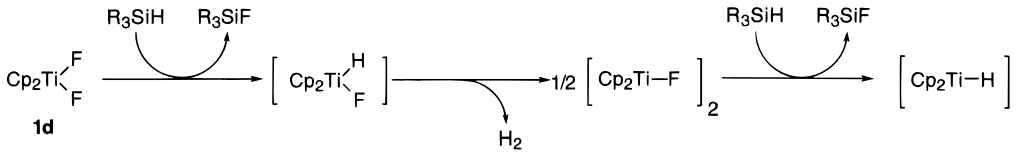
(19) Verdaguer, X.; Buchwald, S. L. Unpublished results.

(20) A dimeric titanocene(III) fluoride has been described; see: Coutts, R. S. P.; Wailes, P. C.; Martin, R. L. *J. Organomet. Chem.* **1973**, *47*, 375.

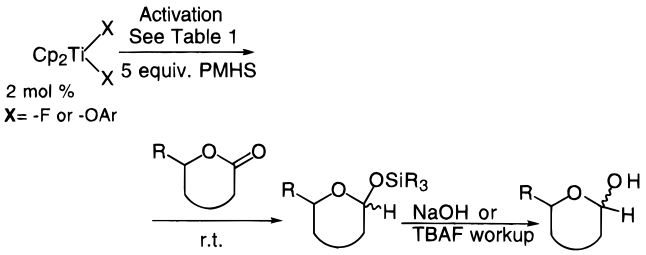
(21) Attempts to use less than 5 equiv of PMHS resulted in incomplete reduction. We believe attachment of a lactol to the siloxane polymer hinders the vicinal Si−H positions, thereby reducing the effective number of hydride equivalents.

(22) Woo, H−G.; Tilley, T. D. *J. Am. Chem. Soc.* **1989**, *111*, 3757.

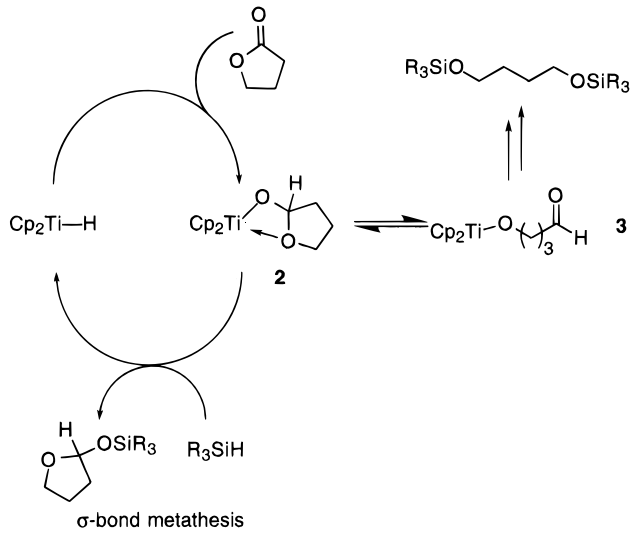
Scheme 2



Scheme 3



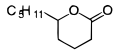
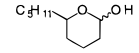
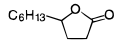
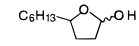
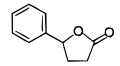
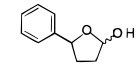
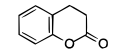
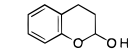
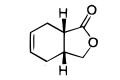
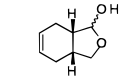
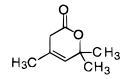
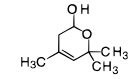
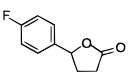
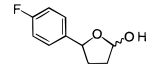
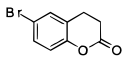
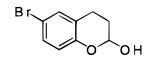
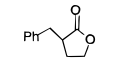
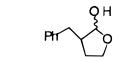
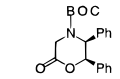
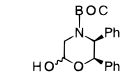
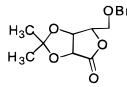
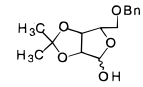
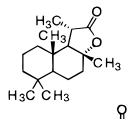
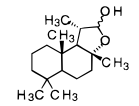
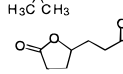
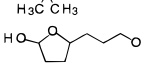
Scheme 4



in the reduction of sterically encumbered lactones and large ring substrates (vide infra).

Scope and Limitations. To probe the efficiency of this new methodology, the partial reduction of a variety of γ- and δ-lactones was carried out (Table 2). The catalyst systems $Cp_2Ti(OR)_2$/(TBAF/alumina)/PMHS and Cp_2TiF_2/PMHS were both shown to be highly effective and afforded the product lactols in similar yields. This procedure tolerates a wide range of potentially reactive functional groups. For example, while the group 4 metallocene-catalyzed hydrosilylation of olefins is well-known,[23] this was not a major side reaction in the reduction of two olefin-containing substrates (Table 2, entries 5 and 6). We,[24a] and others,[24b] have observed competitive reduction of aryl halides as a major side reaction in some cases. As is evident from the results presented here (Table 2, entries 7 and 8), this was not the case under the conditions employed.[25] While early transition metal catalysts can be quite reactive toward a variety of polar functional groups, high degrees of selectivity were manifested as evidenced by the reduction

Table 2. Lactone Hydrosilylation Using 2 mol % $Cp_2Ti(OR)_2$/TBAF or Cp_2TiF_2 as Precatalysts

Entry	Substrate	Lactol	Precat.	Work-up[a]	Yield[b]
1			**1c** **1d**	A	94 90
2			**1c** **1d**	A	97[c,d] 94
3			**1c** **1d**	A	96 89
4			**1c**	B	87
5			**1d**	A	88
6			**1c** **1d**	A	89 76
7			**1c** **1d**	A	96 97
8			**1c**	B	69[e,f]
9			**1c** **1d**	A	93 87
10			**1c**	A	92[f]
11			**1c**	A	91
12			**1c**	A	94[g,h]
13			**1d**	A	88[i]

