DOI: 10.1002/ejoc.200500666

S_N2' Reactions between Lithiated Carbon Nucleophiles and Silylated Vinyloxiranes – Effects of Salts and Solvents on the Stereocontrol

Jean-Charles Marié,[a] Christine Courillon,*[a] and Max Malacria*[a]

Keywords: Alcohols / Allylic compounds / Lithiation / Nucleophilic substitution / Oxygen heterocycles / Silicon

(α,β-Epoxy-γ,δ-alkenyl)-*tert*-butyldimethylsilanes **1** display, a priori, three electrophilic centres and two acidic protons. Depending on the configurations of their oxirane rings, the title compounds react towards lithiated bases either through metallation or S_N2' reactions. In this paper we demonstrate that the *trans*-2-(*tert*-butyldimethylsilyl)-3-vinyloxiran **1a** reacts regioselectively with primary, secondary and tertiary butyllithium in S_N2' fashion, which allows the formation of α-silylated allylic alcohols with diastereomeric ratios of over 7 to 1 in favour of the *Z* olefins. A study of the effect of temperature, time, addition of salt and polarity of the solvent on the diastereoselectivity of the reaction is described and the results are interpreted in terms of different mechanistic models.

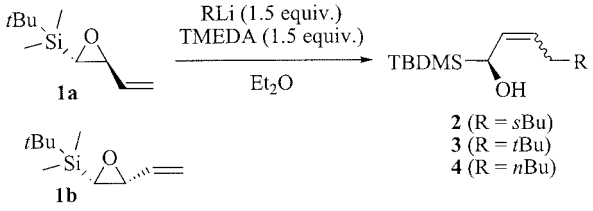
Introduction

(α,β-Epoxy-γ,δ-alkenyl)-*tert*-butyldimethylsilanes **1** are highly functionalized compounds that we are developing as efficient substrates in asymmetric synthesis. We have already reported their stereoselective palladium(0)-catalysed rearrangements into β,γ-unsaturated α-silylated aldehydes[1–5] and their consecutive alkylation/lactonisation tandem transformations into δ-alkylated γ-silylated α,β-unsaturated δ-lactones.[6–8] Compounds **1** have only rarely been described in the literature, in which they are mainly reported to be unstable entities,[9] whereas the reactivities of silylated epoxides[10–16] and vinyloxiranes,[17] especially towards nucleophiles, have been studied thoroughly. However, the chemical behaviour of compounds **1** has been shown to be highly dependent on the configuration of the oxirane moiety. Although we have been able to verify that ring-opening of both *cis*- and *trans*-2-(*tert*-butyldimethylsilyl)-3-vinyloxiran by heteroatomic nucleophiles such as azide anion or phenyl sulfide results mainly in substitution at the position α to the silicon atom, the diastereomers react totally differently towards lithiated bases.[18] From the literature concerning epoxysilanes[19] and vinyloxiranes,[20] we expected deprotonation either α to the silicon atom or at the allylic position, but we discovered that only *cis*-**1b** could be lithiated at the silylated oxiranyl carbon atom in a stereoselective manner.[18,21] Instead, the *trans*-compounds **1** react with lithiated bases in conjugate nucleophilic substitutions (S_N2'), with regio- and stereoselectivities that highlighted the influence of the silylated group on the reactivity of the vinyloxiranes.[18]

[a] Université Pierre et Marie Curie, Laboratoire de Chimie Organique, associé au CNRS, FR2769, Tour 44-54 2ème étage, B 229,
4 place Jussieu 75252 Paris cedex 05, France
E-mail: christine.courillon@upmc.fr
max.malacria@upmc.fr

Results and Discussion

According to Molander's procedure,[22] *trans*-**1a** was treated with *sec*-butyllithium in diethyl ether at low temperature in the presence of TMEDA. Unlike in the case of *cis*-**1a**,[18,21] the first results showed that no metallation had occurred on the substrate, but that the allylic alcohol **2** had been produced quantitatively instead. When the base was *tert*-butyllithium, the α-silylated allylic alcohol **3** was obtained in an excellent yield of 98%, whereas *n*-butyllithium gave lower conversion (33%). In all cases, *trans*-**1a** behaved as an electrophilic species and had undergone stereoselective S_N2' transformations, mainly affording *Z* configurations in the newly formed carbon–carbon double bonds in compounds **2**, **3** and **4** (Scheme 1).



Scheme 1.

Variations of the reaction temperature and time as described in Table 1 show the influence of these factors on the diastereoselectivity of double bond formation. At –116 °C (Entries 1, 2, 6, 7, 11, and 12), the *Z*/*E* ratios of the allylic alcohols do not depend on the nature of the lithiated base. Although the yields are lower in the case of *n*BuLi (En-

tries 11 and 12) than in those of *s*BuLi (Entries 1 and 2) and *t*BuLi (Entries 6 and 7), the diastereomeric ratios at –116 °C are all in the range of 7.4–7.8 to 1. At –30 °C, *n*BuLi gives the allylic alcohol **4** in 44% yield after two hours (Entry 15) whereas *s*BuLi and *t*BuLi bring about total conversion in 30 and 15 minutes, respectively (Entries 5 and 10). *t*BuLi is slightly more nucleophilic than *s*BuLi, and a lot more nucleophilic than *n*BuLi, in the S_N2' reaction with *trans*-**1a**. This range of nucleophilicity is illustrated by Entries 2, 7 and 12, showing yields of 51, 65, and 11%, respectively, for compounds **2**, **3** and **4**. Methyl- and phenyllithium, which are less sterically demanding than the butyllithium reagents, could not convert the starting silylated vinyloxirane **1a** even at room temperature (Entries 16 and 17).

The initial temperature at which the lithiated bases are added plays a role in the S_N2' diastereoselectivity, which decreases when the temperature is raised. This effect is especially important in the cases of *s*BuLi (Entries 4 and 5) and of *t*BuLi (Entries 9 and 10). When the tertiary reagent was added above –78 °C, degradation of the medium was observed (Entries 9 and 10).

