Tetrahedron 66 (2010) 1570–1580

Contents lists available at ScienceDirect

Tetrahedron

journal homepage: www.elsevier.com/locate/tet

# Addition of γ-silyloxyallyltins on ethyl glyoxylate: evaluation of the influence of the experimental conditions on the stereochemical course of the reaction

Alexandre Lumbroso [a], Piotr Kwiatkowski [b,c], Anna Blonska [b], Erwan Le Grognec [a], Isabelle Beaudet [a], Janusz Jurczak [b,c,*], Slawomir Jarosz [b,*], Jean-Paul Quintard [a,*]

[a] Université de Nantes, CNRS, Chimie et Interdisciplinarité: Synthèse, Analyse, Modélisation (CEISAM), UMR CNRS 6230, Faculté des Sciences et des Techniques, 2 rue de la Houssinière, BP 92208, 44322 Nantes Cedex 3, France
[b] Institute of Organic Chemistry, Polish Academy of Sciences, Kasprzaka 44/52, 01-224 Warsaw, Poland
[c] Department of Chemistry, Warsaw University, Pasteura 1, 02-093 Warsaw, Poland

ARTICLE INFO

*Article history:*
Received 28 September 2009
Received in revised form 11 December 2009
Accepted 14 December 2009
Available online 21 December 2009

*Keywords:*
γ-Silyloxyallyltributyltins
Ethyl glyoxylate
Allylstannation
Diastereoselective synthesis
Reaction mechanisms

ABSTRACT

Ethyl glyoxylate was reacted with α-substituted γ-(*t*-butyldimethylsilyloxy)-allyltributyltin in order to obtain selectively each diastereomer of ethyl 3-(*t*-butyldimethylsilyloxy)-2-hydroxyhex-4-enoate and subsequently the corresponding diols. Diastereomers *syn-E*, *anti-E* and *anti-Z* were obtained in good yields with good to high selectivities and the obtained results were rationalized by consideration of cyclic or open transition states in agreement with the experimental conditions and with the structure of the starting reagents.



## 1. Introduction

Stereocontrolled synthesis of functionalized unsaturated diols constitutes a topic of high interest due to the possible use of such precursors as key units in the synthesis of bioactive polyhydroxylated molecules.[1–3] For this purpose the addition of γ-oxygenated allylmetals to aldehydes appears to be a key reaction,[4–7] which might be interesting when allylmetals can be obtained selectively either as *E* or *Z* isomers, as for instance with γ-oxygenated allyltin reagents.[8–11]

Following the pioneering work developed for these species[8,12,13] several groups have used α-, γ- or δ-oxygenated allyltins in order to obtain selectively polyhydroxylated molecules as for instance sugars or modified sugars with well-defined stereochemistry.[14–22] Stereocontrol of this reaction is governed by two types of mechanisms: the concerted chair- like six-membered transition state which occurs more readily with *trans*-isomers[23–25] and the open transition state (operating under Lewis acid assistance through an antiperiplanar transition state[26–28] or a synclinal transition state[29–32]). Accordingly, the stereochemical course of the reaction might be predictable, but in practice the things appear to be much more complicated, even for the very simple crotyltributyltin, due to a subtle balance involving transmetallation by metal salts or 1,3-metallotropy on the allyl unit in addition to the primary expected mechanisms, a situation which complicates hardly the discrimination between the possible mechanisms.[33]

Concerning the oxygenated allyltins, the α-isomers have been proven to isomerize easily and stereospecifically in the presence of boron trifluoride[34] and the reactivity of the γ-oxygenated isomers proved to depend strongly on the structural factors including the size of the α-substituent located on the allyltin[35,36] and also the nature of the aldehydes.[37]

In practice, the complexity of the situation implies a detailed evaluation of the stereochemical trends by considering both substrate and substitution of the allyltin. Keeping in mind the possible synthesis of highly functionalized units from glyoxylates and γ-substituted allyltins, we focused our interest on this specific reaction.

Taking into account the propensity of γ-silyloxyallyltins to give *syn*-addition with aldehydes and iminium salts under boron trifluoride assistance[37–40] and the ability of glyoxylates to afford enantioselective reactions both using the ester of an enantiopure alcohol[41,42] or using chiral (salen)chromium(III) complex promoted

* Corresponding authors. Tel.: +33 251125408; fax: +33 251125402.
*E-mail addresses:* jurczak@icho.edu.pl (J. Jurczak), sljar@icho.edu.pl (S. Jarosz), jean-paul.quintard@univ-nantes.fr (J.-P. Quintard).

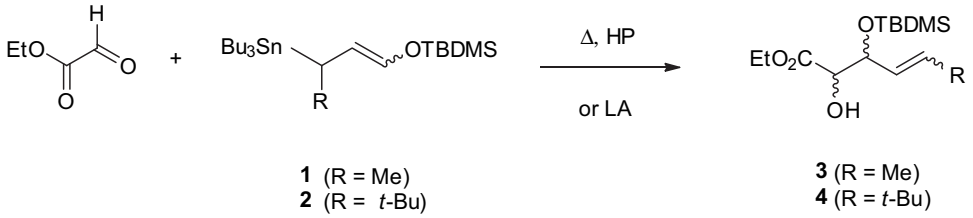
0040-4020/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2009.12.037

reactions,[43] we focused our studies on the stereochemical behaviour of the allylstannation of glyoxylate by γ-silyloxyallyltins.

## 2. Results

The reaction of ethyl glyoxylate with γ-silyloxyallyltins **1*E***, **1*Z*** and **2*E*** was examined under experimental conditions usually favouring the six-membered transition state (thermal or high pressure reactions) or open transition states (antiperiplanar or synclinal transition states) (Scheme 1). The nature of the Lewis acids and their ability to form monodentate complexes (electrophilic assistance on the carbonyl group of the aldehyde) or bidentate complexes (interactions both with the aldehyde oxygen and with the ester function) was carefully examined.

In this case we have been unable to separate the diastereomers obtained from **3-*syn-E*** by liquid chromatography, but we have found from the $^1$H NMR spectra recorded at 293 K and 253 K, that the experimental results were in agreement with a preferred 'sp' conformation with concomitant modification of the chemical shifts in function of the shielding effect of the mandelic aromatic ring. The same reaction performed on **3-*anti-Z***, afforded two diastereomeric bis-*O*-acetyl mandelic esters, which were isolated as pure products, but similar NMR studies at 293 K and 253 K did not exhibit the expected trends, suggesting equilibrium between the 'sp' and 'ap' conformations.[46] We then considered derivatization of **3-*anti-E*** and **3-*anti-Z*** into 3,5-dinitrobenzoates after removal of the silyl group, but no suitable crystals were obtained to allow an X-ray analysis.




**Scheme 1.**

### 2.1. Identification of the diastereomers

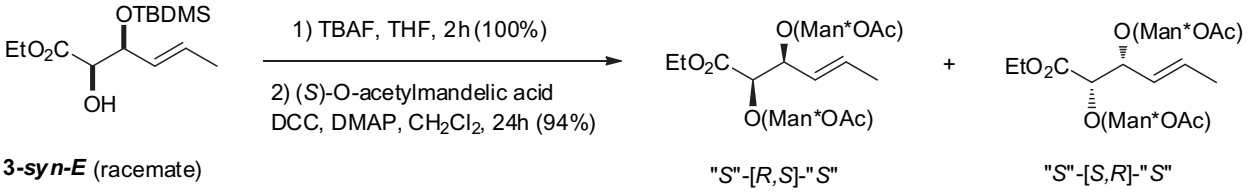
Before discussing the stereochemical aspects as function of the experimental conditions, the obtained diastereomers have to be firmly identified. For this purpose several methods were applied for mixtures allowing an easier purification of a single isomer, focusing on the *syn*/*anti* identification since the *E*/*Z* identification can be safely assigned from the vicinal $^3J_{HH}$ coupling constants between the ethylenic protons.[44] In each case, the *syn*/*anti* identification was based on the previous desilylation of **3** or **4** as diols; then subsequent modifications were attempted in order to obtain an unambiguous assignment.

First, we considered the procedure based on the conversion of diols into bis-(*S*)-mandelic esters as reported by Riguera (Scheme 2).[45]

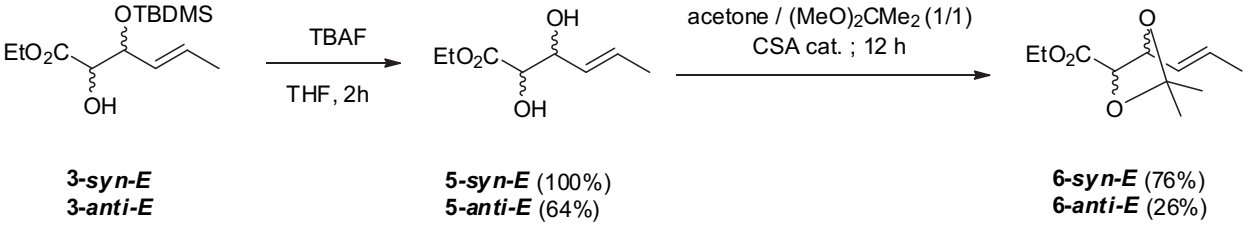
Finally, we found the unambiguous method to assign the structure of each isomer, which involved their conversion into the corresponding acetonide according to Scheme 3.

The *syn* or *anti* configurations of these acetonides were established on the basis of their $^1$H NMR spectra through NOESY experiments.[47] The key argument was the presence of a dipolar coupling between H2 (α-carboxylic proton) and H4 (vinylic proton) in the *syn* isomer and the absence of interaction between these two protons in the *anti* isomer. On the basis of this key argument the identity of **3-*syn-E*** and **3-*anti-E*** was firmly established (and corroborated by further data in the NMR spectra, see Fig. 1 and experimental part).

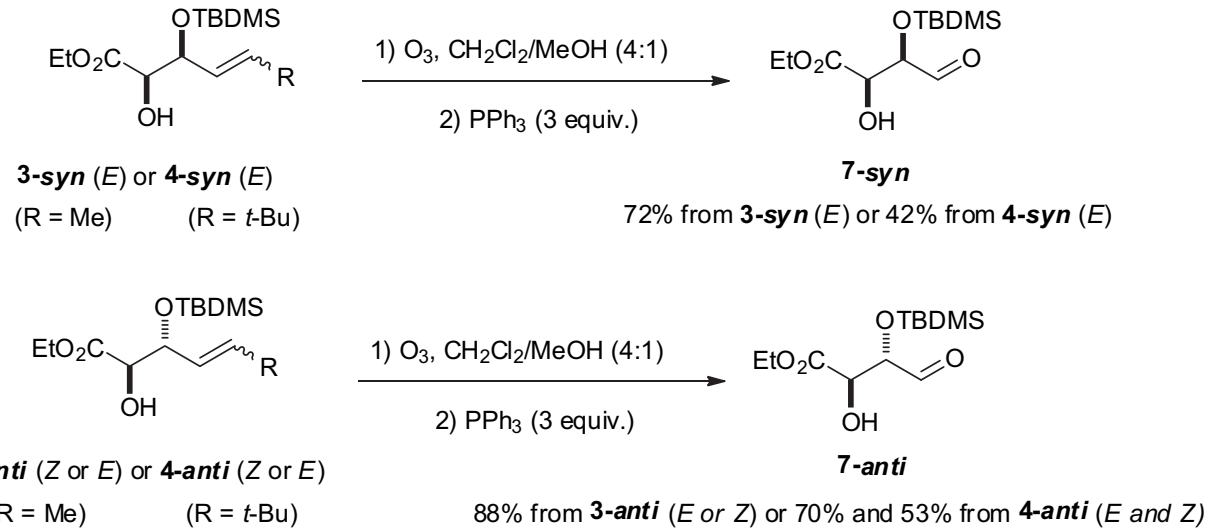
Once the *E* or *Z* configuration was assigned from the NMR spectra, the whole set of identification of the obtained adducts was easily achieved through a correlation with the corresponding




**Scheme 2.**




**Scheme 3.**




**Scheme 4.** Assignment of *syn* or *anti* configurations by correlation with the ozonolysis product **7**.

aldehydes **7-*syn*** and **7-*anti*** obtained after ozonolysis of the double bond according to Scheme 4, since **7-*syn*** and **7-*anti*** were prepared from well identified **3-*syn*-*E*** and **3-*anti*-*E***, the identity of adducts **4-*syn*** and **4-*anti*** was directly deduced.

