Homomethallylation and Homomethcrotylation of Aldehydes

Senior Thesis

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by
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Abstract

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A thesis presented to the Department of Chemistry

School of Arts and Sciences
Brandeis University
Waltham, Massachusetts

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While there are several known methods for stereoselectively allylating carbonyls and related compounds, the number of homoallylation reactions, with one more carbon in the chain, is significantly smaller. The bishomoallyl products are more complex than their allylation counterparts, and can potentially add up to three stereocenters in one reaction. Our group previously developed cyclopropylcarbinyl boronates to homoallylate and homocrotylate aldehydes. Here, we modify the cyclopropylcarbinyl boronate for homomethallylation to place a methyl delta to the hydroxyl of the product, and additionally for homomethcrotylation to add methyls in both beta and delta positions. We have obtained some of the desired bishomomethallyl alcohols, and bishomomethcrotyl alcohols in >95% ee, but isomeric byproducts are always observed.
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**Introduction**

Allylation, the addition of a three carbon chain with a double bond between the second and third carbons, is a useful reaction for building stereochemical complexity. Allylation reagents may potentially react at either end of the carbon chain, although the products resulting from different mechanisms are not distinguishable without additional substitution.

**Scheme 1. Allylation, Crotylation and Homoallylation**

For example, crotyl reagents, which contain an additional methyl after the double bond, may attack aldehydes from either carbon 1 or 2, as seen in Scheme 1. Our work focuses on the homologous reactions of allylation and crotylation, homoallylation and homocrotylation, which add an additional sp³-hybridized carbon in the chain but are less reactive than allylation reagents and therefore have been much less researched.

Allylation can add up to two stereocenters and are more reactive than their alkane counterparts. The product double bond can be further functionalized to epoxides, aldehydes or other functional groups to build larger and more complex molecules. Homoallylation could potentially set three stereocenters in one reaction, eventually leading to natural products such as amphidinolides (Scheme 2), which have exhibited some cytotoxicity toward tumor cell lines.¹a
Allylation via the Grignard reaction or lithium reagents is not very stereoselective, and allyl Grignard reagents tend to dimerize over time, so a variety of other types of reagents are used. Allylation reagents may proceed through different transition states depending primarily on the metal used. The $S_E2$ pathway (Scheme 3) directly transfers the alkyl group from the metal through an open transition state. Due to the reactive nature of the metals used, crotyl double bond geometry is only retained at low temperatures and isomerizes easily at room temperature. In general, the metals used offer poor regioselective control and may react through the other pathways as well. Some Lewis acid-promoted reactions of some stannanes and silanes also proceed through an open, but $S_{E2}'$ transition state, where the alkene end acts as the nucleophile, and syn-1,2 products are favored, regardless of starting alkene geometry. When heated in the absence of Lewis acids, some $S_{E2}'$ (open TS) reagents may also react through cyclic mechanisms.
A third possible mechanism, $S_{E2}'$ (closed TS), reacts through a 6-membered Zimmerman-Traxler transition state and occurs with Lewis acidic metals, boron, silicon halides and tin halides. The relative stereochemistry of 1,2-substituents in the products is determined by the starting alkene geometry: $(Z)$-double bonds lead to syn-1,2 products, while $(E)$-alkenes give anti-1,2 products. The following allylation examples discussed here primarily utilize this mechanism.

Selected Historical Examples

Research on aldehyde allylation dates back several decades. One early reaction, the Hosomi-Sakurai reaction first reported in 1976$^{2a}$, employed Lewis acid-activated allyl- and crotyltrimethylsilanes 1 to allylate aldehydes and ketones. The product stereochemistry was not reported, though the pattern of regioisomers isolated from reactions (Scheme 4) with additional substituents on 1 ($R_2, R_3$ = Me or Ph) led the authors to suggest a cyclic transition state. Later research in allylation supports the open $S_{E2}'$ transition state for this Lewis acid-activated
system. In 1996, Sakurai et al. modified 1 to chiral tartar silyl esters 2, obviating the use of added Lewis acids for activation. The reaction proceeded much more slowly, but selectivities up to 80% ee were obtained if the silicon were also attached to an electron withdrawing group. The authors proposed a closed transition state based on solvent effects, and the 1,2-syn/anti homocrotyl alcohols obtained from (Z)- and (E)-allylsilicates, consistent with $S_E2'$ (closed TS) models.