The electrophilic properties of *trans*-**1a** towards lithiated compounds could be interpreted on the basis of precedent works. Molander has reported that metallation of β-alkylated α,β-epoxysilanes with *trans* relative configurations takes longer than for the *cis* diastereomers.[22] Indeed, deprotonation of the *trans* compounds requires 4 hours at –116 °C, probably due to steric interaction between the β-substituent and the lithiated species.

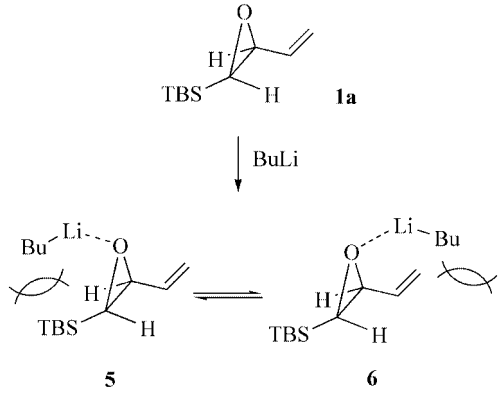
We can speculate on the hypothetical formation of a coordination complex between the lithiated reagent and the oxirane, as proposed by Brandsma.[23] This complex would exist as an equilibrium mixture of two isomeric forms, **5** and **6** (Scheme 2).[22] When a vinyl moiety is linked to the silylated oxirane, steric hindrance by the *tert*-butyldimethylsilyl group should disfavour conformer **5** and direct the base towards the carbon–carbon double bond, favouring the conformational form **6**. According to these observations, we can suggest either an inter- or an intramolecular addition mode.

In the intermolecular model (Scheme 3), the lithiated species plays the role of a Lewis acid in two different conformations: *s-trans* (**5** and **6**) and *s-cis* (**7**). Starting from the unfolded **5**/**6** isomer, in which the interaction between the terminal H^4 vinylic proton and the proton H_α located α to the silicon atom is minimal, the addition of a second equivalent of the lithiated species should give the silylated allylic alcohols **2**, **3** and **4**, with *E* configurations, by route A. The folded form **7** offers a less favourable intermolecular alternative, since the interactions between H^4 and H_α are stronger, but should undergo a S_N2' reaction by route B to give the alcohols **2**, **3** and **4** with *Z* configurations.

Table 1. Stereoselectivities of S_N2' reactions with *trans*-silylated vinyloxiranes.

Entry	Base	Temperature [°C]	Reaction time [h]	*Z*/*E*	Yields (%)
1		–116	4	7.8/1	99 (**2**)
2		–116	1	7.4/1	51 (**2**) + 33 (**1a**)
3	*s*BuLi	–116 to –30	1 (–116°C)	7.1/1	97 (**2**)
4		–78 to –30	1 (–78°C)	3.1/1	93 (**2**)
5		–30	0.5	1.5/1	98 (**2**)
6		–116	4	7.4/1	98 (**3**)
7		–116	1	7.5/1	65 (**3**) + 27 (**1a**)
8	*t*BuLi	–116 to –30	1 (–116°C)	7.1/1	99 (**3**)
9		–78 to –30	1 (–78°C)	3.0/1	40 (**3**)[a]
10		–30	0.25	1.0/1	39 (**3**)[a]
11		–116	4	7.5/1	23 (**4**) + 67 (**1a**)
12		–116	1	7.6/1	11 (**4**) + 79 (**1a**)
13	*n*BuLi	–116 to –30	1 (–116°C)	7.7/1	25 (**4**) + 68 (**1a**)
14		–78 to –30	1 (–78°C)	6.9/1	32 (**4**) + 58 (**1a**)
15		–30	2	6.4/1	44 (**4**) + 52 (**1a**)
16	MeLi[b]	–116 to +25	1 (–116°C)	---	**1a**
17	PhLi[b]	–78 to +25	1 (–78°C)	---	**1a**

[a] TLC showed degradation after workup. [b] Four equivalents of lithiated reagent were used.



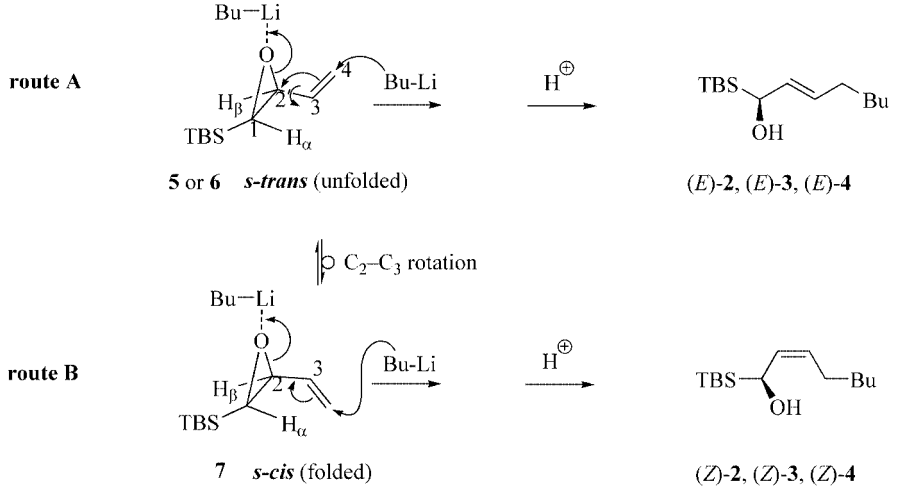
Scheme 2.

The second possible mechanism for this S_N2' reaction is intramolecular (Scheme 4), with *syn* addition of the nucleophile on the oxirane moiety. Pathway C, with a chair-like, cyclic six-centred transition state **8**, affords the *E* alcohols, whereas the boat-like transition state **9** of pathway D gives the *Z* diastereomers.