[a] Workup A: THF/1 M NaOH, 1 h, rt. Workup B: H_2O/1 M TBAF in THF, reflux 2 h. [b] Yields refer to isolated products of >95% purity. All compounds were characterized by IR, ^{1}H NMR, and ^{13}C NMR. [c] The same reaction was run on the 100 mmol scale (93% yield). [d] 0.5 mol % catalyst. [e] No reduction of the aryl bromide was detected. [f] 5 mol % catalyst. [g] Oxidation back to the lactone using PCC/CH_2Cl_2 at room temperature gave a single diastereomer (GC and ^{1}H NMR). [h] 3 mol % catalyst. [i] Phenylsilane was used in place of PMHS.

shown in entries 10 and 11 (Table 2). Hydrosilylation of a lactone with a stereocenter α to the carbonyl afforded the corresponding lactol with no sign of epimerization (Table 2, entry 12). When a lactone containing an ester group was subjected to the hydrosilylation conditions (Table 2, entry 13) the ester moiety was reduced to the alcohol while the lactone moiety was reduced to the lactol. In this case, phenylsilane was used *in lieu* of PMHS in order to avoid possible cross-linking of the siloxane polymer with subsequent gel formation.

Attempts to extend this methodology to the reduction of larger ring lactones and sterically congested lactones were unsuccessful. For example, reduction of ϵ-caprolactone **4** yielded 1,6-hexanediol as the sole product. Reduction of the sterically hindered lactone **5** produced

(23) (a) Kesti, M. R.; Waymouth, R. M. *Organometallics* **1992**, *11*, 1095. (b) Harrod, J. F.; Yun, S. S. *Organometallics* **1987**, *6*, 1381.

(24) (a) Willoughby, C. A.; Buchwald, S. L. *J. Am. Chem. Soc.* **1994**, *116*, 8952. (b) Colomer, E.; Corriu, R. *J. Organomet. Chem.* **1974**, *82*, 367.

(25) Dehalogenation has not been a difficulty in other hydrosilylation reactions we have investigated. See ref 6 and: Carter, M. B.; Schiøtt, B.; Gutiérrez, A.; Buchwald, S. L. *J. Am. Chem. Soc.* **1994**, *116*, 11667.

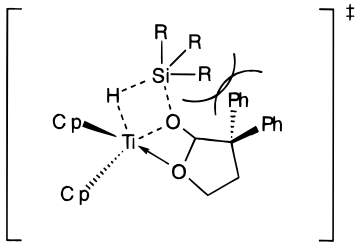
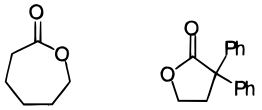


Figure 2. Proposed transition state for the σ-bond metathesis of **5**.

a 1:1 mixture of lactol and diol. These results can be rationalized according to our proposed catalytic cycle based on the two pathways available to the alkoxy



4 **5**

complex **2** (Scheme 4). When the ring size becomes greater than 6, the lactol/aldehyde equilibrium favors the open form **3**.[26] The resulting aldehyde is reduced to yield diol as the observed product. In the case of **5**, we believe σ-bond metathesis in the lactol form is hindered by the two large α-substituents (Figure 2). This allows reduction, *via* the aldehyde form, to yield the corresponding diol to be a competitive pathway.

Control Experiments. A fluoride-catalyzed pathway involving a pentavalent silicon species is an alternative mechanism by which lactones could be reduced to lactols. This is especially true for the $Cp_2Ti(OR)_2$/TBAF/PMHS system.[27] It has been known for some time that TBAF itself can catalyze the hydrosilylation of ketones.[28] A recent report has indicated that TBAF catalyzes the hydrosilylation of esters, ketones, and carboxylic acids to their corresponding alcohols.[29] To rule out this pathway in the present work several experiments were performed.

Using δ-decanolactone as a test case, various quantities of titanium catalyst **1c** were used while keeping the ratio of TBAF to substrate constant at 1:100 (Table 3). When no titanium catalyst was used, the order in which the reagents were added was of crucial importance; the silane needed to be added last for better results; otherwise, the TBAF/PMHS combination formed a polymeric gel. When lactone was added to this gel mixture it required 4 days for complete conversion to the product.[30] If the silane was added last, no gel was formed and the reaction proceeded to completion in 18 h at room temperature (Table 3). For some substrates there was no lactol formation using TBAF. For example, in the reaction of five-membered lactones γ-decanolactone and γ-(4-fluorophenyl)-γ-butyrolactone, polymeric gels were formed (regardless of order of addition) and only starting material was observed after 48 h. In contrast, in the presence of 1 mol % titanium catalyst, hydrosilylation of γ-decanolactone was complete in 5 min at room temperature. In the reaction of a second δ-lactone, dihydrocoumarin, gel formation was not observed, but no conversion to product was seen after 48 h.

We also examined the method of Corriu,[31] in which potassium fluoride was used as a catalyst. When δ-decanolactone in DMSO was exposed to potassium fluoride at 100 °C (the conditions used by Corriu) no conversion to lactol or diol was detected. Neither lactol nor diol was observed when δ-decanolactone was reacted under the conditions used for our protocols substituting potassium fluoride for **1d**.

When neat phenylsilane was used to activate **1c** (Table 1, entry 2), δ-decanolactol was produced in comparable yields and reaction times as the **1c**/TBAF and **1d** systems. These results combined with those discussed above essentially rule out a fluoride-catalyzed reaction as a major contributor in the protocols we have developed.

Conclusions

We have developed a synthetically useful catalytic procedure for the reduction of five- and six-membered lactones employing polymethylhydrosiloxane as the stoichiometric reductant. Two systems were developed wherein straightforward activation of the precatalyst generates an efficient catalyst for the hydrosilylation of lactones. A simple aqueous workup liberates the lactol products, which can be purified and isolated in good to excellent yields. Both of these protocols are carried out at room temperature and provide attractive alternatives to existing methods.