### 2.2. Modification of the stereochemical course of the reaction with the experimental conditions

The results obtained for the addition of γ-silyloxyallyltributyltins **1** and **2** to ethyl glyoxylate are reported in Table 1. In this study, outside of the possible Lewis acid additives, we decided to examine the influence of both: the geometry across the double bond of the allyltin unit (by using **1*E*** or **1*Z***) and the steric hindrance near the tin centre by using **1*E*** or **2*E***. Behind this study, devoted to a general understanding of the factors governing the stereoselectivity of this process, we expected to find appropriate conditions to prepare the desired isomer as highly prevalent component in order to consider possibilities to obtain highly functionalized building blocks of four or six carbon units with well-defined stereochemistry.

*2.2.1. Reactions performed under thermal or high-pressure conditions (Table 1, entries 1–5).* This first set of experiments indicated that adduct **3-*anti*-*Z*** was obtained as the major product (73–77% yield and 88–94% of isomer **3-*anti*-*Z***) from reaction of **1*E*** with ethyl glyoxylate, regardless of the experimental conditions (thermal or high-pressure, Table 1, entries 1,3). This trend appears also to be similar with allyltin **1*Z*** but with lower yields and lower selectivities in favour of **3-*anti*-*E*** (78% for the thermal reaction and 55% under high pressure, entries 2,4). Increase of steric hindrance near the tin centre induced a dramatic decrease both of the yield (8% with **2*E*** against 77% with **1*E***) and of the diastereoselectivity of the reaction (mixture of 4 diastereomers with **4-*anti*-*Z*** obtained as the major isomer but in only 57% of the mixture, entry 5).

*2.2.2. Reactions performed in the presence of boron trifluoride or metal halide.* In this set of experiments, we have first evaluated the reactivity of **1** and **2** with ethyl glyoxylate at −78 °C in $CH_2Cl_2$ in the presence of boron trifluoride since allyltributyltin and (*E*)-crotyltributyltin were known to give good yields under these experimental conditions.[41]

When applied to our reagents (substituted both at the α and γ-positions), this reaction afforded a very low yield (10% or less with **1*E*** and **1*Z***, the **3-*syn*-*E*** was obtained as the major adduct), which slightly increases from **2*E*** but with low selectivity in respect to the major adduct (28% yield, 48% of **4-*syn*-*E***). Because of these disappointing results, we turned our attention to Lewis acids able to form effectively bidentate or monodentate complexes at room temperature.

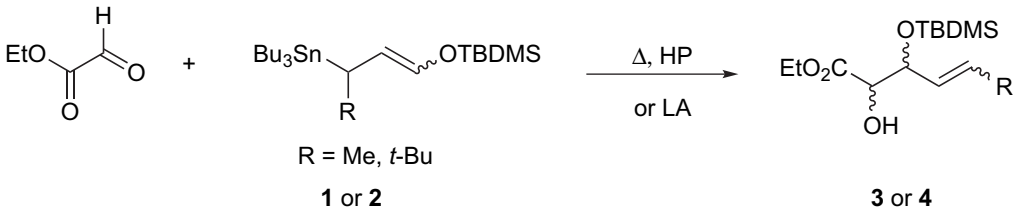
We first examined $MgBr_2$[48] and $ZnBr_2$[49] (Table 1, entries 9–13), which afforded the corresponding products in good yields (81–92%) and good *syn-E* diastereoselectivity (72–87%) with allyltins **1*E*** and **1*Z***; the higher yields were observed for **1*E*** and the higher *syn-E* selectivity for **1*Z***. While, in the presence of $ZnBr_2$, yields appear almost unaffected by the size of the α-substituent (**2*E*** compared to **1*E***), the stereochemical course of the reaction was shifted to a lower preference for the ***anti*-*E*** isomer, a trend which was previously observed for reaction involving α-substituted γ-alkoxyallyltins and benzaldehyde.[35,36] Good yields and high *syn* preference were also noted regardless of the geometry of **1**, when the reaction was performed in the presence of metal halides able to give monodentate complexes as for instance $InCl_3$ (when used in experimental conditions where transmetallation is highly disfavoured, entries 14–15).[33,50] However, $CeCl_3 \cdot 7H_2O$.10% NaI, being often used as a mild Lewis acid for the allylstannation of aldehydes,[51–53] afforded the expected adducts in low yields and high *syn-E* selectivity due to the formation of the β-stannylated aldehyde resulting from the desilylation of the γ-silyloxyallyltin.

*2.2.3. Reactions performed in the presence of aluminium or ytterbium triflates.* $Al(OTf)_3$ or $Yb(OTf)_3$ are known to be efficient catalysts in allylstannation reactions,[54,55] since the strong withdrawing effect of the triflate group increases the Lewis acidity of these metal salts. We applied them in our reactions and, indeed, obtained high yields of the products from both **1*E*** or **1*Z***, but while a high *syn-E* preference (94%) was noted for **1*E***, low selectivities were observed for **1*Z***: the **3-*syn*-*E*** adduct (major product) was highly contaminated with the **3-*anti*-*E*** (entries 18–21).

This low selectivity observed for **1*Z*** can be improved when ethyl glyoxylate was reacted with **1*E*** or **1*Z*** under high pressure in the presence of $Yb(OTf)_3$ in $CH_2Cl_2$. For the allyltin **1*E***, the high *syn-E* preference is still preserved (92%); the same *syn-E* preference was noted also for allyltin **1*Z*** (79%). Finally, it is worth noting that reaction of ethyl glyoxylate with **1** in the presence of trimethylsilyl triflate afforded only degradation products in spite of the efficiency of $Me_3SiOTf$ to promote additions of similar allyltins on imines.[56]

*2.2.4. Reactions performed in the presence of a (salen)chromium(III) complex.* When (salen)metal salts complexes have been used as chiral Lewis acids to promote the allylstannation of aldehydes or

**Table 1**
Reaction of α-substituted γ-silyloxyallyltributyltins with ethyl glyoxylate




R = Me, *t*-Bu

**1** or **2** **3** or **4**

| Entry | Experimental conditions[a] | Allyltin | Adducts[b] | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | N° | Yield (%) | *Syn E* | *'Syn Z'*[c] | *Anti E* | *Anti Z* |
| 1 | 100 °C, 12 h, neat | **1*E*** | **3** | 73 | 0 | 6 | 0 | *94* |
| 2 | | **1*Z*** | **3** | 60 | 10 | 0 | *78* | 11 |
| 3 | HP (11 Kbars, 41 h, $CH_2Cl_2$) | **1*E*** | **3** | 77 | 6 | 6 | 0 | *88* |
| 4 | | **1*Z*** | **3** | 59 | 36 | 0 | *55* | 9 |
| 5 | | **2*E*** | **4** | 8 | 17 | 22 | 4 | 57 |
| 6 | $BF_3{\cdot}Et_2O$ (3 equiv), $CH_2Cl_2$, −78 °C | **1*E*** | **3** | 10 | 74 | 7 | 7 | 12 |
| 7 | | **1*Z*** | **3** | <3 | 64 | 0 | 36 | 0 |
| 8 | | **2*E*** | **4** | 28 | 48 | 26 | 26 | 0 |
| 9 | $MgBr_2$ (2.2 equiv), $CH_2Cl_2$, 25 °C | **1*E*** | **3** | 88 | *78* | 9 | 10 | 3 |
| 10 | | **1*Z*** | **3** | 81 | *87* | 7 | 5 | 1 |
| 11 | $ZnBr_2$ (2.2 equiv), $CH_2Cl_2$, 25 °C | **1*E*** | **3** | 92 | *72* | 3 | 23 | 2 |
| 12 | | **1*Z*** | **3** | 83 | *85* | 10 | 4 | 1 |
| 13 | | **2*E*** | **4** | 86 | 30 | 18 | *42* | 0 |
| 14 | $InCl_3$ (2.2 equiv), $CH_2Cl_2$, 25 °C | **1*E*** | **3** | 87 | *78* | 5 | 14 | 3 |
| 15 | | **1*Z*** | **3** | 85 | *78* | 12 | 7 | 3 |
| 16 | $CeCl_3$, 10% NaI.($7H_2O$) (1.0 equiv), $CH_2Cl_2$, 25 °C | **1*E*** | **3** | 16 | 84 | 0 | 8 | 8 |
| 17 | | **1*Z*** | **3** | <3 | 85 | 10 | 5 | 0 |
| 18 | $Al(OTf)_3$ (10 mol %), $CH_2Cl_2$, 25 °C | **1*E*** | **3** | 90 | *94* | 1 | 3 | 2 |
| 19 | | **1*Z*** | **3** | 88 | *51* | 5 | 44 | 0 |
| 20 | $Yb(OTf)_3$ (10 mol %), $CH_2Cl_2$, 25 °C | **1*E*** | **3** | 92 | *94* | 0 | 4 | 2 |
| 21 | | **1*Z*** | **3** | 96 | *59* | 6 | 34 | 1 |
| 22 | $Yb(OTf)_3$ (10 mol %), $CH_2Cl_2$, 20 °C, HP, 41 h | **1*E*** | **3** | 83 | *92* | 2 | 4 | 2 |
| 23 | | **1*Z*** | **3** | 74 | *79* | 9 | 12 | 0 |
| 24 | (*R*,*R*)-(salen)$Cr^{(III)}$ (5 mol %), $CH_2Cl_2$, 25 °C | **1*E*** | **3** (**8**) | 30 (36) | *93*[d] | 1 | 1 | 4 |
| 25 | | **1*Z*** | **3** | 72 | 27 | 0 | *73*[d] | 0 |
| 26 | | **2*E*** | **4** (**9**) | 14 (10) | 29 | 26 | 25 | 20 |
| 27 | (*R*,*R*)-(salen)$Cr^{(III)}$ (5 mol %), $CH_2Cl_2$, 20 °C, HP, 41 h | **1*E*** | **3** | 73 | *92* | 4 | 3 | 1 |
| 28 | | **1*Z*** | **3** | 69 | 31 | 2 | *66* | 1 |

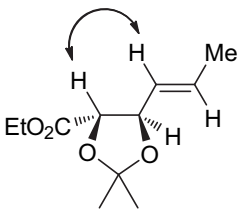
[a] Experimental conditions: see procedures A, B, C, D in the experimental part for further details.
[b] The ratio *syn-E*/'*syn-Z*'/*anti-E*/*anti-Z* was determined on the crude mixture (GC analysis) after NMR identification of each diastereomer as reported in the text.
[c] Alternatively, this minor isomer noted '*syn-Z*' might be a rearranged *Z*-isomer instead of *syn-Z* (see Experimental part).
[d] No ee observed.

glyoxylates by allyltributyltin, the homoallyl alcohols were obtained in good yields and interesting enantiomeric excesses only with (salen)chromium(III) salts complexes.[43,57–59] Furthermore, use of such hindered complexes for conducting these reactions under high pressure induces an increase in the yield and in the enantioselectivity (yields and ee >90% for several examples).[60]

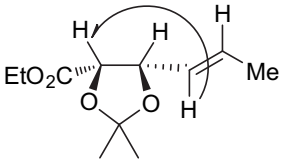
However when γ-substituted allyltins are involved, the stereochemical course of the reaction, in the presence of chiral ligands, appears to be much more complicated.[58,61] While the *anti* preference was observed for sugar allyltins (regardless of their *E* or *Z* configuration) in a high-pressure reaction conducted without any additive,[19] the reaction of crotyltributyltin with butyl glyoxylate performed in the presence of (salen)chromium(III) complexes appears to favour the *syn* adduct (under 1 or $10^4$ bar) with a good enantioselectivity for this isomer, but with a poor enantioselectivity on the minor *anti*-adduct.[58]

Accordingly, the reactivity and stereochemical trends of the reaction involving ethyl glyoxylate with **1*E***, **1*Z*** and **2*E*** in the presence of (*R*,*R*)-(salen)chromium(III) complex (Fig. 2) were explored in order to examine if a favourable situation could occur with these reagents.