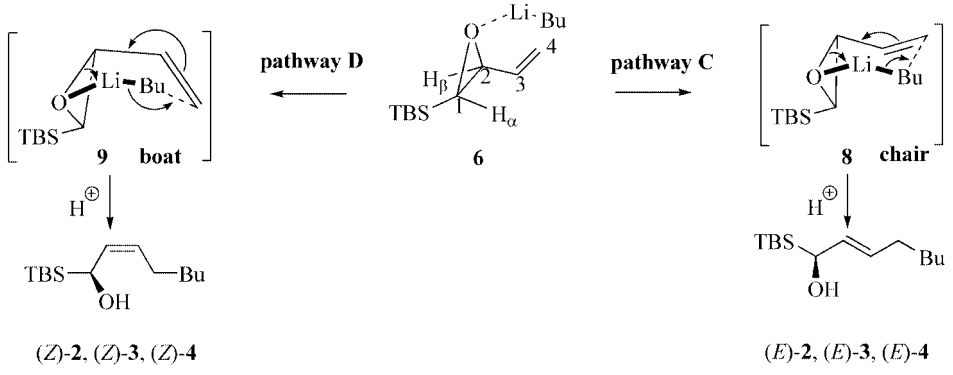
Surprisingly, at this stage of our work, the *Z* allylic alcohols, which are the major diastereomers obtained in this S_N2' reaction, appear to be formed through the less favoured pathways (routes B and D) of both the inter- and the intramolecular possible mechanisms. To confirm these results, a systematic and precise study of this regio- and stereoselective reaction, taking account of factors such as salt, solvent and cosolvent effects, is illustrated below.

In the presence of an excess of lithium chloride (5 equiv.), the S_N2' reaction occurs with a reverse diastereoselectivity and affords a majority of the *E* double bond, with a *Z*/*E* ratio of about 1/2.3. The results, summarized in Table 2, show that *s*BuLi and *t*BuLi both react with lower levels of conversion in the presence of lithium chloride (Entries 1 and 2). The reverse diastereoselectivity observed in the presence of lithium chloride may explain some discrepancies between this study and a previous one we reported in a prior communication.[18] The original use of salt-containing solutions of the butyllithium derivatives is probably the reason for the lower diastereoselectivities we published. The reactions we describe in Table 1, Table 3 and Table 4 are run with crystal-clear solutions of the organolithium derivatives.

Coordination of the lithium cation to the oxygen atom of the oxirane ring probably induces the intermolecular process (Scheme 5). The S_N2' reactions of the organometallic species in the lithium–oxirane complexes **10** and **11** therefore follow route A in Scheme 3 to give (*E*)-**2**, (*E*)-**3** and (*E*)-**4**.

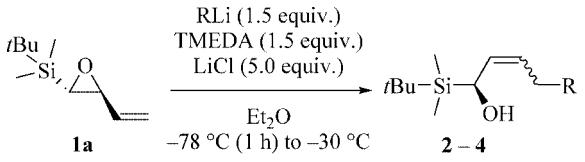


Scheme 3. Intermolecular mechanism.



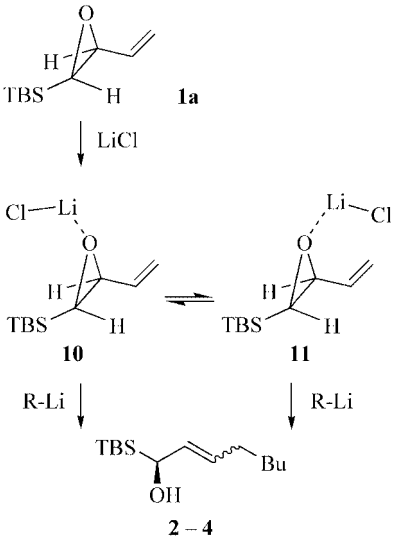
Scheme 4. Intramolecular mechanism.

Table 2. Effect of LiCl on S_N2' reaction of R-Li.



1a 2 – 4

Entry	R-Li	*Z*/*E*	Yields (%)
1	*s*BuLi	1/2.5	28 (**2**) + 68 (**1a**)
2	*t*BuLi	1/2.2	31 (**3**) + 58 (**1a**)
3	*n*BuLi	1/2.4	30 (**4**) + 66 (**1a**)



Scheme 5.

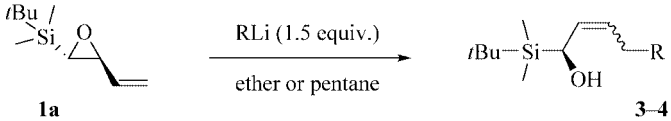
Knowing that, in the presence of lithium chloride, the intramolecular process is not possible and that the intermolecular mechanism predominantly gives the *E* diastereomer, we can draw the conclusion that, without any salt effect, the S_N2' reaction occurs in an intramolecular transformation along pathway D through the boat-like transition state **9**.

The S_N2' reaction was performed both in ether and in pentane with *t*BuLi and *n*BuLi. The results are compared in Table 3 and show weak differences between the two solvents in the case of *n*BuLi (Entries 1 and 2), which, as has been described above, is the least reactive among the three nucleophiles tested in this study. In the presence of the more reactive *t*BuLi, the in pentane stereoselectivity is lower than that in the polar solvent. Indeed, smaller *Z*/*E* ratios are reported when the reactions are carried out in pentane (Entries 4 and 6) than in diethyl ether (Entries 3 and 5).

Different research teams have addressed the study of the structures of lithium organic species in solutions and recent works are still bringing new insights in this field.[24] We analysed our experimental results by suggesting a simple and logical interpretation based on these numerous previous reports.