Experimental Section

General Methods. Toluene and THF were distilled under argon from sodium/benzophenone ketyl before use. Polymethylhydrosiloxane (PMHS, $M_w = 2200$) and tetrabutylammonium fluoride on alumina (15% by wt) were used as obtained from Aldrich. Dichloromethane was used as obtained. Lactones were commercially available unless otherwise noted. Some of the commercial lactones were passed through a plug of neutral alumina prior to use. Flash chromatography was performed on E. M. Science Kieselgel 60 (230−400 mesh). Deactivated silica gel was prepared by mixing NEt_3 and SiO_2 in a 2.5% v/v ratio. Yields, unless otherwise stated, refer to isolated yields of compounds of greater than 95% purity as determined by ^{1}H NMR and GC analysis. All compounds were characterized by ^{1}H NMR, ^{13}C NMR, and IR spectroscopy. Solid samples were also characterized by elemental analysis (E & R Analytical Laboratory, Inc.). Nuclear magnetic resonance (NMR) spectra were recorded at 300 MHz. All ^{1}H NMR spectra are reported in δ units, parts per million (ppm) downfield from tetramethylsilane. All ^{13}C NMR spectra are reported in ppm referenced to deuteriochloroform (77.0 ppm). The ^{19}F NMR spectrum is referenced to an external $CFCl_3$ sample (0 ppm) and reported in ppm. All melting points are uncorrected.

Titanocene Di-*p*-chlorophenoxide (1c). According to the literature procedure,[14] a flame-dried Schlenk flask was charged with titanocene dichloride (10 g, 40 mmol) and sodium hydride (2.3 g, 96 mmol) in toluene (400 mL) under argon. A solution of *p*-chlorophenol (10.3 g, 80 mmol) in toluene (100 mL) was cannulated slowly into the reaction mixture. When the addition was over, the reaction was brought to reflux and the disappearance of *p*-chlorophenol was monitored by TLC. Once the reaction was complete, the reaction mixture was allowed

(26) Hurd, C. D.; Saunders, W. H., Jr. *J. Am. Chem. Soc.* **1952**, *74*, 5324.

(27) (a) Furin, G. G.; Vyazakina, O. A.; Gostevsky, B. A.; Vyazankin, N. S. *Tetrahedron* **1988**, *44*, 2675. (b) Chuit, C.; Corriu, R. J. P.; Reye, C.; Young, J. C. *Chem. Rev. (Washington, D.C.)* **1993**, *93*, 1371.

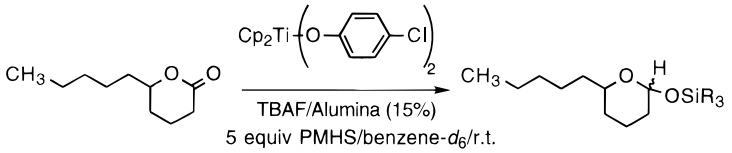
(28) Fujita, M.; Hiyama, T. *J. Org. Chem.* **1988**, *53*, 5405.

(29) *Chem. Eng. News* **1996**; Sept. 16, 42.

(30) Shiihara, I.; Kawai, W.; Ichihashi, T. *J. Polym. Sci.* **1962**, *57*, 837.

(31) For reduction of a lactone see: Boyer, J.; Corriu, R. J. P.; Perz, R.; Poirier, M.; Reye, C. *Synthesis* **1981**, 558. But, lactones were stable to the conditions used in: Chuitt, C.; Corriu, R. J. P.; Perz, R.; Reyé, C. *Synthesis* **1982**, 981.

Table 3. Effect of Catalyst Loading on Substrate Conversion



mol % Ti catalyst (**1c**)	mol % TBAF	time (h)	conversion (%)
0	1	1	7
		18	100
1	1	1	35
2	1	1	93
5	1	0.5	100

to cool to room temperature, and the crude solution was filtered through Celite and concentrated *in vacuo* to give a solid. The solid was recrystallized from toluene/hexane to give orange crystals (11.6 g, 65% yield): mp 127 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.17 (d, 4H), 6.46 (d, 4H), 5.75 (s, 10H).

Titanocene Difluoride (1d). According to the literature procedure,[16] titanocene dichloride (4.98 g, 20 mmol) was dissolved in water to give a 0.125 M red solution. Sodium fluoride (1.68 g, 40 mmol) was added, and the solution was stirred at 50 °C until no traces of red color could be visually detected. The solution was cooled in an ice bath causing titanocene difluoride to precipitate as a yellow solid. The solid was removed by filtration through a coarse frit and dried under vacuum. The solid was further purified by recrystallization from THF to give 3.05 g of yellow solid (71% yield): ^{1}H NMR (300 MHz, $CDCl_3$) δ 6.45 (s, 10 H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 158.1; ^{19}F NMR (288 MHz, $CDCl_3$) δ 64.5.

General Procedure for the Hydrosilylation of Lactones Using Titanocene Di-*p*-chlorophenoxide (1c). In an oven-dried Schlenk flask under argon were placed **1c** (21 mg, 0.05 mmol), TBAF on alumina (15 wt %, 45 mg, 0.025 mmol), and 3 mL of dry toluene. PMHS (0.75 mL, 12.5 mmol) was added to the orange slurry *via* syringe, resulting in a small amount of bubbling. The reaction mixture was stirred at room temperature for 5−10 min during which time a change in color from orange to dark blue occurred. The flask was cooled with a cold water bath, and the lactone (2.5 mmol) was added dropwise *via* syringe. The reaction mixture was stirred at room temperature until consumption of the starting material (0.5−6 h) was complete (TLC analysis). At this point the catalyst was deactivated by exposing the reaction mixture to air. **Notes:** (1) In some cases, activation of the precatalyst (color change to blue) required warming to 50−70 °C for several minutes. (2) Lactones that were solids were dissolved in toluene (2 mL) and added *via* cannula to the activated catalyst in toluene (1 mL).