**Scheme 4. Hosomi-Sakurai Allylations**

Leighton and coworkers employed chiral 1,2-diols, 1,2-diamines and 1,2-amino alcohols in 2002 to make strained 5-membered silacycle reagents such as 3 (Scheme 5). Like Sakurai’s tartrate silyl esters, no Lewis acid activation was necessary since the silacycle’s ring strain creates sufficient Lewis acidity. Yields of up to 80% and 96% ee were achieved with a 2-(methylamino)-1-phenylpropan-1-ol auxiliary. *Cis* - and *trans*-crotylsilanes followed the pattern of (E)- to *anti* and (Z)- to *syn* homocrotyl alcohols, supporting the $S_E2'$ cyclic transition state mechanism.

**Scheme 5. Leighton’s Strained Silacycles**
Denmark’s allyltrichlorosilanes 4 are achiral, but enantioselectivity of the products is controlled by catalytic amounts of activated chiral Lewis bases, typically chiral phosphoramides (Scheme 6). Monodentate chiral promoters such as 5a and 5b gave yields usually between 20-80% and maximum ee’s around 80%. Bidentate Lewis bases such as 5c and 5d fared better, with yields up to 92% and 96% ee. With (E)-crotyl silanes, the anti-1,2-methyl alcohol products were favored over syn in a 99:1 ratio, while (Z)-crotyl silanes favored the syn products, also supporting a closed transition state.

**Scheme 6. Denmark’s Lewis Base-Promoted Allylations**

In the field of boron reagents, one of the earliest examples of allylboration was Mikhailov et al.’s reactions with triallylborane (6). The authors had read Topchiev and coworkers’ reports that 6 reacted with aldehydes to form propene, cyclohexadiene and allyl boronates (Scheme 7, eq. 1), but doubted the results. In Mikhailov’s investigations, 6 was found to react rapidly with aldehydes, even at low temperatures, forming only boronic esters before aqueous workup (eq. 2).
Scheme 7. Topchiev and Mikhailov’s Early Allylation$^{3a-b}$

Perhaps one of the best known allylations is the method developed by Brown in 1983. The Brown allylation utilizes chiral diisopinocampheylboranes [(Ipc)$_2$BH] such as 7 to transfer allyl groups to aldehydes, reaching ee’s between 83 and 96%.$^{3c-d}$ As with crotylsilane reagents, Brown’s reagents react through $S_{E}2’$ transition states—syn-2-methyl homoallyl alcohols are furnished by (Z)-(Ipc)$_2$crotylboranes, while anti homoallyl alcohols arise from (E)-reagents.$^{3e}$ Using high optical purity (Z)-(Ipc)$_2$crotylboranes 8a, Brown and Bhat were able to synthesize the syn alcohols from acetaldehyde in 75% yield and 95% enantioselectivity, and obtained very slightly improved results using (E)-crotylboranes 8b.$^{3f}$ The alkenes of most crotylboranes, including Brown’s, readily isomerize between (E) and (Z), and must be prepared and used under -45 °C.

Scheme 8. The Brown Allylation$^{3c-3f}$
In addition to boranes, boronic esters are also capable of allylboration, and are the basis of our homoallylation and homocrotylation reagents. The first asymmetric allylboration of aldehydes, predating Brown by 2 years, was reported by R. W. Hoffmann in 1981. Hoffmann’s initial chiral boronic esters 9 derived from camphor gave ee’s up to 86% (Scheme 9). The R group can be varied to aryl groups or other chiral groups, with the best enantioselectivities resulting from R = Me. The allyl group can also be modified, and Hoffmann was able to achieve methallylation using boronic ester 10 when R = Ph with ee’s up to 74%.