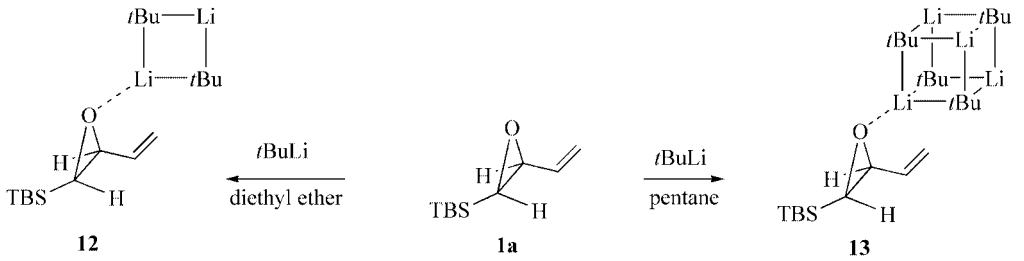
According to Bauer's study on aggregation states of butyllithium species in different kinds of solvents[25] we were able to interpret the effect of the polarity of the solvent on the diastereoselectivities of the S_N2' reactions. Bauer et al. have shown that *t*BuLi is associated in tetrameric entities in apolar solvents such as benzene or hexane and in dimeric structures in diethyl ether, whilst it exists as a monomer in THF. ^{13}C NMR studies have indicated that tetrameric and dimeric aggregations of *n*BuLi exist in equilibrium in THF. Solutions of *n*BuLi in apolar solvents have not been analysed, but comparisons may be drawn with solutions of *n*-PrLi, which is known for its high degree of aggregation in cyclopentane, in which hexa-, octa- and nonameric entities have been characterised. In our case we were able to draw some conclusions relating to differences in the S_N2' reactivity of *trans*-**1a** in ether and in pentane (Scheme 6). In ether (Table 3 Entries 3 and 5), a dimeric form of *t*BuLi is linked to the oxirane and involves complex **12** in an intramolecular mechanism along pathway D (Scheme 4) to give the allylic alcohol (*Z*)-**3** as the major diastereomer. In pentane (Table 3 Entries 4 and 6), the tetrameric complex **13** pres-

Table 3. Effect of solvent polarity on *n*BuLi and *tert*-BuLi S_N2' reaction stereoselectivity.



1a 3–4

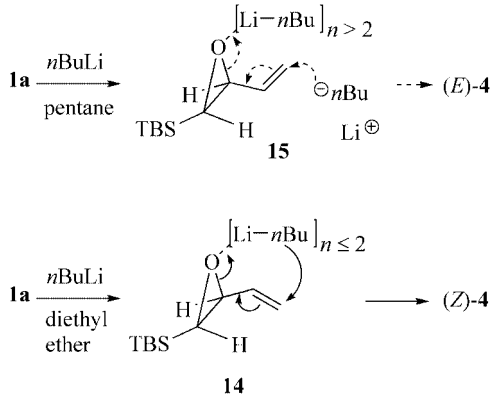
Entry	RLi	Solvent	Temperature [°C]	*Z*/*E*	Yields (%)
1	*n*BuLi	Et_2O	–78 to –30	7.1/1	36 (**4**) + 61 (**1a**)
2	*n*BuLi	*n*-C_5H_{12}	–78 to –30	6.7/1	33 (**4**) + 60 (**1a**)
3	*t*BuLi	Et_2O	–116 to –30	5.3/1	99 (**3**)
4	*t*BuLi	*n*-C_5H_{12}	–116 to –30	2.5/1	98 (**3**)
5	*t*BuLi	Et_2O	–30	4.7/1	83 (**3**)
6	*t*BuLi	*n*-C_5H_{12}	–30	1.7/1	85 (**3**)



Scheme 6. Effect of solvent on the S_N2' reaction of *t*BuLi.

ents more steric hindrance than complex **12**, and the intramolecular process is therefore slowed down, as shown in the decrease of the *Z*/*E* ratio.

When the nucleophile is *n*BuLi, Entries 1 and 2 in Table 3 indicate that the diastereoselectivity is higher than with *t*BuLi both in ether and in pentane, which means both with a low (complex **14**, $n \leq 2$) and a high (complex **15**, $n > 2$) degree of aggregation. In pentane, the aggregation state of *n*BuLi is at least dimeric and probably higher with $n > 2$ in the complex **15** formed with the oxirane. The steric hindrance existing in complex **15** should direct the mechanism towards an intermolecular process, which should give the allylic alcohol (*E*)-**4**. The experimental results show that compound (*Z*)-**4** is mainly obtained and we therefore suggest an equilibrium between complexes **15** and **14**. Complex **14**, with its low degree of aggregation ($n \leq 2$), allows the intramolecular nucleophilic displacement to occur and, therefore, the formation of the allylic alcohol (*Z*)-**4**. In ether, the monomeric or dimeric complex **14** is directly formed and (*Z*)-**4** as explained previously (Scheme 7).



Scheme 7. Effect of solvent on the S_N2' reaction of *n*BuLi.

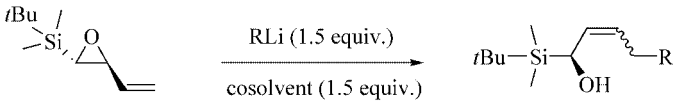
The study of solvent effects on the S_N2' reactions between *t*BuLi or *n*BuLi and the *trans*-**1a** was completed with the use of TMEDA as a cosolvent, as this bidentate ligand has long been added to organolithium compounds in various metallation reactions, especially when silylated oxiranes are the substrates.[26,27] We thus conducted the S_N2' reactions in ether and pentane at different temperatures and in the presence or absence of TMEDA. According to the results summarized in Table 4, the presence of TMEDA does not affect the diastereoselectivities of the reactions in ether when the nucleophiles are added at a low temperature of –78 °C or less (Entries 1 to 4). When *tert*-BuLi is added at –30 °C in ether, the silylated allylic alcohol (*Z*)-**3** is the major diastereomer obtained, in a yield of 83%, whereas in the presence of TMEDA as the cosolvent, degradation is observed and only a 40% yield of an equimolar mixture of (*Z*)-**3** and (*E*)-**3** can be isolated. Entries 5 and 6 in Table 4 show that TMEDA enhances the reactivity of *t*BuLi in ether and produces a loss of diastereoselectivity and partial degradation of the substrate.