General Procedure for the Hydrosilylation of Lactones Using Titanocene Difluoride (1d). In an oven-dried Schlenk flask under argon were placed **1d** (10.8 mg, 0.05 mmol) and dry THF (3 mL). PMHS (0.75 mL, 12.5 mmol) was added to the yellow solution *via* syringe. The reaction flask was stirred in a hot water bath (ca. 60 °C) for 0.5−2 min, resulting in a color change from yellow to dark blue that was accompanied by bubbling. The flask was then cooled in an ice bath, and the lactone (2.5 mmol) was added dropwise *via* syringe. The reaction mixture was stirred at room temperature until consumption of the starting material was complete (0.1−6 h, TLC analysis). At this point, the catalyst was deactivated by exposing the reaction mixture to air. **Note:** Lactones that were solids were dissolved in THF (2 mL) and added *via* cannula to the activated catalyst in THF (1 mL).

Workup A. The reaction mixture was diluted with THF (10 mL), transferred to a 100-mL round-bottom flask, and treated with 1 M NaOH (15 mL). [**CAUTION**: vigorous bubbling!]. The two-phase mixture was stirred for 1 h or until the organic layer became clear. The organic phase was separated, diluted with ether (20 mL), washed twice with 1 M NaOH (10 mL), washed with saturated brine (10 mL), dried ($MgSO_4$), and concentrated *in vacuo*.

Workup B. The toluene (if present) was removed *in vacuo*, and the residue was dissolved in THF (15 mL). Water (0.3 mL) and 1 M TBAF/THF (0.3 mL) were added [**CAUTION:** vigorous bubbling!]. After the bubbling had subsided, the mixture was refluxed for 2 h. The precipitate that had formed was removed by filtration. The resulting filtrate was dried ($MgSO_4$) and concentrated *in vacuo*.

6-Pentyltetrahydropyran-2-ol[32] **(Table 2, Entry 1).** According to the general procedure, (±)-δ-decanolactone (0.45 mL, 2.5 mmol), **1c** (21 mg, 0.05 mmol), TBAF on alumina (15 wt %, 45 mg, 0.025 mmol), PMHS (0.75 mL, 12.5 mmol), and toluene (3 mL) were used. Workup A followed by flash chromatography (10% ethyl acetate in hexanes) afforded 0.407 g (94% yield) of a colorless oil.

According to the general procedure, (±)-δ-decanolactone (0.45 mL, 2.5 mmol), **1d** (10.8 mg, 0.05 mmol), PMHS (0.75 mL, 12.5 mmol), and THF (3 mL) were used. Workup A followed by flash chromatography (10% ether in hexanes) afforded 0.404 g (93% yield) of a colorless oil: IR (film, cm^{-1}) 3403, 2934, 2859, 1459, 1440, 1194, 1068, 1023, 984, 733; ^{1}H NMR (300 MHz, $CDCl_3$) diastereomer A δ 4.65−4.74 (m, 1H), 3.35−3.45 (m, 1H), 3.15 (br s, 1H), 1.05−1.92 (m, 14H), 0.88 (t, J = 7 Hz, 3H); diastereomer B δ 5.32 (s, 1H), 3.88−3.97 (m, 1H), 2.61 (br s, 1H), 1.05−1.92 (m, 14H), 0.88 (t, J = 7 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) mixture of diastereomers δ 96.3, 91.5, 76.4, 68.6, 35.9, 32.7, 31.8, 31.7, 30.9, 30.2, 29.8, 25.0, 24.8, 22.4, 22.0, 17.3, 13.8.

5-Hexyltetrahydrofuran-2-ol[33] **(Table 2, Entry 2).** According to the general procedure, (±)-γ-decanolactone (1.8 mL, 10 mmol), **1c** (21 mg, 0.05 mmol), TBAF on alumina (15 wt %, 45 mg, 0.025 mmol), PMHS (3 mL, 50 mmol), and toluene (6 mL) were used. Workup A followed by flash chromatography (10% ethyl acetate in hexanes) afforded 1.64 g (95% yield) of a colorless oil.

According to the general procedure, (±)-γ-decanolactone (0.45 mL, 2.5 mmol), **1d** (10.8 mg, 0.05 mmol), PMHS (0.75 mL, 12.5 mmol), and THF (3 mL) were used. Workup A followed by flash chromatography (10% ether in hexanes) afforded 0.42 g (97% yield) of a colorless oil: IR (film, cm^{-1}) 3406, 2928, 2857, 1460, 1269, 1193, 1019, 970; ^{1}H NMR (300 MHz, $CDCl_3$) diastereomer A δ 5.53−5.59 (m, 1H), 4.14−4.25 (m, 1H), 2.60 (br s, 1H), 1.20−2.20 (m, 14H), 0.88 (t, J = 7 Hz, 3H); diastereomer B δ 5.44−5.50 (m, 1H), 3.93−4.04 (m, 1H), 2.70 (br s, 1H),1.20−2.20 (m, 14H), 0.88 (t, J = 7 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) mixture of diastereomers δ 98.0, 97.8, 80.8, 78.1, 37.2, 35.4, 33.6, 32.7, 31.6, 31.6, 29.3, 29.1, 29.1, 26.0, 25.8, 22.4, 13.9.

5-Phenyltetrahydrofuran-2-ol[34] **(Table 2, Entry 3).** According to the general procedure (±)-γ-phenyl-γ-butyrolactone (0.35 mL, 2.5 mmol), **1c** (21 mg, 0.05 mmol), TBAF on alumina (15 wt %, 45 mg, 0.025 mmol), PMHS (0.75 mL, 12.5 mmol) and toluene (3 mL) were used. Workup A followed by flash chromatography (20% ethyl acetate in hexanes) afforded 0.39 g (96% yield) of a colorless oil.