The results are reported in Table 1 (entries 24–28) and appear to be highly dependent on the geometry of the allyltin double bond. Compound **1*E*** afforded (at atmospheric pressure) the




**6-*syn-E***




**6-*anti-E***

**Figure 1.** Acetonides **6-*syn-E*** and **6-*anti-E***.

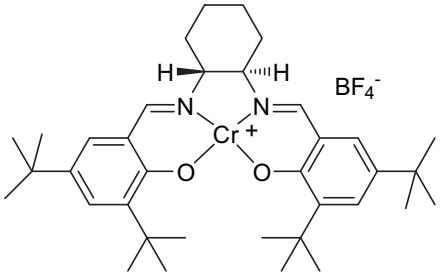
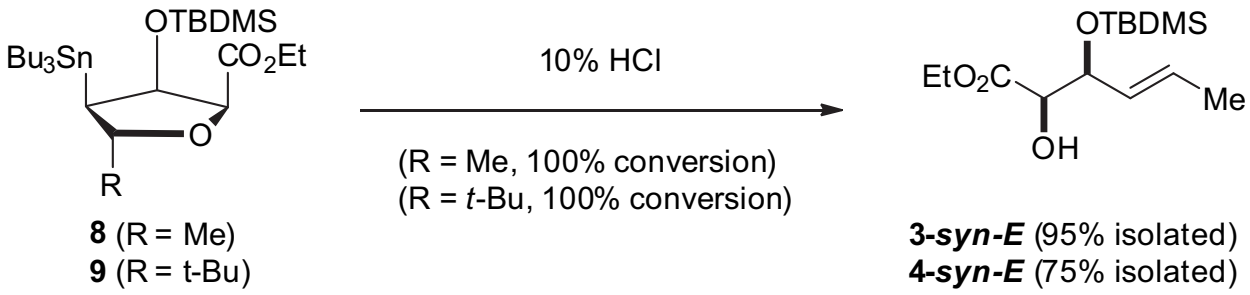



**Figure 2.** (Salen) Chromium(III) complex.




**Scheme 5.**

corresponding adducts in low yield (30%) and with a high preference for **3-*syn*-*E***. It must be underlined also, that an unexpected cyclic organotin derivative **8** was obtained as a side product in 36% yield (entry 24). This observation is interesting because upon treatment with 10% HCl, this compound afforded adduct **3-*syn*-*E*** exclusively (Scheme 5). This type of cyclisation was also observed starting from allyltin **2*E*** affording compound **9**, finally converted into **4-*syn*-*E*** upon acidic treatment.

This result is very important, since the overall yield of this reaction is increased to acceptable level with a high *syn* preference (over 93%) and a possibility to obtain very easily **3-*syn*-*E*** as a pure product from **8** due to the lower polarity of this last compound. Stereochemical behaviour of **1*Z*** is completely different, since adducts were obtained in good yields (72%) with a high preference for **3-*anti*-*E*** (no cyclic product analogue of **8** was observed, Table 1, entry 25).

Finally, increase of the steric hindrance near the tin centre (entry 26) afforded the expected adducts in a very low yield and with low selectivity (4 diastereomers obtained together with 10% of cyclic product **9**, analogue of **8** with R=*t*-Bu, which is converted into **4-*syn*-*E*** upon 10% HCl treatment). When these reactions were performed under high pressure, the cyclic organotin reagent **8** was not formed and the corresponding adducts were obtained in 69–73% yields with high preference for **3-*syn*-*E*** (from **1*E***) and slight preference for **3-*anti*-*E*** (from **1*Z***). However, regardless of the experimental conditions (atmospheric or high pressure) no enantioselectivity was observed [a complementary run using the (*S*,*S*)-(salen)chromium(III) complex corroborated this lack of enantioselectivity].

## 3. Discussion

Among the obtained results, those affording good yields combined with good selectivities will be discussed with an attempt of rationalization in terms of reaction mechanisms by considering the different types of experimental conditions applied to this reaction.

### 3.1. Reactions achieved under thermal activation or under high pressure

Under such experimental conditions as previously reported for more simple allyltin reagents, the allylstannation reaction is usually considered to occur through a six membered cyclic transition state.[23–25] In agreement with previous studies, when the allyltin **1*E*** is used, a chair like transition state is expected with ethoxycarbonyl group and silyl group in pseudo-equatorial positions and the methyl α-substituent in a pseudo-axial position due to the steric hindrance and to the torsional interactions with butyl groups of the tributylstannyl unit (Scheme 6, TS1). In case of **2*E***, where the bulky α-*t*-butyl group has difficulties both to adopt a pseudo-axial position (chair like transition state) or a pseudo-equatorial position (*t*-Bu/$SnBu_3$ interactions), a low *anti-Z* selectivity was observed together with very low yields.

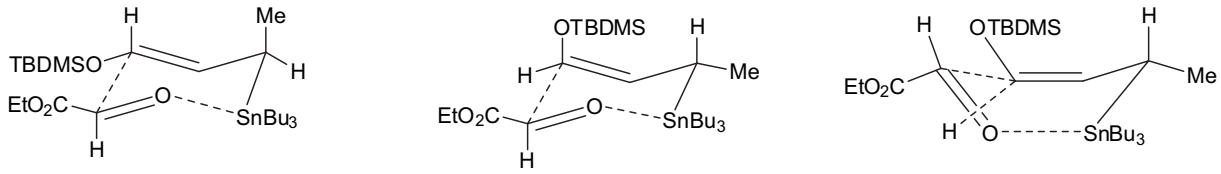
Allylstannation of **1*Z*** should afford the *syn-E* isomer via a chair like transition state with two groups in pseudo-equatorial positions (Scheme 6, TS2). However, because of the unfavourable interaction of the methyl group with $Bu_3Sn$, the reaction might proceed via a twist or boat-like transition state with the methyl group located in pseudo-equatorial position (Scheme 6, TS3), which should provide the *anti-E* isomer (indeed observed as the major product).

Such evolution from chair like to twist[19] or boat transition state[26] has been previously considered under high pressure, but herein the similar trends observed both for reactions performed under thermal or under high-pressure conditions are in agreement with a competition between these two types of cyclic transition states (TS2 and TS3).

### 3.2. Reactions achieved in the presence of Lewis acids

For these reactions, excepted with $BF_3{\cdot}OEt_2$ at −78 °C and with $CeCl_3{\cdot}7H_2O$/NaI (where an hydrolysis of the enol ether function is noted before allylstannation), high yields of homoallylic alcohols were obtained regardless of the nature of the Lewis acid [$MgBr_2$, $ZnBr_2$, $InCl_3$, $Al(OTf)_3$ or $Yb(OTf)_3$] with a high preference for the *syn-E* adduct starting from **1*E*** or **1*Z***. Diastereoselectivity of the process was modified only when γ-silyloxyallyltin bearing bulky substituent at the α-position was used (**2*E***, entry 13).

These results are in agreement with those noted in reaction proceeding through an open transition state and can be explained by usual competition between an antiperiplanar transition state[26–28] and a synclinal transition state[29–32] since no




**Scheme 6.**

transmetallation is expected under these experimental conditions.[33] In practice, among the series of transition states, which might be involved, only meaningful ones are represented in Scheme 7 taking into account the assistance by the Lewis acid and the preferred conformation of allyltins in which the Sn–C allyl bond is orthogonal to the ethylenic double bond.[62,63] On the basis of these schemes involving $ZnBr_2$ as Lewis acid (which remain valid with minor modification when another Lewis acid is involved), it is likely to have a high *syn-E* preference starting from **1*E*** through **AP1-*E*** (formation of the compound *syn-Z* appears to be highly unfavourable through **AP2-*E***). Alternatively when allyltin **1*Z*** is used, the transition states **AP1-*Z*** and **AP2-*Z*** can be involved, but with a preference for **AP1-*Z*** due to the higher stability of this conformation of the allyltin (less steric interactions between R and OTBDMS). Therefore a *syn-E* preference is expected with a higher rate of *syn-Z* when compared to reaction of the allyltin **1*E***.

The unique case involving bulky R substituent (allyltin **2*E***, entry 13) afforded a mixture of compounds where adduct **4-*anti*-*E*** becomes the major component. Due to the steric hindrance of *t*-butyl group combined with dipolar repulsion between the carbonyl and the *t*-butyldimethylsilyloxy group, synclinal transition state **SYNCL-*E*** is likely to occur as a competitive pathway as already pointed out for α-substituted γ-alkoxyallyltributyltins.[35–37] Therefore a mixture of compounds *syn-E* and *anti-E* is reasonably expected.

The same arguments can also justify obtaining of appreciable amounts of the *anti-E* adducts, when **1*Z*** is allowed to react with ethyl glyoxylate in the presence of aluminium or ytterbium triflates because the size of the Lewis acid has also to be taken into account and the transition state **SYNCL-*Z*** allows the best steric decompression.