Scheme 9. Hoffmann’s Asymmetric Allylboration

Other allyl boronic esters include Roush’s tartrate crotylboronates (Scheme 10), first reported in 1985, which are essentially the boron version of Sakurai’s tartrate silyl esters. The allyl boronate 11 reacted with aldehydes in high yields and up to 87% ee on achiral aldehydes. Likewise, (E)- and (Z) crotyl boronic esters 12 led to anti and syn alcohols with 86% ee if R = iPr. The stereochemical configuration of carbon A can easily be reversed by switching between (+)- and (-)-tartrates.
By contrast with allylation, very few methods exist for stereoselective homoallylation of aldehydes. In addition to the stereo- and regioselectivity issues allyl reagents face, homoallyl reagents are also often less reactive. Essentially, three high yield homoallylation methods have been reported: the standard Grignard reaction, the Tamaru-Mori reaction, and the Krauss group’s homoallylboration.

Homoallyl Grignard reagents react with aldehydes to produce bishomoallyl alcohols, but provide neither stereoselectivity nor diastereoselectivity for crotylation or homocrotylation. The second successful homoallylation, the Tamaru-Mori reaction, utilizes 1,3-dienes in the presence of triethylborane and a catalytic amount of Ni(acac)$_2$ (acac = acetylacetonate) to homoallylate aldehydes (Scheme 11).\textsuperscript{4a} However, regioselectivity tends to be poor when the diene is lacking substitution in the C3 position, since the diene may react at either end (Scheme 14). The Tamaru-Mori reaction produces bishomocrotyl alcohols like our reactions, but any 1,3 or 1,2 relationships are anti only. In the proposed catalytic cycle, stereoselectivity is determined in the initial step by unfavorable 1,3-diaxial steric interactions.\textsuperscript{4b}
A possible solution to the general homoallyl reactivity issue is to use cyclopropylcarbinyl reagents instead, since cyclopropyls are known to react with electrophiles and the strained "banana bonds" more closely resemble the π-bonds in allyl groups than ordinary sp\(^3\) carbons do. Cyclopropylcarbinyl reagents are also known to isomerize to homoallyl chains (Scheme 12).\(^{5a}\)

**Scheme 12. Cyclopropylcarbinyl-homoallyl Isomerization\(^{4a}\)**

In 1981, Grignon-Dubois and Dunoguès acylated cyclopropylcarbinyl trimethylsilane 13 with acyl chlorides and obtained mixtures of bishomoallyl, homocrotyl and β-chlorinated ketones (Scheme 13).\(^{5b}\) The reaction does not proceed through a Zimmerman-Traxler transition state;
rather, the cyclopropyl ring opens to attack a dehalogenated acyl chloride, forming a silicon-stabilized cation, which can lose trimethylsilyl chloride or be attacked directly by a chloride ion to give the three products.

**Scheme 13. Cyclopropylcarbinyl Trimethylsilane Homoallylates Acyl Chlorides**

The reactivity of cyclopropylcarbinyl reagents with aldehydes was lower than their reactivity with acyl chlorides. Lucke and Young found that cyclopropylcarbinyl stannanes (Scheme 14, eq. 1 and 2) do not react with benzaldehyde to form bishomoallyl alcohols under high heat or pressure, or in the presence of a small amount of Lewis acid. Additional quantities of Lewis acids only cause the ring to open to homoallyl stannanes.$^5c$

**Scheme 14. No Desired Reactivity with Cyclopropylcarbinyl or Homoallyl Stannanes$^{5c-d}$**
Sugawara and Yoshida have reported that homoallyl stannanes do react with aldehydes in the presence of Lewis acid to produce only very minor amounts of homoallylated products. The major products, however, are cyclopropylcarbinyl alcohols. The authors proposed a model where double bond of the stannane attacks the electrophile, generating a carbocation (Scheme 14, eq. 3). $\gamma$-elimination of the stannyl cation results in the major cyclopropyl products, while a hydride shift, followed by $\beta$-tin elimination gives the minor bishomoallyl alcohol products.

The final successful reported example of homoallylation is our group’s homoallylboration with cyclopropylcarbinyl boronic esters (Scheme 15). Like 13, our reagents require Lewis acid activation, but adapt the cyclic Zimmerman-Traxler transition state found in many allylations for homoallylation, giving us higher reactivity and more stereoselective control than the Tamaru-Mori reaction provides.