(32) Saucy, G.; Borer, R. *Helv. Chim. Acta* **1971**, *54*, 2121.
(33) Dana, G.; Figadère, B.; Touboul, E. *Tetrahedron Lett.* **1985**, *26*, 5683.
(34) Bates, R. W.; Díez-Martín, D.; Kerr, W. J.; Knight, J. G.; Ley, S. V.; Sakellaridis, A. *Tetrahedron* **1990**, *46*, 4063.

According to the general procedure (±)-γ-phenyl-γ-butyrolactone (0.30 mL, 2.1 mmol), **1d** (10.8 mg, 0.05 mmol), PMHS (0.75 mL, 12.5 mmol) and THF (3 mL) were used. Workup A followed by flash chromatography (20% ether in hexanes) afforded 0.32 g (92% yield) of a colorless oil. IR (film, cm^{-1}) 3404, 3062, 3029, 2948, 1603, 1493, 1452, 1350, 1287, 1187, 1029, 980, 755, 700; ^1H NMR (300 MHz, $CDCl_3$): diastereomer A= δ 7.20−7.47 (m, 5H), 5.61 (s, 1H), 4.96−5.04 (m, 1H), 3.40 (br s, 1H), 1.70−2.57 (m, 4H); diastereomer B= δ 7.20−7.47 (m, 5H), 5.70−5.78 (m, 1H), 5.24 (t, J = 8 Hz, 1H), 3.40 (br s, 1H), 1.70−2.57 (m, 4H); ^{13}C NMR (75 MHz, $CDCl_3$) mixture of diastereomers δ 142.6, 142.2, 128.1, 127.2, 127.1, 126.2, 125.4, 98.6, 98.2, 82.6, 79.3, 34.1, 32.8, 32.7, 32.6.

3,4-Dihydro-2*H*-1-benzopyran-2-ol[35] **(Table 2, entry 4).** According to the general procedure dihydrocoumarine (0.35 mL, 2.5 mmol), **1c** (21 mg, 0.05 mmol), TBAF on alumina (15 wt %, 45 mg, 0.025 mmol), PMHS (0.75 mL, 12.5 mmol) and toluene (3 mL) were used. Workup B followed by flash chromatography (5→10% ethyl acetate in hexanes) afforded 0.36 g (87% yield) of a colorless oil. IR (film, cm^{-1}) 3415, 3039, 2939, 2850, 1583, 1491, 1456, 1222, 1115, 1057, 998, 953, 868, 755; ^1H NMR (300 MHz, $CDCl_3$): δ 7.03−7.16 (m, 2H), 6.78−6.93 (m, 2H), 5.57−5.67 (m, 1H), 3.20 (br s, 1H), 2.90−3.06 (m, 1H), 2.70 (dt, J = 11, 3 Hz, 1H), 1.91−2.10 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 151.9, 129.2, 127.3, 122.0, 120.8, 116.8, 92.1, 26.9, 20.2.

2-Oxabicyclo[3.4.0]non-5-ene-1-ol[36] **(Table 2, Entry 5)**. *cis*-Δ^4-Tetrahydrophthalide[37] was prepared by the sodium borohydride reduction[38] of *cis*-1,2,5,6-tetrahydrophthalic anhydride. The product was purified by distillation (87 °C, 0.4 Torr) to give a colorless oil: ^1H NMR (300 MHz, $CDCl_3$) δ 5.73−5.74 (m, 2H), 4.31 (dd, J = 5.6, 8.8 Hz, 1H), 4.01 (dd, J = 1.8,8.8 Hz, 1 H), 2.23−2.81 (m, 5H), 1.86−1.94 (m, 1H).

According to the general procedure, *cis*-Δ^4-tetrahydrophthalide (138 mg, 1.0 mmol), **1d** (4.3 mg, 0.02 mmol), PMHS (0.3 mL, 5 mol), and THF (1.2 mL) were used. Workup A followed by flash chromatography (10% ether in hexanes) afforded 0.125 g (89% yield) of a colorless oil: IR (film, cm^{-1}) 3382, 3025, 2913, 2246, 1717, 1659, 1638, 1438, 1346, 1281, 1211, 1098, 990, 942, 912, 733, 660; ^1H NMR (300 MHz, $CDCl_3$) diastereomer A δ 5.62−5.72 (m, 2H), 5.18−5.2 (m, 1H), 4.1−4.2 (m, 1H), 3.52−3.62 (t, 1H), 2.1−2.45 (m, 4H), 1.8−2.1 (m, 2H); diastereomer B δ 5.62−5.72 (m, 2H), 5.36−5.42 (m, 1H), 4.2−4.3 (m, 1H), 3.38−3.50(dq, 1H), 2.1−2.45 (m, 4H), 1.8−2.1 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) diastereomer A δ 124.7, 124.7, 103.3, 72.1, 41.2, 32.8, 23.7, 22.9; diastereomer B δ 127.1, 125.7, 97.7, 72.6, 44.9, 36.4, 28.8, 25.0.

3,6-Dihydro-4,6,6-trimethyl-2*H*-pyran-2-ol[39] **(Table 2, Entry 6).** According to the general procedure, 3,6-dihydro-4,6,6-trimethyl-2*H*-pyran-2-one (0.35 mL, 2.5 mmol), **1c** (21 mg, 0.05 mmol), TBAF on alumina (15 wt %, 45 mg, 0.025 mmol), PMHS (0.75 mL, 12.5 mmol), and toluene (3 mL) were used. Workup A followed by flash chromatography (10% ethyl acetate in pentane) afforded 0.31 g (89% yield) of a colorless oil.