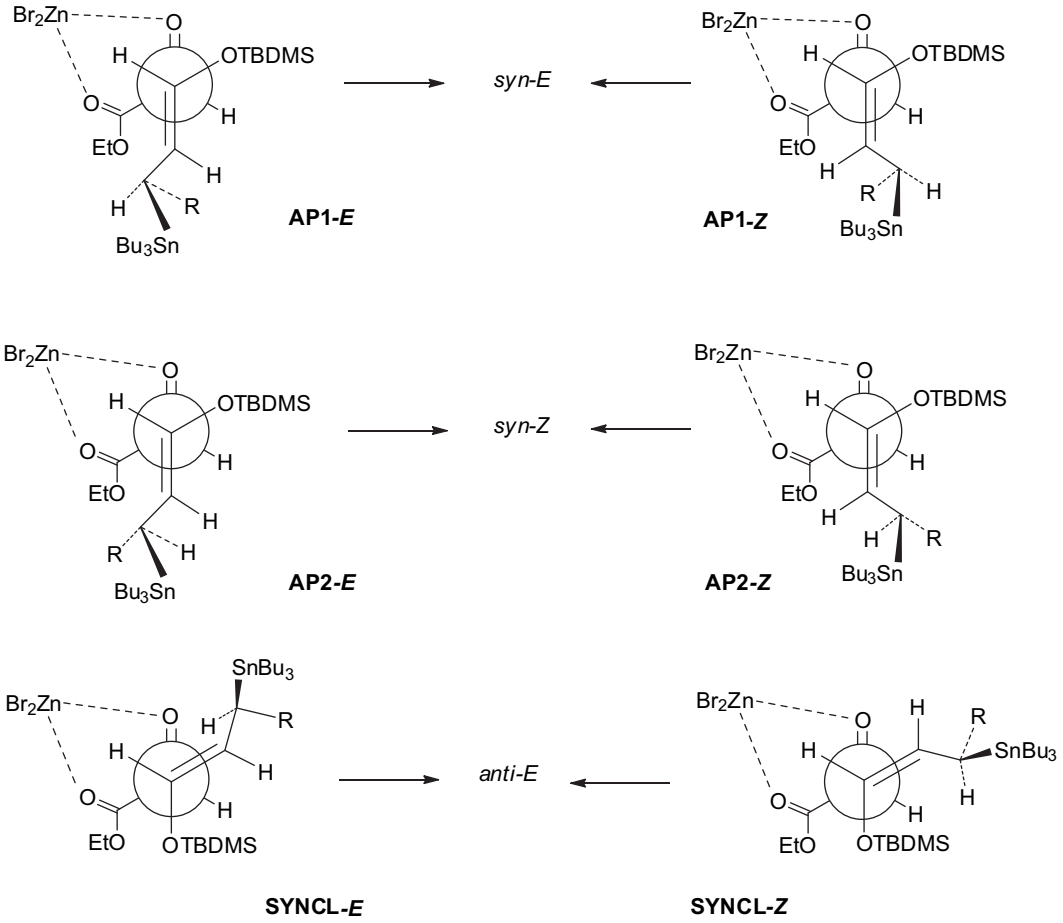
The presence of '**4-*syn*-*Z***' adduct as minor component (or its regioisomer) might be explained by a partial isomerisation of **2*E*** into **2*Z*** in the presence of the Lewis acid. The amount of '**3-*syn*-*Z***' might be explained similarly (partial isomerisation of **1*E*** into **1*Z***), but in both cases, if involved, such a process has a small extent.

### 3.3. Reactions achieved in the presence of (salen)chromium(III) complex

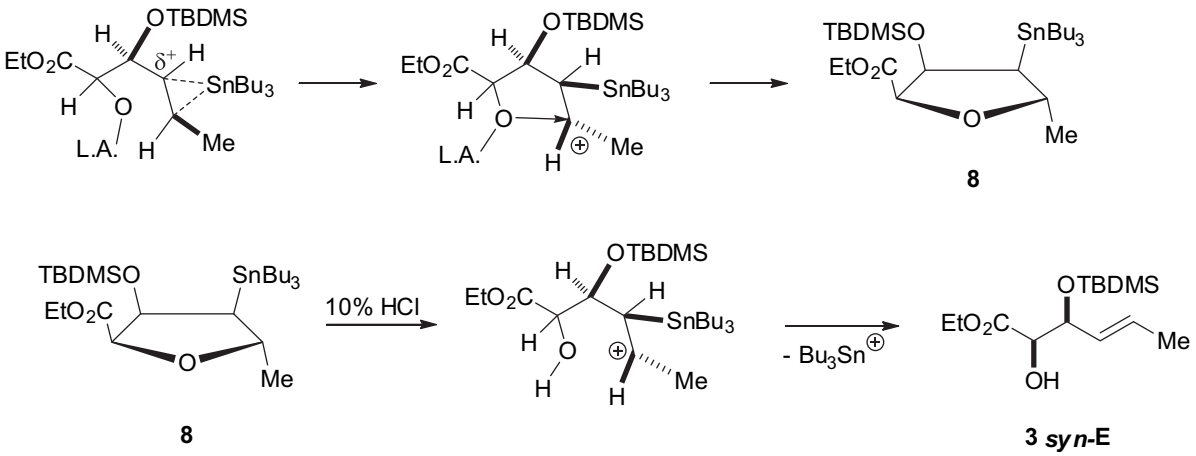
Once more the (salen)chromium(III) complex must be considered as a very bulky Lewis acid and while the primary trend seems a reaction through **AP1-*E*** starting from **1*E*** (very high *syn-E* preference), the competition with a synclinal transition state allowing the best decompression (like **SYNCL-*Z***, Scheme 7) get reinforced with **1*Z*** affording the *anti-E* adduct as the major compound.

In both cases, a minor influence on the stereochemical course of the reaction was noted either under atmospheric pressure or under high pressure. However, application of high pressure prevented formation of tetrahydrofuran derivative **8** from the allyltin **1*E***.

Formation of an aza-heterocycle of the same type has been already described in allylstannation of imines by γ-silyloxyallyltributyltins; no further comments were, however, provided to explain these results.[56] Compound **8** appears to be a cyclization




**Scheme 7.** Possible open transition states for $ZnBr_2$ assisted allylstannation of ethyl glyoxylate.




**Scheme 8.** Formation of compound **8** and protonolysis into **3** ***syn-E***.

product derived from the primary formed *syn-E* junction followed by a 1,2 shift of tributylstannyl group (Scheme 8).

Acidic treatment of **8** affords exclusively the **3-*syn-E*** isomer, providing highly stereoselective access to this compound (97%) with an acceptable yield (30+36%) considering the overall transformation. It is of interest to note that functionalized tetrahydrofurans have been previously obtained by treatment of homoallylic alcohols with very strong Lewis acids like triflates or triflimides.[64,65]

The cyclic ether analogue **9**, obtained under similar conditions from **2*E***, afforded the *syn-E* compound, but of low synthetic interest, since a mixture of the four possible diastereomers was obtained in this case (Table 1, entry 26). Finally no enantioselectivity with the (*R*,*R*)-(salen)chromium(III) complex was observed; this can be hardly discussed because of the lack of comparison for very similar systems.

## 4. Conclusion

Allylation of ethyl glyoxylate with α-substituted γ-silyloxyallyltributyltins can afford highly different mixtures of diastereomers as function of the experimental conditions, but an increase in the bulk of the α-substituent (R=*t*-Bu) has negative effect both in terms of yields and diastereoselectivity. For less hindered α-methyl γ-silyloxyallyltributyltin, among the four possible isomers, three of them can be obtained with good yields and good selectivities:

- For the preparation of **3-*anti-Z***, the thermal reaction of neat compounds appears to be the more efficient one starting from **1*E*** (73% yield, 94% selectivity).
- For the preparation of **3-*syn-E***, the use of **1*E*** combined with an activation by $Al(OTf)_3$ or $Yb(OTf)_3$ appears to be the more suitable choice (over 90% yield and 94% *syn-E* selectivity).
- For the preparation of **3-*anti-E***, two types of experimental conditions are possible (with different mechanisms): use of **1*Z*** under thermal conditions (60% yield, 78% *anti-E*) or in the presence of (salen) chromium(III) complex (72% yield, 73% *anti E*).
- No valuable route can be proposed for the selective synthesis of **3-*syn-Z***.

From these results, it appears that high pressure technique (10 Kbar), which is believed to improve some results, does not bring noticeable improvements, except to prevent formation of cyclization products from **1*E*** in the presence of (salen) chromium(III) complex, but the stereochemical preference observed in this case (*syn-E* isomer) can be more easily achieved using Al or Yb triflates catalysis.

In terms of mechanisms, even quite difficult to rationalize on minor isomers, we have been able to propose a reasonable rationalization of the whole set of results through cyclic transition states and open transition states (antiperiplanar and synclinal).

Even too complex to be generalized for prediction of stereochemical results, the main trends observed in this work should be of interest for the choice of appropriate experimental conditions for reaction of glyoxylates with γ-silyloxyallyltributyltins.

## 5. Experimental section

### 5.1. General

For $^{1}H$, $^{13}C$ and $^{119}Sn$ spectra, chemical shifts are given in ppm as $\delta$ values related to tetramethylsilane ($^{1}H$, $^{13}C$) or tetramethylstannane ($^{119}Sn$) and coupling constants are given in hertz. When given, assignments were done after HMQC or/and COSY correlations. Mass spectra were recorded either in ESI or in EI mode (70 eV) in direct introduction mode or GC-MS mode. Organostannyl fragments are given for $^{120}Sn$, which means that the given abundance is broadly one third of the overall abundance of the organostannyl fragment when compared to organic ones. HRMS spectra for compounds **3-7** were recorded on a Thermo-Finnigan MAT 95 XL in Lyon I University, while HRMS spectra for stannylated compounds **8** and **9** were obtained on a MALDI-TOF apparatus in INRA of Nantes. In this last case, the determinations were obtained on the $^{116}Sn$ isotope in order to have a cleaner measurement (absence of an M+1 contribution in the isotopic pattern). $CH_2Cl_2$ was dried with $CaH_2$ prior to use. TLC analyses were conducted on silica-coated aluminium plates (Silica gel $60F_{254}$). γ-silyloxyallyltins **1*E*** and **1*Z*** were prepared according to reported procedures.[9] Ozonolysis was carried out with a BMT 802 N apparatus from A.C.W. (Marcoussis, France).

### 5.2. Preparation of γ-silyloxyallyltin 2*E*[40]

In a Schlenk tube, a suspension of CuCN (312 mg, 3.48 mmol) in THF (30 mL), without use of HMPA as co-solvent as previously reported,[40] was cooled to −78 °C before addition of *t*-BuLi (4.64 mL, 6.96 mmol). The mixture was stirred for 5 min at −78 °C and warmed to −50 °C. The yellow solution was then cooled to −78 °C and β-tributylstannylacrolein (1 g, 2.90 mmol) dissolved in 5 mL of THF was added dropwise. The mixture become red and was stirred at −78 °C for 15 min. TBDMSCl (1.31 mg, 8.69 mmol) was added in one portion and the mixture was stirred at −78 °C for 1 h. Saturated aqueous $NH_4Cl$ was added (25 mL). The organic layer was

separated, the aqueous one extracted with $Et_2O$ (3×50 mL) and the combined organic extracts were dried ($MgSO_4$). After concentration under vacuum, the crude product was purified by flash chromatography on silica gel (Hexanes/$Et_2O$ 95:5) to give pure **2*E*** as colourless oil (1.5 g, 79%). Physical data were found in good agreement with those already reported.[40]

### 5.3. General procedure for allylation reactions under thermal conditions (Procedure A)

Ethyl glyoxylate (309 mg, 3 mmol) and γ-oxygenated allyltin **1*E***, **1*Z*** (475.4 mg, 1 mmol) or **2*E*** (517.5 mg, 1 mmol) were placed in a Schlenk tube without any solvent, and the mixture was kept at 100 °C for 12 h. The crude product was analysed by GC and diastereomers were separated by flash chromatography on silica gel (Hexanes/$Et_2O$: 9/1).

### 5.4. General procedure for allylation reactions under high-pressure conditions (Procedure B)

The γ-oxygenated allyltin **1*E*/1*Z*** (475.4 mg, 1 mmol) or **2*E*** (517.5 mg, 1 mmol) and ethyl glyoxylate (306 mg, 3 mmol) were placed in a 2 mL Teflon cell. The cell was filled with $CH_2Cl_2$, closed and placed in a high-pressure vessel, and the pressure was slowly increased to 11 kbar at 20 °C. After stabilization of the pressure, the reaction mixture was kept under these conditions for 41 h before decompression. Then, the reaction mixture was diluted with $Et_2O$ and dried over $MgSO_4$. After concentration under vacuum, the residue was analysed by GC and diastereomers were separated by flash chromatography on silica gel (Hexanes/$Et_2O$ 9:1).

According to the procedure B, $Yb(OTf)_3$ (62 mg, 0.1 mmol) or (salen)chromium(III) complex (34 mg, 0.05 mmol) used as additives were also added in the 2 mL Teflon cell, which was placed in the high-pressure vessel under 10 kbar for 41 h.