**Scheme 15. Cyclopropylcarbinyl Boronic Esters May Homoallylate Aldehydes in an $S_{E2}'$ Fashion**

Boronic ester 14 gave yields ranging from 80% to 95% $^{6a}$, but provided no stereoselective control since the reagent is achiral and no information about diastereoselectivity because only one stereocenter is made. Therefore, homologous homocrotylation reagents were synthesized by cyclopropanating ($Z$)- and ($E$)-crotyl pinacol boronic esters, then exchanging pinacol for 1,3-propanediol to boronates 15 and 16. The stereoselectivity of the final boronic ester is reversed.
from ordinary crotyl reagents—boronic esters originating from the (E)-crotyl compound formed a trans-cyclopropylcarbinyl boronic ester, which gave syn-1,3-substituted alcohols, while the opposite was true for reagents synthesized from the (Z)-crotyl compound.

**Scheme 16. Synthesis of Racemic and Optically Active Homocrotylation Reagents**

Since the reagents synthesized from pinacol crotyl boronic esters are racemic, we have also synthesized enantiopure 16 using an N,N,N’,N’-l-tartaramide auxiliary during cyclopropanation. Syn-1,3 alcohols were obtained with ee’s up to 97-98% or 99:1 dr.6b The transition states of these “homocrotyl” reagents are homologous to the closed S_E2’ allylation transition states (Scheme 17).

**Scheme 17. Mechanism of Homocrotylation Reactions**
We herein report our attempts at homomethallylation, with a methyl delta to the final hydroxyl, and enantiopure homomethycrotylation, which attempts to place methyls both beta and delta to the hydroxyl.
Results and Discussion

*Methycyclopropylcarbinyl boronate synthesis and homomethallylation*

**Scheme 18. Summary of Reagent to Product Substitution Patterns**

As we were previously able to add substituents in the $R_2$ and $R_4$ positions (Scheme 18), we then turned our attention to investigating the reagent’s tolerance for methyl substitution at the $R_3$ position. Our original plan was to follow the same synthetic route (Scheme 19) of cyclopropanation and diol exchange used in the synthesis of 14, but the desired starting pinacol boronate 17 was not commercially available.

**Scheme 19. Original Planned Synthetic Route of 19 and Synthesis of 17**

We synthesized 17 by palladium-catalyzed cross coupling of bis(pinacolato)diboron and methallyl acetate, and a Grignard reaction between 2-methallylmagnesium chloride and pinacol isopropyl borate. Both reactions gave disappointingly low yields (10% and 25%, respectively), so a second route was developed (Scheme 20). Commercially available 20 was cyclopropanated by the Simmons-Smith reaction with good yields to 21 and then homologated to 18 with
LiCH₂Cl. Oxidative hydrolysis with NaIO₄ and HCl followed by condensation with 1,3-propanediol afforded the final boronate 19 after distillation with overall 55% yield over 3 steps.

Scheme 20. Synthesis of 17 from Pinacol Isopropenyl Boronic Ester 18

With 19 in hand, we attempted homomethallylation on three aldehydes 22a-c using the same conditions that provided the best homoallylation results (Table 1). Although 19 seemed to react more quickly (reaction times of 2 h or under) than 14 isolated yields of the desired S₂E₂’ bishomomethallyl alcohols 23a-c were low (10-20%) and S₂E₂ products (24) were frequently observed (entries 2-5). An old batch of AlCl₃ failed to promote any reaction, while the aldehyde was consumed within 45 minutes when the experiment was repeated with new AlCl₃ (entry 9), but gave no alkenes.

We believe the significant amounts of 24 is due to the Thorpe-Ingold effect, which states that quaternary carbons in rings favor ring closure over ring opening. The 23/24 product ratio was approximately 1:1 at room temperature and could be adjusted to very slightly in favor 23 or 24 by lowering the temperature to 0 °C or increasing to 40 °C, respectively, consistent with the observation of S₂E₂ products in homoallylation reactions at elevated temperatures. Under the standard conditions used for homoallylation, only benzaldehyde (22a) gave no S₂E₂ products (entry 1). The effects of additional substituents on 22a were not investigated.
Table 1. Homomethallylation with Boronate 19