According to the general procedure, 3,6-dihydro-4,6,6-trimethyl-2*H*-pyran-2-one (0.35 mL, 2.5 mmol), **1d** (10.8 mg, 0.05 mmol), PMHS (0.75 mL, 12.5 mmol), and THF (3 mL) were used. Workup A followed by flash chromatography (10% ether in hexanes) afforded 0.27 g (76% yield) of a colorless oil: IR (film, cm^{-1}) 3386, 2972, 2928, 1679, 1439, 1381, 1238, 1179, 1127, 1072, 1009, 956, 861, 733; ^1H NMR (300 MHz, $CDCl_3$) δ 5.32 (s, 1H), 5.13−5.21 (m, 1H), 3.30 (br s, 1H), 1.99−2.81 (m, 2H), 1.69 (s, 3H), 1.30 (s, 3H), 1.26 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 127.8, 127.7, 89.9, 74.4, 36.6, 29.7, 26.9, 22.6.

5-(4-Fluorophenyl)tetrahydrofuran-2-ol (Table 2, Entry 7). According to the general procedure, (±)-γ-(4-fluorophenyl)-γ-butyrolactone (0.37 mL, 2.5 mmol), **1c** (21 mg, 0.05 mmol), TBAF on alumina (15 wt %, 45 mg, 0.025 mmol), PMHS (0.75 mL, 12.5 mmol), and toluene (3 mL) were used. Workup A followed by flash chromatography (20% ethyl acetate in hexanes) afforded 0.47 g (96% yield) of a white solid.

According to the general procedure, (±)-γ-(4-fluorophenyl)-γ-butyrolactone (0.38 mL, 2.5 mmol), **1d** (10.9 mg, mmol), PMHS (0.75 mL, 12.5 mmol), and THF (3 mL) were used. Workup A followed by flash chromatography (20% ether in hexanes) afforded 0.45 g (97% yield) of a white solid: mp 51−52 °C; IR (KBr, cm^{-1}) 3394, 2987, 2948, 2903, 1602, 1508, 1221, 1036, 984, 840; ^1H NMR (300 MHz, $CDCl_3$) diastereomer A δ 7.39 (dd, J = 5, 7 Hz, 2H), 7.60 (t, J = 8 Hz, 2H), 5.52−5.58 (m, 1H), 4.93−4.98 (m, 1H), 4.27 (d, J = 3 Hz, OH), 1.65−2.51 (m, 4H); diastereomer B δ 7.60 (t, J = 8 Hz, 2H), 7.25 (dd, J = 5, 7 Hz, 2H), 5.66−5.70 (m, 1H), 5.19 (t, J = 7 Hz, 1H), 4.16 (d, J = 3 Hz, OH), 1.65−2.51 (m, 4H); ^{13}C NMR (75 MHz, $CDCl_3$) mixture of diastereomers δ 162.1 (^1J = 243 Hz), 160.2 (^1J = 243 Hz), 138.4 (^4J = 3 Hz), 137.9 (^4J = 3 Hz), 128.1 (^3J = 8 Hz), 127.2 (^3J = 8 Hz), 115.1 (^2J = 23 Hz), 98.4, 94.4, 82.2, 78.9, 34.2, 32.8. Anal. Calcd for $C_{10}H_{11}FO_2$: C, 65.92; H, 6.09. Found: C, 65.93; H, 6.26.

6-Bromo-3,4-dihydro-2*H*-1-benzopyran-2-ol[40a] **(Table 2, Entry 8).** According to the literature procedure,[40] dihydrocoumarine was allowed to react with bromine. The resulting solid was washed with pentane to remove unreacted starting material and recrystallized from pentane/CH_2Cl_2 to give a white solid: mp 97−98 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 7.35−7.41 (m, 2H), 6.94 (d, 1H), 2.97−3.02 (m, 2H), 2.76−2.81 (m, 2H).

According to the general procedure, a solution of 6-bromo-3,4-dihydro-2*H*-1-benzopyran-2-one (228 mg, 1 mmol) in toluene (2 mL), **1c** (21 mg, 0.05 mmol), TBAF on alumina (15 wt %, 45 mg, 0.025 mmol), PMHS (0.3 mL, 5 mmol), and toluene (1 mL) were used. Workup B followed by flash chromatography (deactivated silica gel, 5 → 20% ethyl acetate in hexanes) afforded 158 mg (69% yield) of a colorless oil: IR (film, cm^{-1}) 3408, 2941, 1574, 1482, 1409, 1222, 1185, 1124, 1052, 951, 868, 812; ^1H NMR (300 MHz, $CDCl_3$) δ 7.15−7.21 (m, 2H), 6.67 (d, J = 6 Hz, 1H), 5.56 (s, 1H), 3.70 (br s, 1H), 2.88−2.99 (m, 1H), 2.63 (dt, J = 11, 3 Hz, 1H), 1.84−2.99 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 151.0, 131.7, 130.2, 124.2, 118.6, 112.8, 92.0, 26.5, 20.0.

3-Benzyltetrahydrofuran-2-ol (Table 2, Entry 9). Via the literature procedure,[41] γ-butyrolactone was added to a refluxing suspension of sodium in diethyl carbonate. The α-carbethoxy-γ-butyrolactone was purified by distillation (10 Torr, 140−150 °C) to give a clear liquid: ^1H NMR (300 MHz, $CDCl_3$): δ 4.42−4.57 (m, 1H), 4.1−4.39 (m, 3H), 3.51−3.58 (m, 1H), 2.6−2.73 (m, 1H), 2.38−2.57 (m, 1H), 1.32 (t, J = 7 Hz).