In pentane, the presence of TMEDA has little influence on the yields of the reaction when *t*BuLi is added to the silylated vinyloxirane **1a**, but induces the opposite stereoselectivity. Instead of compound (*Z*)-**3** being formed as the major diastereomer (Entries 7, 9, and 11), the effect of TMEDA in pentane is to promote compound (*E*)-**3**, with *E*/*Z* ratios ranging from 2.1 to 3.5 (Entries 8, 10 and 12). These results are not surprising in view of the important role of TMEDA in solvation of organolithium species and especially in the cleavage of aggregates to lower degrees of aggregation. This effect enhances the reactivity of the lithiated species.[28] Our results show a greater effect of TMEDA in pentane than in ether, as confirmed by Collum's work, which demonstrated that the hexameric form of *n*BuLi, for instance, can be converted into dimeric species in an apolar solvent such as toluene, whereas in a polar solvent such as THF, TMEDA could not support complete disaggregation of LiHMDS.[29] In pentane, disaggregation of *t*BuLi to monomeric or dimeric entities by strong coordination to TMEDA should produce more steric hindrance and push the mechanism towards the intermolecular S_N2' process (Scheme 8). This mechanistic hypothesis is supported by the result of Entry 13 when TMEDA and $BF_3{\cdot}Et_2O$ are added in pentane. Complexation of the oxirane by the boron fluoride prevents *t*BuLi from performing any intramolecular displacement and therefore gives rise to (*E*)-**3** as the major compound.

The complexation power of TMEDA in polar solvents such as ether is not strong enough to change the structures of the butyllithium species, which remain dimeric or monomeric and therefore capable of reacting in an intramolecular process to give the *Z* diastereomers as the major compounds (Entries 1 to 6).

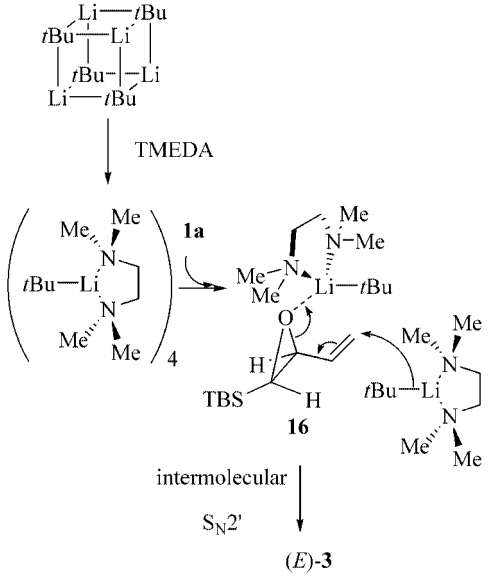
The reactivity of compounds **1** has shown that, of the two groups attached to the oxirane, the effect of the silyl group dominates. Not only do deprotonations occur preferentially in the position α to the vinyl functionality, as we have previously reported,[18,21] but nucleophilic openings of

Table 4. Effect of TMEDA as a cosolvent in the S_N2' reaction of BuLi species.



1a **3–4**

Entry in ether	RLi	Cosolvent	Temperature [°C]	*Z*/*E*	Yields (%)
1	*n*BuLi	TMEDA	–78 to –30	6.9/1	32 (**4**) + 58 (**1a**)
2	*n*BuLi	---	–78 to –30	7.1/1	36 (**4**) + 61 (**1a**)
3	*t*BuLi	TMEDA	–116 to –30	7.1/1	99 (**3**)
4	*t*BuLi	---	–116 to –30	5.3/1	99 (**3**)
5	*t*BuLi	TMEDA	–30	1.0/1	39 (**3**)
6 in pentane	*t*BuLi	---	–30	4.7/1	83 (**3**)
7	*t*BuLi	---	–30	1.7/1	85 (**3**)
8	*t*BuLi	TMEDA	–30	1/2.3	81 (**3**)
9	*t*BuLi	---	–116 to –30	2.5/1	98 (**3**)
10	*t*BuLi	TMEDA	–116 to –30	1/3.5	99 (**3**)
11	*t*BuLi	---	–78 to –30	2.0/1	98 (**3**)
12	*t*BuLi	TMEDA	–78 to –30	1/2.1	89 (**3**)
13	*t*BuLi	TMEDA, $BF_3{\cdot}Et_2O$	–78 to –30	1/3.4	70 (**3**) + 19 (**1a**)



Scheme 8. Effect of TMEDA in pentane.

the oxirane also occur preferentially with scission of the C–O bond α to the silicon atom rather than to the vinyl group. Of particular interest is the behaviour of primary, secondary and tertiary butyllithiums towards *trans*-**1a**, which reacts as an electrophilic substrate, undergoing chemo- and diastereoselective S_N2' reactions. The thorough study of these reactions we report in this paper demonstrates that we are able to optimize and dictate the diastereoselectivity of this nucleophilic substitution by judicious choice of the temperature of the addition of the organolithium, the polarity of the solvent and the presence of TMEDA or LiCl. We were indeed able to favour the formation of either the *Z* or the *E* diastereomers of different α-silylated allylic alcohols, which are potent precursors in further asymmetric synthesis. The scope of this reaction with respect to the type of substituent that can be linked to the double bond is currently under investigation in our group.

Experimental Section

^1H NMR and ^{13}C NMR spectra were recorded at room temperature at 400 MHz and 200 MHz, respectively, on a Bruker ARX 400 spectrometer. Chemical shifts are reported in ppm referenced to the residual proton resonances of the solvents. Coupling constants are expressed in Hertz. Infrared (IR) spectra were recorded with a Bruker tensor 27 (ATR diamond) spectrometer. Thin-layer chromatography (TLC) was performed on Merck silica gel (60 F 254). Silica gel (Merck Geduran SI, 40–63 mm) was used for column chromatography.

All melting points are uncorrected. THF and Et_2O were distilled from sodium/benzophenone ketyl, CH_2Cl_2, pentane and toluene were distilled from CaH_2, and amines were distilled from KOH.