### 5.5. General procedure for allylation reactions in the presence Lewis acid ($ZnBr_2$, $MgBr_2$, $InCl_3$, $CeCl_3$): Procedure C

In a round-bottomed flask under an argon atmosphere, ethyl glyoxylate (309 mg, 3 mmol) and γ-oxygenated allyltin **1*E***, **1*Z*** (475.4 mg, 1 mmol) or **2*E*** (517.5 mg, 1 mmol) were dissolved in dry $CH_2Cl_2$ (15 ml). Lewis acid was added (2.2 equiv) and the mixture was stirred at room temperature (when using $CeCl_3.7H_2O$, 10% NaI, 1.0 equiv was added). The reaction was monitored by TLC (hexanes/$Et_2O$: 95/5). Water was added, organic layer was separated, the aqueous one extracted with $CH_2Cl_2$ (2×20 mL), and the combined extracts were dried ($MgSO_4$). After concentration under vacuum, the residue was analysed by GC and diastereomers were separated by flash chromatography on silica gel (Hexanes/$Et_2O$: 9/1).

According to general procedure C, lanthanide triflate (2.2 equiv) was added at 0 °C and the mixture was allowed to warm-up to room temperature. Similarly, according to procedure B, (salen) chromium (III) complex (34 mg, 0.05 mmol) was added in one portion at room temperature before starting the reaction.

### 5.6. General procedure for allylation reactions in the presence of $BF_3{\cdot}OEt_2$ (Procedure D)

In a Schlenk tube, ethyl glyoxylate (103 mg, 1 mmol) and γ-oxygenated allyltin **1*E*/1*Z*** (712 mg, 1.5 mmol) or **2*E*** (517.5 mg, 1 mmol) were dissolved in dry $CH_2Cl_2$ (6 mL). The mixture was cooled to −78 °C and $BF_3{\cdot}OEt_2$ (380 μL, 3 mmol) was added dropwise. The mixture was stirred for 2 h at −78 °C and quenched with saturated aqueous $NaHCO_3$ (6 mL). The organic layer was separated, the aqueous one was extracted with $CH_2Cl_2$ (2×10 mL) and the combined organic extracts were dried ($MgSO_4$). After concentration under vacuum, the residue was analysed by GC and diastereomers were separated by flash chromatography on silica gel (Hexanes/$Et_2O$: 9/1).

### 5.7. Gas chromatography analysis

GC analysis of the four diastereomers of **3** was performed on an HP 6890 apparatus (FID, carrier gas $N_2$, split 98/2) using a phenylsilicone capillary column (Macherey Nagel Optima δ3, 30 m×0.25 mm×0.3 μm). The flow rate of carrier gas was 1.3 mL $min^{-1}$ and the effective analysis was achieved at 110 °C in isothermal mode (45 min) before heating at 12 °C $min^{-1}$ until 300 °C for elimination of high boiling organotin residues.

**3-*anti*-*E***: 32.4; **3-*anti*-*Z***: 35.2; **3-*syn*-*E***: 36.7; **3-*syn*-*Z***: 38.8 min.

GC analyses of the four diastereomers of **4** and those of **3** were performed using the same column in isothermal mode (80 °C for 100 min) before heating at 12 °C $min^{-1}$ until 300 °C.

**4-*syn*-*Z***: 85.05; **4-*anti*-*E***: 85.80; **4-*syn*-*E***: 86.47; **4-*anti*-*Z***: 86.55 min.

### 5.8. Physicochemical data

*5.8.1. Ethyl (3E)-3-tert-butyldimethylsilyloxy-2-hydroxy-hex-4-enoate **(3-syn-E)**.* IR (neat) 3485, 3012, 2950, 2929, 2856, 1736, 1665, 1256, 1098, 966, 838, 778. HRMS (ESI): *m/z* calcd for $C_{14}H_{29}O_4Si$ $[M+H]^+$=289.1835, found: 288.1837. MS (CI, $NH_3$) *m/z*: 306 ($[M+NH_4]^+$, 100), 289 (23), 185 (4), 174 (38), 157 (42); (EI) *m/z*: 231 (26), 199 (4), 185 (100), 159 (27), 157 (21), 149 (30), 141 (14), 129 (10), 83 (10), 75 (51), 73 (56). $^1H$ NMR ($CDCl_3$, 300MHz): 5.72 (ddq, 1H, $^3J$=15.5, $^4J$=0.9, $^3J$=6.1), 5.61 (ddq, 1H, $^3J$=7.1, $^3J$=15.5, $^4J$=1.2), 4.42 (bdd, 1H, $^3J$=1.9, $^3J$=7.1), 4.26 (dq, 1H, $^2J$=11.1, $^3J$=7.1), 4.19 (dq, 1H, $^2J$=11.1, $^3J$=7.1), 4.02 (dd, 1H, $^3J$=1.9, $^3J$=9.9), 2.91 (d, $1H_{hydroxyl}$, $^3J$=9.9), 1.7 (dd, 3H, $^3J$=6.1, $^4J$=1.2), 1.30 (t, 3H, $^3J$=7.1), 0.85 (s, 9H), 0.0 (s, 6H). $^{13}C$ NMR ($CDCl_3$, 75MHz): 172.7 ($C_1$), 130.6 ($C_5$), 128.4 ($C_4$), 75.4 ($C_2$), 75.2 ($C_3$), 61.5 (1C), 25.8 (3C), 18.1 (1C), 17.8 ($C_6$), 14.3 (1C), −3.9 and −5.0 (2C).

*5.8.2. Ethyl (3Z)-3-tert-butyldimethylsilyloxy-2-hydroxy-hex-4-enoate **(3-syn-Z)**.* MS (CI, $NH_3$) *m/z*: 306 (8), 289 (12), 185 (30), 174 (53), 157 (100), 92 (19); (EI) *m/z* (%): 231(4), 199 (6), 185 (96), 159 (28), 157 (28), 149 (40), 141(16), 83 (12), 75 (98), 73 (100), 55 (20). $^1H$ and $^{13}C$ NMR: No meaningful signals (product always obtained as minor component in mixture with other isomers).

*5.8.3. Ethyl (3E)-3-tert-butyldimethylsilyloxy-2-hydroxy-hex-4-enoate **(3-anti-E)**.* IR: 3509, 3036, 2957, 2929, 2857, 1734, 1671, 1256, 1223, 1096, 967, 938, 837, 777. HRMS (ESI): *m/z* calcd for $C_{14}H_{28}O_4SiNa$ $[M+Na]^+$=311.1649, found: 311.1642. MS (CI, $NH_3$) *m/z*: 306 (8), 289 (12), 271 (11), 185 (38), 174 (76), 157 (100), 92 (30), 74 (20); (EI) *m/z*: 231 (10), 186 (14), 185 (95), 157 (28), 155 (20), 149 (34), 141 (16), 75 (92), 73 (100), 55 (22). $^1H$ NMR ($CDCl_3$, 300MHz): 5.66 (ddq, 1H, $^3J$=15.4, $^4J$=0.8, $^3J$=6.3,), 5.50 (ddq, 1H, $^3J$=15.4, $^3J$=7.2, $^4J$=1.5), 4.33 (bdd, 1H, $^3J$=7.2, $^3J$=3.4), 4.24 (dq, 1H, $^2J$=10.8, $^3J$=7.2), 4.19 (dq, 1H, $^2J$=10.8, $^3J$=7.2), 4.13 (dd, 1H, $^3J$=6.7, $^3J$=3.4), 2.90 (d, $1H_{hydroxyl}$, $^3J$=6.7), 1.70 (bd, 3H, $^3J$=6.3), 1.28 (t, 3H, $^3J$=7.2), 0.86 (s, 9H), 0.03 and 0.05 (2s, 6H). $^{13}C$ NMR ($CDCl_3$, 75MHz): 172.0 ($C_1$), 129.6 ($C_4$), 128.5 ($C_5$), 76.5 ($C_3$), 75.1 ($C_2$), 61.4, 25.8 (3C), 18.2, 17.8 ($C_6$), 14.3 (1C), −4.2 and −4.8 (2C).

*5.8.4. Ethyl (3Z)-3-tert-butyldimethylsilyloxy-2-hydroxy-hex-4-enoate **(3-anti-Z)**.* IR: 3396, 2930, 1733, 1634, 1235, 1096, 1056, 770. HRMS (ESI): *m/z* calcd for $C_{14}H_{28}O_4SiNa$ $[M+Na]^+$=311.1655, found: 311.1653.

MS (CI, $NH_3$) *m/z*: 306 (6), 289 (3), 271 (3), 199 (6), 185 (16), 174 (56), 157 (100), 149 (8), 92 (22), 90 (16), 75 (8), 73 (20); (EI) *m/z* (%): 231(10), 199 (5), 185 (100), 159 (30), 157 (27), 149 (34), 75 (98), 73 (97). $^1H$ NMR ($CDCl_3$, 300MHz): 5.58 (dq, 1H, $^3J$=11.2, $^3J$=6.6), 5.75 (bdd, 1H, $^3J$=11.2, $^3J$=8.8), 4.72 (dd, 1H, $^3J$=8.8, $^3J$=3.2), 4.23 (q, 2H,

$^3J$=7.1), 4.12 (dd, 1H, $^3J$=6.8, $^3J$=3.2), 2.99 (d, 1H$_{hydroxyl}$, $^3J$=6.8), 1.67 (bd, 3H, $^3J$=6.6), 1.30 (t, 3H, $^3J$=7.1), 0.87 (s, 9H), 0.07 and 0.03 (2s, 6H). $^{13}$C NMR ($CDCl_3$, 75MHz): 172.3 ($C_1$), 130.0 ($C_4$), 126.6 ($C_5$), 75.6 ($C_2$), 71.2 ($C_3$), 61.7, 26.0 (3C), 18.3, 14.5, 13.8 ($C_6$), −4.2 and −4.7(2C).

*5.8.5. Ethyl (4E)-3-tert-butyldimethylsilyloxy-2-hydroxy-6,6-dimethylhept-4-enoate* ***(4-syn-E)***. IR: 3501, 2957, 2929, 2902, 2857, 1745, 1652, 1472, 1253, 1026, 977, 942, 836, 776. HRMS (ESI): *m*/*z* calcd for $C_{17}H_{34}O_4SiNa$ $[M+Na]^+$=353.2124, found 353.2123. MS (CI, $NH_3$), *m*/*z*: 348 (4), 331 (2), 313 (4), 273 (5), 227 (17), 216 (33), 199 (100), 181 (17); (EI) *m*/*z*: 297 (4), 273(10), 255 (6), 227(100), 199 (11), 181(12), 149 (18), 107(45), 95 (18), 75 (46), 73 (60). $^1$H ($CDCl_3$, 300MHz): 5.70 (dd, 1H, $^3J$=15.7, $^4J$=0.6), 5.51 (dd, 1H, $^3J$=15.7, $^3J$=7.8), 4.41 (ddd, 1H, $^3J$=7.8, $^3J$=2.4, $^4J$=0.6), 4.25 (dq, 1H, $^2J$=10.8, $^3J$=7.2), 4.17 (dq, 1H, $^2J$=10.8, $^3J$=7.2), 4.02 (dd, 1H, $^3J$=9.7, $^3J$=2.4), 2.92 (d, 1H$_{hydroxyl}$, $^3J$=9.7), 1.31 (t, 3H, $^3J$=7.2), 1.02 (s, 9H), 0.84 (s, 9H), 0.00 (s, 6H). $^{13}$C ($CDCl_3$, 75MHz) 172.7 ($C_1$), 144.7 ($C_5$), 124.2 ($C_4$), 75.9 ($C_3$), 75.5 ($C_2$), 61.5, 33.1, 30.4 (3C), 25.8 (3C), 18.2, 14.3, −3.7, −4.9.