<table>
<thead>
<tr>
<th>Entry</th>
<th>Aldehyde</th>
<th>Conditions</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R = Ph (22a)</td>
<td>PhBCl₂, r.t., 2 h</td>
<td>Complete conversion, only formed 23a</td>
</tr>
<tr>
<td>2</td>
<td>R = PhC₂H₄ (22b)</td>
<td>PhBCl₂, r.t., 2 h</td>
<td>Incomplete conversion, mixture of 23b and 24b products</td>
</tr>
<tr>
<td>3</td>
<td>R = C₇H₁₅ (22c)</td>
<td>PhBCl₂, r.t., 2 h</td>
<td>Complete conversion, mixture of 23c and 24c products</td>
</tr>
<tr>
<td>4</td>
<td>22c</td>
<td>PhBCl₂, 0 °C, 3 h</td>
<td>Incomplete conversion, 23c slightly favored over 24c</td>
</tr>
<tr>
<td>5</td>
<td>22c</td>
<td>PhBCl₂, 40 °C, 1.5 h</td>
<td>Complete conversion, 23c slightly favored over 24c</td>
</tr>
<tr>
<td>6</td>
<td>22b</td>
<td>PhBCl₂, r.t., 4 h</td>
<td>Complete conversion, mixture of homomethcrotyl alcohols</td>
</tr>
<tr>
<td>7</td>
<td>22b</td>
<td>Sc(OTf)₃, r.t., 3 d</td>
<td>Incomplete conversion, mixture of homomethcrotyl alcohols</td>
</tr>
<tr>
<td>8</td>
<td>22b</td>
<td>BF₃·OEt₂, r.t., 0.5 h</td>
<td>Complete conversion, mixture of homomethcrotyl alcohols</td>
</tr>
<tr>
<td>9</td>
<td>22b</td>
<td>AlCl₃, r.t., 2 d</td>
<td>Complete conversion, no alkenes seen</td>
</tr>
</tbody>
</table>

*Conditions: 1.0 equiv of aldehyde, 1.5 equiv of Lewis acid, 3.0 equiv of 19, 6.0 equiv of K₂CO₃, the solvent was DCM in all cases.

Minor amounts of syn- and anti-homomethcrotyl alcohols 25 were seen in all reactions, but not isolated or identified until they became the major products (Table 1, entries 7-8), where the Lewis acid activator was changed to Sc(OTf)₃ or BF₃·OEt₂. In one case, a PhBCl₂-promoted homomethallylation only gave homomethcrotyl alcohol products (entry 6), but this result was not reproducible. Two alcohols were isolated from this run, and assigned as anti- and syn-25b by comparison with literature ¹H NMR values. It is unknown if this particular outcome was caused by impurities in PhBCl₂ or K₂CO₃, which were redistilled or dried every few months.
A possible mechanism leading to 25 is shown in Scheme 21. A cyclopropylcarbinyl-homoallyl isomerization of 19 (Scheme 12) or the active species X₂B(cyclopropylcarbinyl) may occur, followed by a reverse hydroboration to produce a diene and boron species 26. 26 can re-hydroborate at either end of the diene. One route leads to boron species 27 with either an (E)- or (Z)- double bond, which would react with an aldehyde through the S_E2’ (closed) transition state described earlier and give the observed syn and anti homomethcrotyl alcohols.

**Dimethycyclopropylcarbinyl boronate synthesis and homomethcrotylation**

Since we were unable to achieve high selectivity for of S_E2’ products over S_E2 products with 19, we decided to examine the effect of an additional substituent in the R₄ position (Scheme 18). Additional ring strain arising from cis substituents on the cyclopropane ring in dimethycyclopropylcarbinyl boronate 28 might favor the desired ring-opening S_E2’ pathway (Scheme 22). Boronate 29 would have trans R₃ and R₄ substituents, but the ring strain resulting from a methyl and the R₂ carbon may also favor S_E2’ homomethcrotylation.
Scheme 22. The Thorpe-Ingold Effect and Ring Strain on Boronates with R₃ substitution

Neither boronic esters of pinacol 2-butenyl (Z-30) nor a tartaramide-protected version (Z-31) were commercially available, so we began synthesis of the dimethylcyclopropylcarbinyl boronate 28 via a Grignard reaction between trimethylborate and 1-methyl-1-propenylmagnesium bromide (Scheme 23). The Grignard reagent interconverts between the (E)- and (Z)-isomers easily, and the reaction gave a 1:1 mixture of desired Z-31 and undesired E-31 products after protection with N,N,N’,N’-tetramethyl tartaramide.