General Procedure for Ring-Opening with Lithiated Nucleophiles: When dry LiCl (115 mg, 2.71 mmol, 5 equiv., see Table 2) was required, it was introduced first into the reaction flask and cooled down, and compound **1a** was added. TMEDA (122 μL, 0.81 mmol, 1.5 equiv.; see Table 4) was added to a cooled solution (see Table 1 for the temperature) of the *trans* silylated vinyloxirane **1a** (100 mg, 0.54 mmol, 1.0 equiv.) in diethyl ether or pentane (5 mL; see Table 3). After 5 min, *s*BuLi (1.3 M in cyclohexane, 0.63 mL,

0.81 mmol, 1.5 equiv.) or *t*BuLi (1.5 M in pentane, 0.54 mL, 0.81 mmol, 1.5 equiv.) or *n*BuLi (2.5 M solution in hexane, 0.32 mL, 0.81 mmol, 1.5 equiv.) was carefully added dropwise. The reaction mixture was stirred for the time indicated in Table 1 and, if necessary, warmed up progressively to –30 °C. The medium was then quenched with a 1:1 solution of propionic acid in diethyl ether. After 15 min, the medium was treated with a saturated aqueous NH_4Cl solution and the organic phase was neutralised with a saturated aqueous $NaHCO_3$ solution. The aqueous layer was extracted twice with ethyl acetate, the combined organic layers were washed with brine and dried with $MgSO_4$, and the solvents were removed in vacuo. The crude products were purified by flash chromatography on silica gel (petroleum ether/CH_2Cl_2, 90:10) and the diastereomers (*E* and *Z*) could be separated (for yields see Table 1).

(*Z*)-1-(*sec*-Butyldimethylsilyl)-5-methylhept-2-en-1-ol [(*Z*)-2]: Compounds (*E*)-**2** and (*Z*)-**2** could be separated, each of them as a mixture of inseparable diastereomers $C_1(S)$-$C_5(R)$ and $C_1(S)$-$C_5(S)$. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.55 (t, *J* = 10.7 Hz, 1 H, C*H*=CHCH$_2$), 5.34 (m, 1 H, CH=C*H*CH$_2$), 4.37 (d, *J* = 10.2 Hz, 1 H, C*H*OH), 1.90 (m, 2 H, =CHC*H*$_2$), 1.34 (m, 2 H, C*H*$_2$CH$_3$), 1.17 (m, 1 H, C*H*CH$_3$), 0.93 (s, 9 H, *tBu*Si), 0.85 (t, *J* = 6.6 Hz, 3 H, CH$_2$C*H*$_3$), 0.84 (d, *J* = 6.6 Hz, 3 H, CHC*H*$_3$), 0.00 (s, 3 H, C*H*$_3$Si), –0.10 (s, 3 H, C*H*$_3$Si) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 132.2 (C=*C*HCH$_2$), 128.6 (HOCH*C*H=C), 62.5 (*C*HOH), 35.4 (*C*HCH$_3$), 34.9 (C=CH*C*H$_2$), 30.0 (*C*H$_2$CH$_3$), 27.4 [(*C*H$_3$)$_3$C], 19.4 (*C*H$_3$CH), 17.4 [(CH$_3$)$_3$*C*], 12.0 (CH$_2$*C*H$_3$), –7.2 (*C*H$_3$Si), –8.4 (*C*H$_3$Si) ppm. IR (neat): $\tilde{\nu}$ = 3450, 3020, 2960, 1650, 1250, 830 cm^{-1}. NH_3-CIMS: *m*/*z* (%) = 260 [*M* + 18]$^+$ (8), 243 [*M* + 1]$^+$ (26), 242 [*M*]$^+$ (100), 225 [*M* – OH]$^+$ (70). $C_{14}H_{30}OSi$ (242.472): calcd. C 69.35, H 12.47; found C 69.11, H 12.27.

(*E*)-1-(*sec*-Butyldimethylsilyl)-5-methylhept-2-en-1-ol [(*E*)-2]: ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.69 (dd, *J* = 15.2, 6.6 Hz, 1 H, C*H*=CHCH$_2$), 5.52 (dt, *J* = 15.2, 7.1 Hz, 1 H, CH=C*H*CH$_2$), 4.13 (d, *J* = 6.6 Hz, 1 H, C*H*OH), 2.12 (dt, *J* = 13.7, 7.1 Hz, 1 H, C=CHC*H*H′), 1.94 (dt, *J* = 13.7, 7.1 Hz, 1 H, C=CHCH*H*′), 1.46–1.37 (m, 2 H, C*H*$_2$CH$_3$), 1.19 (m, 1 H, CHC*H*$_3$), 1.01 (s, 9 H, *tBu*Si), 0.92 (t, *J* = 6.6 Hz, 3 H, CH$_2$C*H*$_3$), 0.91 (d, *J* = 6.6 Hz, 3 H, CHC*H*$_3$), 0.06 (s, 3 H, C*H*$_3$Si), 0.00 (s, 3 H, C*H*$_3$Si) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 131.2 (C=*C*HCH$_2$), 128.0 (HOCH*C*H=C), 61.8 (*C*HOH), 34.7 (*C*HCH$_3$), 34.2 (C=CH*C*H$_2$), 29.2 (*C*H$_2$CH$_3$), 26.6 [(*C*H$_3$)$_3$C], 18.8 (*C*H$_3$CH), 16.7 [(CH$_3$)$_3$*C*], 11.2 (CH$_2$*C*H$_3$), –8.0 (*C*H$_3$Si), –9.1 (*C*H$_3$Si) ppm. IR (neat): $\tilde{\nu}$ = 3460, 3030, 2950, 1670, 1250, 850 cm^{-1}. NH_3-CIMS: *m*/*z* (%) = 243 [*M* + 1]$^+$ (35). 242 [*M*]$^+$ (100). 225 [*M* – OH]$^+$ (67). $C_{14}H_{30}OSi$ (242.472): calcd. C 69.35, H 12.47; found C 69.41, H 12.55.