*5.8.6. Ethyl (4Z)-3-tert-butyldimethylsilyloxy-2-hydroxy-6,6-dimethylhept-4-enoate or/and rearranged product (noted* ***'4-syn-Z')***. MS (EI), *m*/*z* (%): 297 (3), 273(5), 227(100), 149 (10), 107(41), 95 (17), 75 (64), 73 (79). $^1$H NMR ($CDCl_3$, 300MHz) (mixture with **4-*syn*-*E***, meaningful signals non-overlapped with those of **4-*syn*-*E***): 5.96 (ddd, 1H, *J*=6.1, *J*=2.4, *J*=1.3), 5.90 (dt, 1H, *J*=6.1, $J_{2H}$=2), 5.23 (bdt, 1H, *J*∼6.3, $J_{2H}$∼2.3), 4.76 (ddd, 1H, *J*=6.2, *J*=2.1, *J*=1.3). $^{13}$C NMR ($CDCl_3$, 75MHz) (meaningful signals: mixture with **4-*syn*-*E***): 171.5 ($C_1$), 130.6 ($C_5$), 126.2 ($C_4$), 96.1 ($C_3$), 84.9 ($C_2$), 61.2, 35.5, 28.3 (3C), 26.9 (3C), 17.7, 14.3, −3.7 and −4.9.

*5.8.7. Ethyl (4E)-3-tert-butyldimethylsilyloxy-2-hydroxy-6,6-dimethylhept-4-enoate* ***(4-anti-E)***. IR: 3447, 2958, 2929, 2857, 1734, 1652, 1473, 1387, 1257, 1203, 976, 837, 777. HRMS (ESI): *m*/*z* calcd for $C_{17}H_{34}O_4SiNa$ $[M+Na]^+$=353.2124, found: 353.2124. MS (CI, $NH_3$), *m*/*z*: 348 (66), 331 (10), 313 (2), 273 (7), 227 (31), 216 (57), 199 (100), 181 (12); EI, *m*/*z*: 273 (16), 255 (8), 227 (100), 199 (24), 181 (30), 149 (9), 107 (18), 95 (10), 75 (17), 73 (13), 57 (8). $^1$H NMR ($CDCl_3$, 300MHz): 5.60 (dd, 1H, $^3J$=15.4, $^4J$=0.7), 5.41 (dd, 1H, $^3J$=15.4, $^3J$=7.5), 4.33 (ddd, 1H, $^3J$=7.5, $^3J$=3.3, $^4J$=0.7), 4.23 (dq, 1H, $^2J$=11.1, $^3J$=7.2), 4.19 (dq, 1H, $^2J$=11.1, $^3J$=7.2), 4.13 (dd, 1H, $^3J$=6.6, $^3J$=3.3), 2.92 (d, 1H$_{hydroxyl}$, $^3J$=6.6), 1.29 (t, 3H, $^3J$=7.2), 1.00 (s, 9H), 0.88 (s, 9H), 0.06 and 0.02 (2s, 6H). $^{13}$C NMR ($CDCl_3$, 75MHz): 172.0 ($C_1$), 144.8 ($C_5$), 123.3 ($C_4$), 77.4 ($C_3$), 75.6 ($C_2$), 61.4, 33.1, 29.4 (3C), 25.9 (3C), 18.3, 14.4, −4.0 and −4.7.

*5.8.8. Ethyl (4Z)-3-tert-butyldimethylsilyloxy-2-hydroxy-6,6-dimethylhept-4-enoate* ***(4-anti-Z)***. IR: 3526, 2957, 2857, 1717, 1653, 1252, 1097, 863, 836, 810, 777. MS (CI, $NH_3$), *m*/*z*: 348 (12), 331(4), 216 (100), 199 (85), 181 (6), 175 (11); MS (EI), *m*/*z*: 273 (9), 228 (18), 227 (100), 199 (7), 181 (11), 149 (15), 107 (36), 95 (23), 75 (62), 73 (71), 57 (23). $^1$H NMR ($CDCl_3$, 300MHz): 5.39 (dd, 1H, $^3J$=12.4, $^4J$=0.9), 5.22 (dd, 1H, $^3J$=12.4, $^3J$=9.1), 4.94 (ddd, 1H, $^3J$=9.1, $^3J$=2.7, $^4J$=0.9), 4.28 (dq, 1H, $^2J$=10.5, $^3J$=7.2), 4.20 (dq, 1H, $^2J$=10.5, $^3J$=7.2), 4.11 (dd, 1H, $^3J$=7.8, $^3J$=2.7), 3.10 (d, 1H$_{hydroxyl}$, $^3J$=7.8), 1.30 (t, 3H, $^3J$=7.2), 1.13 (s, 9H), 0.85 (s, 9H), 0.07 and 0.03 (2s, 6H). $^{13}$C NMR ($CDCl_3$, 75MHz): 172.1 ($C_1$), 144.5 ($C_5$), 128.8 ($C_4$), 75.4 ($C_2$), 71.9 ($C_3$), 61.4, 32.9, 31.1 (3C), 25.6 (3C), 18.0, 14.2, −3.8 and −4.3.

*5.8.9. Ethyl (4E)-2,3-dihydroxyhex-4-enoate* ***(5-syn-E)***. In a round-bottomed flask **3-*syn*-*E*** (274 mg, 0.95 mmol) was dissolved in THF (5 mL) and tetrabutylammonium fluoride (1.9 mL, 1 M in THF) was added. The mixture was stirred 2 h at room temperature and water (5 mL) was added. After dilution of the mixture with $Et_2O$, the organic layer was separated and the aqueous layer extracted with $Et_2O$ (3×5 mL). The organic extracts were combined and dried ($MgSO_4$). Concentration under vacuum gave the crude product, which was purified by flash chromatography on silica gel (Hexane/$Et_2O$: 2/8) to give pure **5-*syn*-*E*** as a colourless oil (165 mg, 0.95 mmol, 100%).

IR: 3396, 2980, 2929, 2856,1736, 1674, 1636, 1446, 1208, 967. HRMS (CI): *m*/*z* calcd for $C_8H_{15}O_4$ $[M+H]^+$=175.0970, found: 175.0968; MS (CI, $NH_3$) *m*/*z*: 192 (100), 175 (5), 174 (19), 157 (7); MS (EI) *m*/*z*: 159 (9), 104 (66), 83 (21), 76 (77), 71 (93), 43 (71), 41 (100), 39 (73). $^1$H NMR ($CDCl_3$, 300MHz) 5.78 (ddq, 1H, $^3J$=15.3, $^3J$=6.3, $^4J$=1.2), 5.60 (ddq, 1H, $^3J$=15.3, $^3J$=6.3, $^4J$=1.5), 4.32 (m, 1H), 4.24 (q, 2H, $^3J$=7.2), 4.10 (bdd, 1H, $^3J$=6.0, $^3J$=3.0), 3.38 (d, 1H$_{hydroxyl}$, $^3J$=6.0), 2.65 (d, 1H$_{hydroxyl}$, $^3J$=7.5), 1.70 (bd, 3H, $^3J$=6.3), 1.28 (t, 3H, $^3J$=7.2). $^{13}$C NMR ($CDCl_3$, 75MHz): 172.9 ($C_1$), 129.3 ($C_4$), 128.6 ($C_5$), 74.0 ($C_3$), 73.5 ($C_2$), 61.9 (C), 17.7 ($C_6$), 14.1 (C).

*5.8.10. Ethyl (4E)-2,3-dihydroxyhex-4-enoate* ***(5-anti-E)***. **5-*anti*-*E*** was prepared according to the procedure described for **5-*syn*-*E*** using **3-*anti*-*E*** (173 mg, 0.6 mmol), 3 ml of THF and tetrabutylammonium fluoride (1.2 mL, 1 M in THF). **5-*anti*-*E*** was obtained as colourless oil (67 mg, 0.38 mmol, 64%).

$^1$H NMR ($CDCl_3$, 300MHz): 5.77 (ddq, 1H, $^3J$=15.3, $^3J$=6.6, $^4J$=0.9), 5.50 (ddq, 1H, $^3J$=15.3, $^3J$=6.9, $^4J$=1.5), 4.40–4.20 (m, 4H), 1.71 (bd, 3H, $^3J$=6.6), 1.29 (t, 3H, $^3J$=7.2). $^{13}$C NMR ($CDCl_3$, 75MHz): 172.3 ($C_1$), 130.1 ($C_5$), 127.6 ($C_4$), 74.0 ($2C_{2,3}$), 62.0 (C), 17.9 ($C_6$), 14.3 (C).

## 5.9. Identification of *syn* and *anti* diastereomers

*5.9.1. Attempted identification using mandelic esters.* In a round-bottomed flask **5-*syn*-*E*** (32 mg, 0.18 mmol) was dissolved in dichloromethane (1 mL) and (*S*)-mandelic acid (77 mg, 0.40 mmol), dicyclohexylcarbodiimide (82 mg, 0.40 mmol) and dimethylaminopyridine (5 mg, 0.04 mmol) were successively added. After 24 h at room temperature under stirring, the mixture was concentrated under vacuum and the white residue was diluted in ether (2 mL). The heterogeneous mixture was filtered through a pad of Celite and the solid was washed with ether (2×5 mL). The liquid organic phase was successively washed by water (5 mL), an aqueous saturated $NaHCO_3$ solution (5 mL), water (5 mL), HCl (10%) (5 mL), water (5 mL), brine (5 mL), dried ($MgSO_4$) and concentrated under vacuum. The crude product was purified by flash chromatography on silica gel (hexane/ether: 7/3) to give bis-(*S*)-mandelic esters '*S*'-[*R*,*S*]-'*S*' and 'S'-[*S*,*R*]-'*S*' as a mixture of diastereomers (89 mg, 0.17 mmol, 94%).

The same procedure was used for **5-*anti*-*Z*** (54 mg, 0.31 mmol). The crude product was purified by flash chromatography on silica gel (hexane/ether: 7/3) to give pure bis-(*S*)-mandelic esters '*S*'-[*R*,*R*]-'*S*' and '*S*'-[*S*,*S*]-'*S*' (160 mg, 0.30 mmol, 98%).

$^1$H NMR spectra of bis-(*S*)-mandelic esters in 4:1 $CS_2/CD_2Cl_2$ were recorded on a 400 MHz apparatus at 298 K and 253 K, but while $\Delta\delta^{T1T2}$ might be in agreement with Riguera's reports when considering only the '*syn*' isomers, consideration of $\Delta\delta^{T1T2}$ in the case of the '*anti*' isomers exhibited inconsistent variations of these parameters (see Supplementary data: $^1$H NMR spectra at 298 and 253 K and $\Delta\delta^{T1T2}$ values in ppm).

*5.9.2. Identification using acetonide derivatives*

*5.9.2.1. Ethyl 2,2-dimethyl-5-[(1E)-prop-1-en-1-yl]-1,3-dioxolane-4-carboxylate* ***(6-syn-E)***. To a solution of **5-*syn*-*E*** (134 mg, 0.77 mmol) in a 1:1 mixture of acetone/2,2-dimethoxypropane (29 mL) in a round-bottomed flask, CSA (87 mg, 0.38 mmol) was added in one portion. After 12 h, the reaction was partitioned between $Et_2O$ (30 ml) and water (30 ml) and the organic layer was separated and dried ($MgSO_4$). Concentration under reduced pressure gave crude acetonide, which was purified by flash

chromatography on silica gel (Hexanes/$Et_2O$ 6:4) to afford pure **6-*Syn-E*** as a colourless oil (125 mg, 0.58 mmol, 76%).