Scheme 23. Initial Attempts to Synthesize Z-30 and Z-31

Miyaura’s rhodium-catalyzed hydroboration was also tried, although we realized later that the conditions were intended to favor anti addition of the alkyne, which would give the undesired E-30 product. Surprisingly, the exclusive product isolated appeared to be Z-30 according to a
comparison of its $^1$H NMR spectrum with literature data; it was an off-white solid rather than the expected oil. Moreover, it decomposed when subjected to the oxidation conditions used in the synthesis of 14.

We synthesized Z-30 again by an uncatalyzed syn hydroboration$^{7c}$ between 2-butyne and catecholborane, by heating the two reactants neat in a sealed tube at 80 °C for 2.5 days. Pinacol in pentane was added to yield a pinacol boronate stable enough for column chromatography (Scheme 24). Yields of Z-30 were typically in the 55-65% range, but this hydroboration could be done on a 12 g scale. Our asymmetric Simmons-Smith conditions$^{6b}$ require the pinacol to be hydrolyzed off and replaced with a chiral diol, so Z-30 was once again subjected to previous oxidation conditions, but decomposed just as before.

**Scheme 24. Synthesis of Optically Active Boronate 28**

Switching to Aue’s less acidic oxidation system of NH$_4$OAc and NaIO$_4$ in acetone/water$^{7c}$ avoided the decomposition, although the reaction took longer and the product was contaminated with acetic acid. This was removed by a combination of stirring with K$_2$CO$_3$(s) and azeotropic removal with toluene. We attempted to avoid acetic acid contamination by NH$_4$OAc with citric acid, a slightly stronger and more water-soluble acid, but like HCl, this caused decomposition.
within about 6 hours. Despite the increased reaction time and the need to remove acetic acid, the new oxidation generally provided very good yields of 80-95% of Z-29. We asymmetrically cyclopropanated Z-31 to 32 with CH₂I₂, Et₂Zn and 0.5 equiv of L-tartaramide at -78 °C, and then the diol was exchanged back to pinacol for purification by column chromatography. It is worth noting that this sequence could likely be optimized to reduce the number of diol exchanges at the boronate moiety. Adding L-tartaramide after hydroboration instead of pinacol to reach Z-31 directly, followed by asymmetric cyclopropanating to 32 would remove one step and 3 days of reaction time. Our priority at first, however, was to use known reactions to generate optically active and racemic 28. The absolute stereochemistry of 32 is still undetermined, and the configuration drawn in Scheme 24 is tentatively assigned by analogy to our previous asymmetric cyclopropanation examples.⁶b We homologated 32 to 33 using the same conditions for the synthesis of 19, and then hydrolyzed using the newer NH₄OAc/NaIO₄ system, although the old hydrolysis conditions may have been acceptable on the more stable boronate. Distillation after the addition of 1,3-propanediol gave optically active 28 in overall about 40% yield over 5 steps. Racemic 28 (Scheme 25) was synthesized from Z-30 by the same route as described in Scheme 20, but oxidized to the boronic acid with NH₄OAc and NaIO₄ in acetone/water, with an overall yield of around 42% over 4 steps.

**Scheme 25. Synthesis of Racemic 28 from Z-30**
We then homomethcrotylated aldehydes 22a-c, with varying results (Table 2). The absolute configuration of 34a-c is tentatively assigned by analogy to our previous homocrotylation reactions. As with all our previous reactions with propanediol cyclopropylcarbinyl boronates, no homoallylation occurs without a Lewis acid. The yield of bishomomethcrotyl alcohol 34b increased from 10-20% in homomethallylation up to 37% (entry 4), though is still far from the excellent yields obtained by homoallylation and homocrotylation. Chiral HPLC analysis of the benzoyl ester of 34b indicated a good ee of >95%, almost as good as the 97% ee’s from homocrotylation.