(*Z*)-1-(*tert*-Butyldimethylsilyl)-5,5-dimethylhex-2-en-1-ol [(*Z*)-3]:[18] Two separable diastereomers (*Z*)-**3** and (*E*)-**3** were obtained as colourless oils. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.61 (t, *J* = 10.7 Hz, 1 H, C*H*=CHCH$_2$), 5.43 (dt, *J* = 10.7, 5.6 Hz, 1 H, CH=C*H*CH$_2$), 4.39 (d, *J* = 10.7 Hz, 1 H, C*H*OH), 2.04 (ddd, *J* = 14.7, 5.6, 1.0 Hz, 1 H, C=CHC*H*H′), 1.78 (ddd, *J* = 14.2, 5.6, 1.6 Hz, 1 H, C=CHCH*H*′), 0.94 (s, 9 H, *tBu*CH$_2$), 0.89 (s, 9 H, *tBu*Si), 0.02 (s, 3 H, C*H*$_3$Si), –0.08 (s, 3 H, C*H*$_3$Si) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 132.4 (C=*C*HCH$_2$), 126.6 (HOCH*C*H=C), 62.1 (*C*HOH), 41.5 (C=CH*C*H$_2$), 30.8 [*C*(CH$_3$)$_3$], 29.3 [C(*C*H$_3$)$_3$], 27.1 [(*C*H$_3$)$_3$CSi], 17.1 [(CH$_3$)$_3$*C*Si], –7.5 (*C*H$_3$Si), –8.6 (*C*H$_3$Si) ppm. IR (neat): $\tilde{\nu}$ = 3450, 2990, 1650, 1250, 830 cm^{-1}. $C_{14}H_{30}OSi$ (242.472): calcd. C 69.35, H 12.47; found C 69.04, H 12.31.

(*E*)-1-(*tert*-Butyldimethylsilyl)-5,5-dimethylhex-2-en-1-ol [(*E*)-3]:[18] ^{1}H NMR (400 MHz, C_6D_6): δ = 5.59 (dd, *J* = 15.2, 5.4 Hz, 1 H, C*H*=CHCH$_2$), 5.44 (dt, *J* = 15.2, 6.9 Hz, 1 H, CH=C*H*CH$_2$), 3.93 (d, *J* = 5.9 Hz, 1 H, C*H*OH), 1.90 (d, *J* = 6.4 Hz, 2 H, CHC*H*$_2$), 1.03 (s, 9 H, *tBu*CH$_2$), 0.89 (s, 9 H, *tBu*Si), 0.09 (s, 3 H, C*H*$_3$Si), –0.02 (s, 3 H, C*H*$_3$Si) ppm. ^{13}C NMR (100 MHz, C_6D_6): δ = 136.3 (C=*C*HCH$_2$), 124.8 (HOCH*C*H=C), 67.8 (*C*HOH), 48.4 (C=CH*C*H$_2$), 30.6 [*C*(CH$_3$)$_3$], 28.9 [C(*C*H$_3$)$_3$], 26.6 [(*C*H$_3$)$_3$CSi], 16.5 [(CH$_3$)$_3$*C*Si], –6.2 (*C*H$_3$Si), –7.8 (*C*H$_3$Si) ppm. IR (neat): $\tilde{\nu}$ = 3460, 3020, 2970, 1680, 1270, 850 cm^{-1}. NH_3-CIMS: *m*/*z* (%) = 243 [*M* + 1]$^+$ (37), 242 [*M*]$^+$ (100), 225 [*M* – OH]$^+$ (63). $C_{14}H_{30}OSi$ (242.472): calcd. C 69.35, H 12.47; found C 69.01, H 12.25.

(*Z*)-1-(*n*-Butyldimethylsilyl)oct-2-en-1-ol [(*Z*)-4]: The two separable diastereomers (*Z*)-**4** and (*E*)-**4** were obtained as colourless oils. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.51 (t, *J* = 10.7 Hz, 1 H, C*H*=CHCH$_2$), 5.34 (m, 1 H, CH=C*H*CH$_2$), 4.40 (d, *J* = 10.2 Hz, 1 H, C*H*OH), 2.06 (m, 1 H, =CHC*H*H′), 1.92 (m, 1 H, =CHCH*H*′), 1.36–1.24 [m, 6 H, (C*H*$_2$)$_3$], 0.94 (s, 9 H, *tBu*Si), 0.87 [t, *J* = 7.1 Hz, 3 H, C*H*$_3$-(CH$_2$)$_3$], 0.02 (s, 3 H, C*H*$_3$Si), –0.08 (s, 3 H, C*H*$_3$Si) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 131.1 (C=*C*HCH$_2$), 129.6 (HOCH*C*H=C), 62.3 (*C*HOH), 31.7 (C=CH*C*H$_2$), 29.5 (C=CHCH$_2$*C*H$_2$), 27.9 [C=CH(CH$_2$)$_2$*C*H$_2$], 27.1 [(*C*H$_3$)$_3$CSi], 22.6 (*C*H$_2$CH$_3$), 17.1 [(CH$_3$)$_3$*C*Si], 14.1 (CH$_2$*C*H$_3$), –7.6 (*C*H$_3$Si), –8.7 (*C*H$_3$Si) ppm. IR (neat): $\tilde{\nu}$ = 3450, 2930, 1660, 1250, 830 cm^{-1}. NH_3-CIMS: *m*/*z* (%) = 243 [*M* + 1]$^+$ (20), 242 [*M*]$^+$ (100), 225 [*M* – OH]$^+$ (85). $C_{14}H_{30}OSi$ (242.472): calcd. C 69.35, H 12.47; found C 69.34, H 12.51.