IR: 3446, 2927, 2855, 1689, 1590, 1757, 1449, 1097, 968. HRMS (CI): *m/z* calcd for $C_{11}H_{19}O_4$ $[M+H]^+$=215.1283, found 215.1280; MS (CI, $NH_3$) *m/z*: 232 (100), 215 (10), 174(95), 157 (83), 144 (21); MS (EI) *m/z*: 199 (8), 157 (45), 144 (22), 87 (38), 83 (100), 73 (24), 43 (55). $^1$H NMR ($CDCl_3$, 300MHz): 5.87 (ddq, 1H, $^3J$=15.1, $^3J$=6.5, $^4J$=0.9), 5.54 (ddq, 1H, $^3J$=15.1, $^3J$=7.5, $^4J$=1.8), 4.49 (bt, 1H, $^3J$=8.0), 4.24 (dq, 1H, $^2J$=10.6, $^3J$=7.1), 4.22 (dq, 1H, $^2J$=10.6, $^3J$=7.1), 4.16 (d, 1H, $^3J$=8.0), 1.75 (dd, 3H, $^3J$=6.5, $^4J$=1.8), 1.47 and 1.46 (2s, 6H), 1.28 (t, 3H, $^3J$=7.1). A NOESY experiment showed strong interaction between $H_2$ and $H_4$, attesting of the configuration of this diastereomer (see Fig. 1). $^{13}$C NMR ($CDCl_3$, 75MHz): 170.4 ($C_1$), 132.0 ($C_5$), 127.4 ($C_4$), 111.0 (C), 80.4 ($C_3$), 79.3 ($C_2$), 61.4 (C), 27.1, 25.9, 17.9 ($C_6$), 14.3.

*5.9.2.2. Ethyl 2,2-dimethyl-5-[(1E)-prop-1-en-1-yl]-1,3-dioxolane-4-carboxylate **(6-anti-E)**.* **6-*anti-E*** was prepared according to the procedure described for **6-*syn-E*** using **5-*anti-E*** (83 mg, 0.48 mmol), 18 mL of a 1:1 mixture of acetone/2,2-dimethoxypropane and CSA (52 mg, 0.24 mmol). **6-*anti-E*** was obtained as a colourless oil (27 mg, 0.12 mmol, 26%).

$^1$H NMR ($CDCl_3$, 300MHz): 5.87 (dq, 1H, $^3J$=15.2, $^3J$=6.4), 5.35 (ddq, 1H, $^3J$=15.2, $^3J$=7.8, $^4J$=1.2), 4.76 (bt, 1H, $^3J\sim$7.5), 4.60 (d, 1H, $^3J$=7.1), 4.21 (dq, 1H, $^2J$=10.8, $^3J$=7.2), 4.16 (dq, 1H, $^2J$=10.8, $^3J$=7.2), 1.71 (dd, 3H, $^3J$=6.4, $^4J$=1.2), 1.62 and 1.39 (2s, 6H), 1.25 (t, 3H, $^3$J=7.2). A NOESY experiment exhibited no interaction between $H_2$ and $H_4$ (*Cf* Fig. 1). $^{13}$C NMR ($CDCl_3$, 75MHz): 169.8 ($C_1$), 132.1 ($C_5$), 125.3 ($C_4$), 110.9 (C), 78.9 ($C_3$), 77.7 ($C_2$), 61.0, 27.1, 25.7, 17.9 ($C_6$), 14.4.

## 5.10. Ozonolysis of compounds 3 and 4

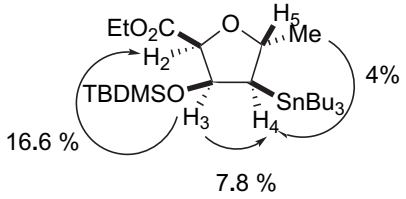
*5.10.1. General procedure for ozonolysis.* Ozone gas was bubbled in a solution of **3** or **4** (1 mmol) in 10 mL of a 4:1 mixture of $CH_2Cl_2$/MeOH at −78 °C during 10 min. Argon was then passed through the solution for 10 min at −78 °C to remove any excess of ozone. Triphenylphosphine was added (723 mg, 2.76 mmol) and the mixture was warmed up to room temperature and stirred for 12 h. The crude solution was concentrated under reduced pressure and then purified by flash chromatography on silica gel (hexanes/$Et_2O$ 7:3) to give pure aldehydes **7-*syn*** (72% yield from **3-*syn-E*** and 42% from **4-*syn-E***) and **7-*anti*** (88% yield from **3-*anti-E***, 89% from **3-*anti-Z***, 53% from **4-*anti-Z*** and 70% from **4-*anti-E***) as colourless oils.

*5.10.2. Ethyl 3-tert-butyldimethylsilyloxy-2-hydroxy-4-oxobutanoate **(7-syn)**.* IR (neat) 3446, 2856, 2359, 1734, 1254, 1097, 837, 779. MS (CI, $NH_3$) *m/z*: 294 (100), 277 (10). $^1$H NMR ($CDCl_3$, 300MHz): 9.66 (d, 1H, $^3J$=0.9), 4.57 (dd, 1$H_2$, $^3J$=9.7, $^3J$=1.8), 4.37 (dd, 1$H_3$, $^3J$=1.8, $^3J$=0.9), 4.32 (dq, 1H, $^2J$=10.5, $^3J$=6.9), 4.17 (dq, 1H, $^2J$=10.5, $^3J$=6.9), 3.08 (d, 1$H_{hydroxyl}$, $^3J$=9.7), 1.31 (t, 3H, $^3J$=6.9), 0.89 (s, 9H), 0.10 and 0.02 (s, 6H). $^{13}$C NMR ($CDCl_3$, 75MHz): 201.8 ($C_4$), 171.5 ($C_1$), 78.9 ($C_3$), 72.2 ($C_2$), 62.3, 25.7 (3C), 18.2, 14.2, −4.1, −4.4.

*5.10.3. Ethyl 3-tert-butyldimethylsilyloxy-2-hydroxy-4-oxobutanoate **(7-anti)**.* $^1$H NMR ($CDCl_3$, 300MHz): 9.61 (d, 1H, $^3J$=0.6), 4.52 (dd, 1H, $^3J$=5.7, $^3J$=1.9), 4.34 (dq, 1H, $^2J$=10.8, $^3J$=7.2), 4.27 (dd, 1H, $^3J$=1.9, $^3J$=0.6), 4.18 (dq, 1H, $^2J$=10.8, $^3J$=7.2), 3.13 (d, 1$H_{hydroxyl}$, $^3J$=5.7), 1.27 (t, 3H, $^3J$=7.2), 0.91 (s, 9H), 0.11 (s, 6H). $^{13}$C NMR ($CDCl_3$, 75MHz): 201.9 ($C_4$), 171.4 ($C_1$), 80.2 ($C_3$), 73.1 ($C_2$), 62.5, 25.7 (3C), 18.2, 14.3, −4.4, −4.8.

## 5.11. Characterization of tetrahydrofuran derivatives 8 and 9

*5.11.1. Ethyl 3-tert-butyldimethylsilyloxy-5-methyl-4-tributylstannyl-tetrahydrofuran-2-carboxylate **(8)**.* IR: 2928, 2855, 1733, 1463, 1375, 1251, 1111, 838, 776. HRMS (MALDI-TOF): *m/z* calcd for $C_{26}H_{54}O_4SiNa^{116}Sn$ $[M+Na]^+$=597.2707, found 597.2692; MS (CI, $NH_3$) *m/z*: 596 (3), 579 ($M+H^+$, 100); MS (EI) *m/z* (%): *organotin fragments*: 578 (3), 521 (16), 389 (7), 291.0 (31), 235.0 (8), 179 (25), 121 (4). *organic fragments* 185.0 (28), 155 (100), 83 (16), 73 (14). $^1$H NMR ($CDCl_3$, 300MHz): 4.56 (dd, $H_3$, $^3J_{H2H3}$=4.9, $^3J_{H3H4}$=3.7, $^3J_{Sn-H}$=33), 4.32 (d, $H_2$, $^3J_{H2H3}$=4.9), 4.30–4.20 (m, $H_5$+1$H_{ester}$: $^2J$=10.8, $^3J$=6.0), 4.09 (dq, 1$H_{ester}$, $^2J$=10.8, $^3J$=7.2), 1.61 (dd, $H_4$, $^3J_{H4H5}$=6.3, $^3J_{H3H4}$=3.7), 1.55–1.39 (m, 3$H_{6+}$6H$_\beta$), 1.37–1.25 (m, 3H+6H$_\gamma$), 0.95–0.83 (m, 24H), 0.06 (s, 6H). NOE experiments:




$^{13}$C NMR ($CDCl_3$, 75MHz) 170.1 ($C_1$), 82.9 ($C_2$, $^3J_{Sn-C}$=17), 80.6 ($C_5$, $^2J_{Sn-C}$<5), 78.6 ($C_3$, $^2J_{Sn-C}$=7), 60.8 ($C_{ester}$), 39.3 ($C_4$, $^1J_{Sn-C}$=266/254), 29.2 (3C, $^2J_{Sn-C}$=20), 27.6 (3C, $^3J_{Sn-C}$=59), 25.2 (3C), 23.5 ($C_6$, $^3J_{SnC}$=23), 17.8 ($C^{IV}$, $^1J_{SiC}$=68), 14.3 ($C_{ester}$), 13.7 (3C), 8.7 (3C, $^1J_{Sn-C}$=324/309), −4.3, −4.7. $^{119}$Sn ($CDCl_3$, 112MHz) −18.2.

*5.11.2. Ethyl [5-(tert-butyl)-3-(tert-butyldimethylsilyloxy)-4-(tributylstannyl)-tetrahydrofuran]-2-carboxylate **(9)**.* IR: 2955, 2928, 2855, 1732, 1464, 1254, 1122, 1057, 1122, 836, 774. HRMS (MALDI-TOF): *m/z* calcd for $C_{29}H_{60}O_4SiNa^{116}Sn$ $[M+Na]^+$=639.3176, found 616.3160; MS (CI, $NH_3$) *m/z*: 638 (22), 621($M+H^+$, 100), 563 (17), 489 (12). MS (EI) *m/z* (%) *Organotin fragments*: 563 (65), 291 (89), 235 (60), 179 (63), 121 (6). *Organic fragments*: 227 (32), 197 (100), 75 (23), 73 (24), 57 (44). $^1$H NMR($CDCl_3$, 300MHz) 4.51 (d, $H_3$, $^3J_{H2H3}$=3.3, $^3J_{H3H4}$=0, $^3J_{Sn-H}$=36), 4.26 (dq, 1$H_{ester}$, $^2J$=10.2, $^3J$=7.2), 4.25 (d, $^3J_{H2H3}$=3.3), 4.07 (dq, 1$H_{ester}$, $^2J$=10.2, $^3J$=7.2), 3.83 (d, $H_5$, $^3J_{H4H5}$=5.6, $^3J_{Sn-H}$=65), 1.62 (d, $H_4$, $^3J_{H4H5}$=5.6, $^3J_{H3H4}$=0), 1.56–1.41 (m, 6H$_\beta$), 1.39–1.24 (m, 6H$_\gamma$+3$H_{ester}$: $^3J_{2H}$=7.2), 0.94 (s, 9H), 0.93–0.86 (m, 15H), 0.82 (s, 9H), 0.04 and 0.09 (2s, 6H). $^{13}$C NMR ($CDCl_3$, 75 MHz): 168.8 ($C_1$), 92.3 ($C_5$), 83.6 ($C_2$), 78.1 ($C_3$, $^2J_{Sn-C}$=14), 60.7, 34.8 ($C^{IV}$, $^3J_{Sn-C}$=22), 33.5 ($C_4$, $^1J_{Sn-C}$=270–258), 29.3 (3C, $^2J_{Sn-C}$=19), 27.6 (3C, $^3J_{Sn-C}$=58), 26.4 (3C), 25.8 (3C), 18.0 ($C^{IV}$), 14.3, 13.7 (3C), 9.1 (3C, $^1J_{Sn-C}$=319–304), −4.0, -5.2. $^{119}$Sn ($CDCl_3$, 112MHz): −11.8.