Table 2. Homomethcrotylation with Optically Active Boronate 28

<table>
<thead>
<tr>
<th>Entry</th>
<th>Aldehyde</th>
<th>Conditions</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R = Ph (22a)</td>
<td>3 equiv PhBCl₂, 3 equiv 28, r.t., 3 h</td>
<td>Primarily 35a products, 34a could not be isolated</td>
</tr>
<tr>
<td>2</td>
<td>22a</td>
<td>3 equiv 28, 0 °C, 16 h</td>
<td>About 10% 34a, large amount of 35a</td>
</tr>
<tr>
<td>3</td>
<td>R=PhC₂H₄ (22b)</td>
<td>3 equiv 28, r.t., 2 d</td>
<td>Mostly alkene byproducts, 34b observed, minor amounts of S₂E₂ products</td>
</tr>
<tr>
<td>4</td>
<td>22b</td>
<td>3 equiv 28, 0 °C, 16h</td>
<td>37% yield of 34b, &gt;95% ee, smaller amount of alkene byproducts</td>
</tr>
<tr>
<td>5</td>
<td>R = C₇H₁₅ (22c)</td>
<td>6 equiv 28, 0 °C to r.t., 16 h</td>
<td>Complete after 20 min at 0 °C, mostly 35c</td>
</tr>
<tr>
<td>6</td>
<td>22c</td>
<td>3 equiv 28, 0 °C, 16h</td>
<td>Mostly 35c</td>
</tr>
<tr>
<td>7</td>
<td>22b</td>
<td>0 equiv PhBCl₂, r.t., 1 d</td>
<td>No reaction</td>
</tr>
</tbody>
</table>

*a Conditions: 1.0 equiv of aldehyde, 1.5 equiv of PhBCl₂ except entries 1 and 7, 3.0 equiv of 28 except entry 5, 6.0 equiv of K₂CO₃ (s), the solvent was DCM in all cases

Undesired S₂E₂ products were minor side products, and observed primarily in reactions at room temperature (entry 3). The major byproducts were homomethcrotyl alcohols 35a-c, and in
reactions with 22a and 22c, were produced in much greater amounts than the desired products (entries 1-2, 5-6). A possible pathway to 35a-c is proposed in Scheme 26.

Scheme 26. Formation of Homomethcrotylation Side Products

As with 19, 28 (or the active species) may ring open to the homomethallyl species, then undergo a reverse hydroboration to 26 and a diene. Subsequent re-hydroboration at either end gives boron species 36, which crotylates aldehydes to give 35.

A mixture of at least two unknown alkenes was also observed in all reactions. Comparison with literature $^1$H NMR values indicates that the mixture likely does not contain the anti-bishomomethcrotyl alcohols. $^1$H NMR (entry 1) and TLC of crude reactions of entries 1, 6 and 7 indicate the possible presence of 34a and 34c, but the putative desired products could not be separated from the mixture of unknown alkenes.

Homomethcrotylation reactions at room temperature with 3 equiv of boronate were completed in comparable times of 2 h to homomethallylation, but reactions at 0 °C often required at least 16 h to complete. Homomethcrotylation of octanaldehyde with 6 equiv. of boronate was complete within 20 min, but in general deviations from the standard conditions of 1.5 equiv. of PhBCl$_2$ and 3.0 equiv. of boronate resulted in larger amounts of side products. Like homomethallylation, lowering the temperature does favor the desired product, so decreasing the temperature further may give higher yields and ee’s.
Conclusion

Two new analogues of our homoallylation reagent 14 with additional substituents at 1 and 2 different positions were synthesized to homomethallylate and homomethcrotylate aldehydes. The desired bishomomethallyl and bishomomethcrotyl alcohols were isolated in both cases (10-20% yields of bishomomethallyl alcohols and 37% of bishomomethcrotyl alcohols), but significant amounts of isomeric byproducts were always observed. The modest yields of the desired products are partly due to the difficulty of purification. Conducting reactions at lowered temperatures favored formation of desired products, very slightly in the case of homomethallylation, and more significantly for homomethcrotylation. Some selectivity was obtained in the homomethcrotylation reactions, with >95% ee of 34b obtained. Further determination of reagent and bishomomethcrotyl alcohols’ ee’s are in progress, as well as their absolute and relative configurations. Since we now know that the cyclopropylcarbinyl boronate can tolerate two substituents simultaneously, new combinations of more extensive substitution may be attempted. In addition, our homoallylation reactions and its variations may be optimized for scales larger than 1 mmol. Future work would also focus on expanding the substrate scope to imines to obtain corresponding amines.
Experimental