(*E*)-1-(*n*-Butyldimethylsilyl)oct-2-en-1-ol [(*E*)-4]: ^{1}H NMR (400 MHz, $CDCl_3$): δ = 5.61 (dd, *J* = 15.2, 7.1 Hz, 1 H, C*H*=CHCH$_2$), 5.46 (dtd, *J* = 15.3, 7.1, 1.0 Hz, 1 H, CH=C*H*CH$_2$), 4.04 (dd, *J* = 7.1, 1.0 Hz, 1 H, C*H*OH), 2.02 (q, *J* = 7.1 Hz, 2 H, C=CHC*H*$_2$), 1.37–1.24 [m, 6 H, (C*H*$_2$)$_3$], 0.93 (s, 9 H, *tBu*Si), 0.87 [t, *J* = 7.1 Hz, 3 H, C*H*$_3$-(CH$_2$)$_3$], 0.01 (s, 3 H, C*H*$_3$Si), –0.05 (s, 3 H, C*H*$_3$Si) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 132.2 (C=*C*HCH$_2$), 127.8 (HOCH*C*H=C), 67.0 (*C*HOH), 32.5 (C=CH*C*H$_2$), 31.5 (C=CHCH$_2$*C*H$_2$), 29.4 [C=CH(CH$_2$)$_2$*C*H$_2$], 27.1 [(*C*H$_3$)$_3$C], 22.6 (*C*H$_2$CH$_3$), 17.0 [(CH$_3$)$_3$*C*], 14.1 (CH$_2$*C*H$_3$), –7.6 (*C*H$_3$Si), –8.8 (*C*H$_3$Si) ppm. IR (neat): $\tilde{\nu}$ = 3450, 2930, 1680, 1250, 830 cm^{-1}. NH_3-CIMS: *m*/*z* (%) = 243 [*M* + 1]$^+$ (22), 242 [*M*]$^+$ (100), 225 [*M* – OH]$^+$ (67). $C_{14}H_{30}OSi$ (242.472): calcd. C 69.35, H 12.47; found C 69.20, H 12.65.

Acknowledgments

The authors thank the ministry of research for J.-C. M.'s grant and the Institut Universitaire de France for generous financial support of this work.

[1] F. Gilloir, M. Malacria, *Tetrahedron Lett.* **1992**, *33*, 3859–3862.
[2] F. Le Bideau, C. Aubert, M. Malacria, *Tetrahedron: Asymmetry* **1995**, *6*, 697–700.
[3] C. Courillon, R. Le Fol, E. Vandendris, M. Malacria, *Tetrahedron Lett.* **1997**, *38*, 5493–5496.
[4] F. Le Bideau, F. Gilloir, Y. Nilsson, C. Aubert, M. Malacria, *Tetrahedron Lett.* **1995**, *36*, 1641–1644.
[5] F. Le Bideau, F. Gilloir, Y. Nilsson, C. Aubert, M. Malacria, *Tetrahedron* **1996**, *52*, 7487–7510.
[6] F. Marion, S. Calvet, C. Courillon, M. Malacria, *Tetrahedron Lett.* **2002**, *43*, 3369–3371.
[7] S. Calvet, C. Courillon, M. Malacria, *Arkivoc* **2002**, 189–195.
[8] F. Marion, S. Calvet, J.-C. Marié, C. Courillon, M. Malacria, *Eur. J. Org. Chem.* **2006**, 453–462, preceding article.
[9] a) F. Chevalier, H. Al-Badri, N. Collignon, *Heteroat. Chem.* **1999**, *10*, 231–236; b) T. Kawai, M. Isobe, S. C. Peters, *Aust. J. Chem.* **1995**, *48*, 115–131; c) J. Robertson, J. N. Burrows, *Tetrahedron Lett.* **1994**, *35*, 3777–3780; d) J. E. Van Epp, D. R. Boyd,

G. A. Berchtold, *J. Org. Chem.* **1981**, *46*, 1817–1820; e) D. R. Boyd, G. A. Berchtold, *J. Org. Chem.* **1979**, *44*, 468–470.
[10] E. W. Colvin, *Chem. Org. Silicon Compd.* **1998**, *2*, 1667–1685.
[11] A. P. Davis, G. J. Hughes, P. Lowndes, C. M. Robbins, E. J. Thomas, G. H. Whitham, *J. Chem. Soc. Perkin Trans. 1* **1981**, *7*, 1934–1941.
[12] P. F. Hudrlik, A. M. Hudrlik, *Adv. Silicon Chem.* **1993**, *2*, 1–89.
[13] D. C. Chauret, J. M. Chong, *Tetrahedron Lett.* **1993**, *34*, 3695–3698.
[14] M. Masnyk, J. Wicha, *Chem. Ber.* **1994**, *127*, 677–683.
[15] A. R. Bassindale, M.-C. Soobramanien, P. G. Taylor, *Bull. Soc. Chim. Fr.* **1995**, *132*, 604–608.
[16] W. Adam, M. Prein, M. J. Richter, *Tetrahedron* **1996**, *52*, 1231–1234.
[17] J. A. Marshall, *Chem. Rev.* **1989**, *89*, 1503–1511.
[18] J.-C. Marié, C. Courillon, M. Malacria, *Synlett* **2002**, 553–556.
[19] J. J. Eisch, J. E. Galle, *J. Am. Chem. Soc.* **1976**, *98*, 4646–4648.
[20] J. J. Eisch, J. E. Galle, *J. Org. Chem.* **1990**, *55*, 4835–4840.
[21] J.-C. Marié, C. Courillon, M. Malacria, *Tetrahedron* **2003**, *59*, 9759–9766.
[22] G. A. Molander, K. Mautner, *J. Org. Chem.* **1989**, *54*, 4042–4050.
[23] S. Harder, J. Boersma, L. Brandsma, *Organometallics* **1990**, *9*, 511–516.
[24] L. M. Pratt, B. Ramachandran, *J. Org. Chem.* **2005**, *70*, 7238–7242.
[25] W. Bauer, W. R. Winchester, P. v. Ragué Schleyer, *Organometallics* **1987**, *6*, 2371–2379.
[26] J. J. Eisch, J. E. Galle, *J. Organomet. Chem.* **1988**, *341*, 293–313.
[27] G. A. Molander, K. Mautner, *Pure Appl. Chem.* **1990**, *62*, 707–712.
[28] P. Beak, W. J. Zajdel, D. B. Reitz, *Chem. Rev.* **1984**, *84*, 471–523.
[29] D. B. Collum, *Acc. Chem. Res.* **1992**, *25*, 448–454.

Received: September 1, 2005
Published Online: November 15, 2005