## 5.12. Hydrolysis of 8 or 9 into 3-*syn-E* and 4-*syn-E*

In a round-bottomed flask **8** (105 mg, 0.18 mmol) was dissolved in THF (10 mL) and HCl (10%) was added dropwise (1 mL). After stirring 30 min at room temperature, water (5 mL), $Et_2O$ (20 mL) was added. The organic layer was separated, washed with water (2×5 mL) and dried over $MgSO_4$. Concentration under vacuum gave the crude product, which was purified by flash chromatography on silica gel (hexane/ether: 6/4) to give pure **3-*syn-E*** as a colourless oil (49 mg, 0.17 mmol, 95%).

The same procedure was used for **9** (24 mg, 0.04 mmol). The crude product was purified by flash chromatography on silica gel (Hexane/$Et_2O$:7/3) to give pure **4-*syn-E*** as a colourless oil (10 mg, 0.030 mmol, 75%).

## Acknowledgements

We gratefully acknowledge Chemtura (Bergkamen) for gift of organotin starting materials, ICSN (CNRS, Gif-sur-Yvette) for a Ph.D. grant (AL), CNRS and MESR for financial support. We wish also to warmly acknowledge Egide programs (PHC Polonium N°14160ZM) and French Embassy in Poland for supporting this work.

## Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.tet.2009.12.037.

## References and notes


1. Yamamoto, Y. *J. Org. Chem.* **2007**, *72*, 7817–7831.
2. Marshall, J. A. *J. Org. Chem.* **2007**, *72*, 8153–8166.
3. Williams, D. R.; Nag, P. P. In *Tin Chemistry: Fundamentals, Frontiers and Applications*; Davies, A. G., Gielen, M., Pannell, K. H., Tiekink, E. R. T., Eds.; John Wiley & Sons: Chichester, UK, 2008; pp 515–560.
4. Hoffmann, R. W.; Kemper, B.; Metternich, R.; Lehmeier, T. *Liebigs Ann. Chem.* **1985**, 2246–2260.
5. Marshall, J. A. *Chem. Rev.* **1996**, *96*, 31–48.
6. Marshall, J. A. *Chem. Rev.* **2000**, *100*, 3163–3186.
7. Lombardo, M.; Trombini, C. *Chem. Rev.* **2007**, *107*, 3843–3879.
8. Koreeda, M.; Tanaka, Y. *Tetrahedron Lett.* **1987**, *28*, 143–146.
9. Marshall, J. A.; Welmaker, G. S. *J. Org. Chem.* **1992**, *57*, 7158–7163.
10. Watrelot, S.; Parrain, J.-L.; Quintard, J.-P. *J. Org. Chem.* **1994**, *59*, 7959–7961.
11. Madec, D.; Ferezou, J.-P. *Tetrahedron Lett.* **1997**, *38*, 6657–6660.
12. Quintard, J. P.; Elissondo, B.; Pereyre, M. *J. Org. Chem.* **1983**, *48*, 1559–1560.
13. Keck, G. E.; Abbott, D. E.; Wiley, M. R. *Tetrahedron Lett.* **1987**, *28*, 139–142.
14. Roush, W. R.; VanNieuwenhze, M. S. *J. Am. Chem. Soc.* **1994**, *116*, 8536–8543.
15. Thomas, E. J. *Chem. Commun.* **1997**, 411–418.
16. Yu, C.-M.; Youn, J.; Jung, J. *Angew. Chem., Int. Ed.* **2006**, *45*, 1553–1556.
17. Thomas, E. J. *Chem. Rec.* **2007**, *7*, 115–124.
18. Marshall, J. A.; Hinkle, K. W. *J. Org. Chem.* **1996**, *61*, 105–108.
19. Jarosz, S.; Szewczyk, K.; Gawel, A.; Luboradzki, R. *Tetrahedron: Asymmetry* **2004**, *15*, 1719–1727.
20. Jarosz, S.; Nowogródzki, M.; Kolaczek, M. *Tetrahedron: Asymmetry* **2007**, *18*, 2674–2679.
21. Jarosz, S.; Blonska, A.; Cmoch, P. *Tetrahedron: Asymmetry* **2008**, *19*, 1127–1133.
22. Yasuda, M.; Tsuruwa, K.; Azauma, T.; Babu, S. A.; Baba, A. *Tetrahedron* **2009**, *65*, 9569–9574.
23. Servens, C.; Pereyre, M. *J. Organomet. Chem.* **1972**, *35*, C20–C21.
24. Jephcote, V. J.; Pratt, A. J.; Thomas, E. J. *J. Chem. Soc., Perkin Trans. 1* **1989**, 1529–1535.
25. Quintard, J. P.; Dumartin, G.; Elissondo, B.; Rahm, A.; Pereyre, M. *Tetrahedron* **1989**, *45*, 1017–1028.
26. Yamamoto, Y.; Asao, N. *Chem. Rev.* **1993**, *93*, 2207–2293.
27. Yamamoto, Y.; Yatagai, H.; Ishihara, Y.; Maeda, N.; Maruyama, K. *Tetrahedron* **1984**, *40*, 2239–2246.
28. Yamamoto, Y.; Yatagai, H.; Naruta, Y.; Maruyama, K. *J. Am. Chem. Soc.* **1980**, *102*, 7107–7109.
29. Denmark, S. E.; Fu, J. *Chem. Rev.* **2003**, *103*, 2763–2794.
30. Keck, G. E.; Dougherty, S. M.; Savin, K. A. *J. Am. Chem. Soc.* **1995**, *117*, 6210–6223.
31. Denmark, S. E.; Weber, E. J.; Wilson, T. M.; Willson, T. M. *Tetrahedron* **1989**, *45*, 1053–1065.
32. Denmark, S. E.; Weber, E. J. *J. Am. Chem. Soc.* **1984**, *106*, 7970–7971.
33. Fargeas, V.; Zammattio, F.; Chrétien, J.-M.; Bertrand, M.-J.; Paris, M.; Quintard, J.-P. *Eur. J. Org. Chem.* **2008**, 1681–1688.
34. Marshall, J. A.; Welmaker, G. S.; Gung, B. W. *J. Am. Chem. Soc.* **1991**, *113*, 647–656.
35. Watrelot-Bourdeau, S.; Parrain, J.-L.; Quintard, J.-P. *J. Org. Chem.* **1997**, *62*, 8261–8263.
36. Marshall, J. A.; Welmaker, G. S. *J. Org. Chem.* **1994**, *59*, 4122–4125.
37. Fliegel, F.; Beaudet, I.; Quintard, J.-P. *J. Organomet. Chem.* **2001**, *624*, 383–387.
38. Madec, D.; Ferezou, J.-P. *Tetrahedron Lett.* **1997**, *38*, 6661–6664.
39. Chevallier, F.; Beaudet, I.; Le Grognec, E.; Toupet, L.; Quintard, J.-P. *Tetrahedron Lett.* **2004**, *45*, 761–764.
40. Chevallier, F.; Le Grognec, E.; Beaudet, I.; Fliegel, F.; Evain, M.; Quintard, J.-P. *Org. Biomol. Chem.* **2004**, *2*, 3128–3133.
41. Yamamoto, Y.; Maeda, N.; Maruyama, K. *J. Chem. Soc., Chem. Commun.* **1983**, 774–775.
42. Kiegiel, K.; Balakier, T.; Kwiatkowski, P.; Jurczak, J. *Tetrahedron: Asymmetry* **2004**, *15*, 3869–3878.
43. Kwiatkowski, P.; Chaladaj, W.; Jurczak, J. *Tetrahedron Lett.* **2004**, *45*, 5343–5346.
44. In order to simplify the discussion, the identity "*syn*" or "*anti*" is used here but has been determined subsequently by measurement of NOE effects on acetonides.
45. Freire, F.; Calderon, F.; Seco, J. M.; Fernandez-Mayoralas, A.; Quinoa, E.; Riguera, R. *J. Org. Chem.* **2007**, *72*, 2297–2301.
46. See Experimental section and Supplementary data.
47. Linghu, X.; Satterfield, A. D.; Johnson, J. S. *J. Am. Chem. Soc.* **2006**, *128*, 9302–9303.
48. Charette, A. B.; Mellon, C.; Motamedi, M. *Tetrahedron Lett.* **1995**, *36*, 8561–8564.
49. Fujiwara, J.; Sato, T. *J. Organomet. Chem.* **1994**, *473*, 63–70.
50. Fraboulet, G.; Fargeas, V.; Paris, M.; Quintard, J.-P.; Zammattio, F. *Tetrahedron* **2009**, *65*, 3953–3960.
51. Bartoli, G.; Bosco, M.; Giuliani, A.; Marcantoni, E.; Palmieri, A.; Petrini, M.; Sambri, L. *J. Org. Chem.* **2004**, *69*, 1290–1297.
52. Bartoli, G.; Giuliani, A.; Marcantoni, E.; Massaccesi, M.; Melchiorre, P.; Lanari, S.; Sambri, L. *Adv. Synth. Cat.* **2005**, *347*, 1673–1680.
53. Chrétien, J.-M.; Zammattio, F.; Gauthier, D.; Le Grognec, E.; Paris, M.; Quintard, J.-P. *Chem. Eur. J.* **2006**, *12*, 6816–6828.
54. Aspinall, H. C.; Greeves, N.; McIver, E. G. *Tetrahedron Lett.* **1998**, *39*, 9283–9286.
55. Aspinall, H. C.; Dwyer, J. L. M.; Greeves, N.; McIver, E. G.; Woolley, J. C. *Organometallics* **1998**, *17*, 1884–1888.
56. Shimizu, M.; Ando, H.; Niwa, Y. *Lett. Org. Chem.* **2005**, *2*, 512–514.
57. Kwiatkowski, P.; Jurczak, J. *Synlett* **2005**, 227–230.
58. Kwiatkowski, P.; Chaladaj, W.; Jurczak, J. *Tetrahedron* **2006**, *62*, 5116–5125.
59. Chaladaj, W.; Kwiatkowski, P.; Majer, J.; Jurczak, J. *Tetrahedron Lett.* **2007**, *48*, 2405–2408.
60. Kwiatkowski, P.; Chaladaj, J.; Jurczak, J. *Synlett* **2005**, 2301–2304.
61. Aoki, S.; Mikami, K.; Terada, M.; Nakai, T. *Tetrahedron* **1993**, *49*, 1783–1792.
62. Wickham, G.; Young, D.; Kitching, W. *J. Org. Chem.* **1982**, *47*, 4884–4895.
63. Dumartin, G.; Quintard, J.-P.; Pereyre, M. *J. Organomet. Chem.* **1983**, *252*, 37–46.
64. Coulombel, L.; Favier, I.; Duñach, E. *Chem. Commun.* **2005**, 2286–2288.
65. Coulombel, L.; Rajzmann, M.; Pons, J.-M.; Olivero, S.; Duñach, E. *Chem. Eur. J.* **2006**, *12*, 6356–6365.