According to the literature procedure,[42] the α-carbethoxy-γ-butyrolactone (dissolved in ethanol) was added *via* syringe to a sodium suspension in ethanol to form a white precipitate. Benzyl bromide and additional ethanol are added. Following workup, the product was purified by flash chromatography (10→20% ethyl acetate in hexanes) to give (±)-α-benzyl-γ-butyrolactone: ^1H NMR (300 MHz, $CDCl_3$) δ 7.15−7.39 (m, 5H), 4.07−4.30 (m, 2H), 3.17−3.32 (m, 1H), 2.70−2.81 (m, 2H), 2.18−2.31 (m, 1H), 1.91−2.01 (m, 1H).

Following the general procedure, a solution of (±)-α-benzyl-γ-butyrolactone (440 mg, 2.5 mmol) in toluene (2 mL), **1c** (21 mg, 0.05 mmol), TBAF on alumina (15 wt %, 45 mg, 0.025 mmol), PMHS (0.75 mL, 12.5 mmol), and toluene (1 mL) were used. Workup A followed by flash chromatography (20% ethyl acetate in hexanes) afforded 0.42 g (93% yield) of a white solid.

According to the general procedure, a solution of (±)-α-benzyl-γ-butyrolactone (176 mg, 1 mmol) in THF (0.6 mL), **1d** (4.3 mg, 0.02 mmol), PMHS (0.3 mL, 5 mmol), and THF (0.6 mL) were used. Workup A followed by flash chromatography (20% ether in hexanes) afforded 0.16 g (87% yield) of a white solid: mp 70−71 °C; IR (KBr, cm^{-1}) 3347, 3022, 2984, 2947, 2898, 1496, 1454, 1272, 1122, 1007, 886, 704; ^1H NMR (300

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MHz, $CDCl_3$) mixture of diastereomers δ 7.10−7.30 (m, 5H), 5.25_a (t, J = 3 Hz, 1H), 5.20_b (s, 1H), 4.56_b (d, J = 3 Hz, 1H), 4.47_a (s, 1H), 3.70−4.12 (m, 2H), 1.50−2.97 (m, 5H); ^{13}C NMR (75 MHz, $CDCl_3$) mixture of diastereomers δ 140.9, 139.8, 128.6, 128.5, 128.2, 128.1, 125.9, 125.7, 101.9, 97.6, 66.8, 66.4, 47.1, 45.9, 37.7, 34.5, 29.1, 28.6. Anal. Calcd for $C_{11}H_{14}O_2$: C, 74.13; H, 7.92. Found: C, 74.42; H, 8.21.

(±)-*tert*-Butyl 6-Hydroxy-2,3-diphenyl-4-morpholinecarboxylate (Table 2, Entry 10). According to the general procedure, a solution of (±)-*tert*-butyl 6-oxo-2,3-diphenyl-4-morpholinecarboxylate (353 mg, 1 mmol) in THF (4 mL), **1c** (21 mg, 0.05 mmol), TBAF on alumina (15 wt %, 45 mg, 0.025 mmol), PMHS (0.3 mL, 5 mmol), and THF (1 mL) were used. Workup A followed by flash chromatography (deactivated silica gel, 10 → 30% ethyl acetate in hexanes) afforded 325 mg (92% yield) of a white solid: mp 164−165 °C; IR ($CHCl_3$, cm^{-1}) 3399, 3019, 2979, 1685, 1408, 1367, 1224, 1165, 1124, 1055, 926; ^{1}H NMR (300 MHz, $CDCl_3$) mixture of diastereomers and rotamers δ 7.02−7.50 (m, 10H), 5.40−5.78 (m), 5.00−5.13 (m), 4.16 (d, J = 13 Hz), 4.03 (d, J = 13 Hz), 3.90 (d, J = 14 Hz), 3.39 (d, J = 13 Hz), 3.02−3.15 (m); ^{13}C NMR (75 MHz, $CDCl_3$) mixture of diastereomers and rotamers δ 155.2, 154.7, 154.4, 137.6, 137.5, 136.6, 136.4, 129.9, 129.6, 129.6, 129.5, 129.1, 128.2, 127.7, 127.6, 127.6, 127.5, 127.2, 127.1, 126.9, 126.7, 126.0, 125.8, 125.6, 94.2, 94.0, 90.4, 90.0, 80.8, 80.7, 80.6, 80.5, 77.7, 70.6, 59.3, 58.0, 56.6, 55.9, 44.6, 43.7, 43.0, 42.2, 28.2. Anal. Calcd for $C_{21}H_{30}NO_4$: C, 70.96; H, 7.09; N, 3.94. Found: C, 70.91; H, 7.08; N, 3.96.

5-*O*-Benzyl-2,3-*O*-isopropylidene-D-ribofuranose[44] (Table 2, Entry 11). Starting with D-ribono-γ-lactone, the secondary hydroxyl groups were protected with 2,2-dimethoxypropane to give 2,3-*O*-isopropylidene-D-ribono-γ-lactone. The primary alcohol was protected using sodium hydride and benzyl bromide according to the literature procedure.[42] Flash chromatography was performed (deactivated silica gel, 10 → 30% ethyl acetatae in hexanes) to yield 5-*O*-benzyl-2,3-*O*-isopropylidene-D-ribono-1,4-lactone as a colorless oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.2−7.4 (m, 5H), 4.68−4.81 (m, 2H), 4.65 (t, 1H), 4.51 (q, 2H), 3.64−3.74 (m, 2H), 1.47 (s, 3H), 1.36 (s, 3H).

According to the general procedure, a solution of 5-*O*-benzyl-2,3-*O*-isopropylidene-D-ribono-1,4-lactone (695 mg, 2.5 mmol) in toluene (2 mL), **1c** (21 mg, 0.05 mmol), TBAF on alumina (15 wt %, 45 mg, 0.025 mmol), PMHS (0.75 mL, 12.5 mmol), and toluene (1 mL) were used. Workup A followed by flash chromatography (20% ethyl acetate in hexanes) afforded 0.67 g (95% yield) of a colorless oil: IR (film, cm^{-1}) 3417, 3063, 3030, 2985, 2939, 2866, 1454, 1374, 1210, 1073, 871, 741, 699; ^{1}H NMR (300 MHz, $CDCl_3$) (7/1) mixture of diastereomers, major δ 7.25−7.43 (m, 5H), 5.28 (d, J = 11 Hz, 1H), 4.74 (AB, J = 7 Hz, 2H), 4.64 (AB, J = 11 Hz, 2H), 4.62 (d, J = 11 Hz, OH), 4.55, 4.51, 4.36−4.40 (m, 1H), 3.63 (dq, J = 9, 2 Hz, 2H), 1.46 (s, 3H), 1.29 (s, 3H); minor δ 7.25−7.43 (m, 5H), 5.57 (dd, J = 10, 4 Hz, 1H), 4.74 (AB, J = 7 Hz, 2H), 4.64 (AB, J = 11 Hz, 2H), 4.55, 4.51, 4.20−4.23 (m, 1H), 3.91 (d, J = 11 Hz, OH), 3.58 (dq, J = 9, 2 Hz, 2H), 1.54 (s, 3H), 1.37 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) major δ 136.1, 128.5, 128.2, 127.9, 111.8, 103.5, 87.2, 85.2, 81.8, 73.8, 70.9, 26.2, 24.6; minor δ 137.5, 128.4, 127.6, 127.3, 112.9, 97.6, 81.6, 79.1, 73.4, 71.7, 25.9, 24.5.

Perhydro-1α,3aβ,6,6,9aβ-pentamethyl-*trans*-3a-*transoid*-9a,9b-*trans*-5a-naphtho[2,1-*b*]furan-2-ol (Table 2, Entry 12). (+)-11α-Methylsclareolide[43] was prepared from (3a*R*)-(+)-scalerolide by forming the anion with LDA and quenching with methyl iodide. The resulting product was purified by flash chromatography (5% ethyl acetate in hexanes) and epimerized to a single diastereomer by refluxing in methanol for 2 days with sodium *tert*-butoxide: mp 130 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.63 (sextet, 1H), 2.08 (dt, 1H), 1.89 (dq, 1H), 1.38−1.77 (m, 7H), 1.36 (s, 3H), 1.30 (d, J = 7 Hz, 3H), 1.16−1.27 (m, 3H), 0.98 (s, 3H), 0.90 (s, 3H), 0.85 (s, 3H).

According to the general procedure, a solution of (+)-11α-methylsclareolide (460 mg, 1.7 mmol) in toluene (2 mL), **1c** (21 mg, 0.05 mmol), TBAF on alumina (15 wt %, 45 mg, 0.025 mmol), PMHS (0.75 mL, 12.5 mmol), and toluene (1 mL) were used. Workup A followed by flash chromatography (10% ethyl acetate in hexanes) afforded 0.43 g (94% yield) of a white solid: mp 115−116 °C; IR (KBr, cm^{-1}) 3384, 2934, 2866, 1461, 1382, 1220, 1063, 1009, 972, 924, 819, 733; ^{1}H NMR (300 MHz, $CDCl_3$) (8/1) mixture of diastereomers major δ 4.95 (dd, J = 5, 5 Hz, 1H), 4.26 (d, J = 3 Hz, OH), 2.16 (ddq, J = 10, 5, 5 Hz,1H), 1.82−1.93 (m, 1H), 1.55−1.78 (m, 3H), 1.34 (s, 3H), 1.15 (d, J = 6 Hz, 3H), 0.92 (s, 3H), 0.90−1.50 (m, 8H), 0.86 (s, 3H), 0.81 (s, 3H); minor δ 5.27 (dd, J = 5, 5 Hz, 1H), 3.84 (d, J = 5 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) major diastereomer δ 105.8, 83.1, 66.1, 56.9, 42.1, 40.3, 40.1, 37.6, 33.6, 33.0, 25.0, 20.9, 20.4, 18.12, 18.0, 16.2. Anal. Calcd for $C_{17}H_{30}O_2$: C, 76.64; H, 11.35. Found: C, 76.83; H, 11.40.

5-(3-Hydroxypropyl)tetrahydrofuran-2-ol (Table 2, Entry 13). (±)-Methyl γ-butyrolactone-γ-propionate[46] was prepared from 4-ketopimelic acid by hydrogenation (80 psi) over Adam's catalyst (PtO_2). The lactone acid was converted to the methyl ester by refluxing in methanol with catalytic sulfuric acid. Purification was accomplished by flash chromatography (30 → 50% ether in hexanes): ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.50−4.60 (m, 1H), 3.69 (s, 3H), 2.30−2.64 (m, 5H), 1.63−2.10 (m, 3H).

Using the general procedure, methyl (±)-γ-butyrolactone-γ-propionate (0.175 g, 1.01 mmol), **1d** (4.4 mg, 0.02 mmol), phenylsilane (0.66 mL, 5.4 mmol), and THF (1.2 mL) were used. Workup A followed by flash chromatography (40% ether in hexanes) afforded 0.123 g (84% yield) of a colorless oil: ^{1}H NMR (300 MHz, $CDCl_3$) diastereomer A δ 5.45−5.50 (m, 1H), 4.8−4.9 (m, 1H), 3.98−4.09 (m, 1H), 3.5−3.8 (m, 2H), 3.0−3.3 (br s, 1H), 1.4−2.2 (m, 8H); diastereomer B δ 5.51−5.60 (m, 1H), 4.9−5.1 (m, 1H), 4.20−4.30 (m, 1H), 3.5−3.8 (m, 2H), 3.0−3.3 (br s, 1H), 1.4−2.2 (m, 8H); ^{13}C NMR (75 MHz, $CDCl_3$) mixture of diastereomers δ 98.5, 98.4, 81.0, 78.3, 62.8, 62.7, 34.2, 34.0, 33.3, 32.5, 29.9, 29.8, 29.7, 29.5.

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