A. General considerations
B. Cyclopropanation
C. Homologation
D. Diol exchanges involving oxidation to boronic acids
E. Grignard reactions
F. Homomethallylation and homomethcrotylation
G. Known compounds
H. NMR spectra
I. HPLC chromatograms

A. General considerations

Air and water sensitive reactions were performed using standard Schlenk techniques under N₂.

All commercially purchased compounds were used as received without further purification unless otherwise noted. Reactions were carried out in oven-dried glassware under a nitrogen atmosphere and were stirred magnetically. The phrase "concentrated" refers to removal of solvents by means of a rotary evaporator attached to a Welch 1400 oil pump (bled to 5-300 mm Hg as needed) followed by removal of residual solvents at < 1 Torr on a vacuum manifold attached to a Welch 1400 vacuum pump. Volatile compounds (all pinacol, propanediol boronates and octanal-derived alcohols) were dried by blowing N₂ gas over concentrated solutions. SiliaFlash® F60 (230-400 mesh) from SiliCycle® was used for flash column chromatography unless specifically indicated. TLC plates were analyzed by short wave UV illumination, or by staining with iodine on silica or vanillin stain (15g vanillin in 250 mL ethanol and 2.5 mL concentrated sulfuric acid) and heating on a hot plate. Tetrahydrofuran (THF), dichloromethane (DCM), toluene and diethyl ether (Et₂O) were obtained by degassing with argon and passage through activated alumina columns. NMR spectra were recorded on Varian 400-MR or Varian Inova 400 spectrometers. Chemical shifts are reported in δ (ppm downfield from tetramethylsilane) and referenced to TMS or their residual solvent peaks (7.26 ppm or
77.16 ppm for CDCl₃). Coupling constants are reported in Hz with multiplicities denoted as s (singlet), d (doublet), dd (doublet of doublets), dq (doublet of quartets), t (triplet), q (quartet), qd (quartet of doublets), p (pentet), m (multiplet) and br (broad). GC-MS spectra were collected on an Agilent Technologies 7890A gas chromatograph with 5975 VLC MSD triple-axis mass detector using electron impact (EI). High performance liquid chromatography (HPLC) analyses were performed on an Agilent 1100 Series instrument equipped with a quaternary pump, using chiral columns (250 × 4.6 mm, 5 µm), monitored by UV absorption. Optical rotation values were measured on a Jasco Digital Polarimeter using a cell with a path length of 1 dm (c given in g/100 mL)

B. Cyclopropanation

Representative procedure for the cyclopropanation of propenyl pinacol boronic esters (21, racemic 32)

A solution of Et₂Zn (3.4 mL, 33.1 mmol) in 80 mL DCM was cooled to -20 °C in a dry ice/isopropanol cold bath. Trifluoroacetic acid (2.5 mL, 33.1 mmol) was added dropwise by syringe over about 5 minutes. After 10 minutes of stirring, CH₂I₂ (3.33 mL, 33.1 mmol) was also added dropwise by syringe over about 5 minutes. After an additional 10 minutes of stirring, Z-30 (3.01 g, 16.5 mmol) was added via cannula and the cooling bath removed. The reaction warmed up to room temperature and stirred for 3 h, and then was quenched with sat. aqueous NH₄Cl. The aqueous layer was extracted 3x with DCM. The combined organic layers were quickly dried with anhydrous MgSO₄, filtered, and concentrated. The crude pink oil was
purified by column chromatography over silica gel (30:1 pentane/ether, R_f = 0.3) to give racemic 32 (2.96 g, 91%) as a colorless oil.

![racemic 32](image)

^{1}H NMR (400 MHz, CDCl_3) δ 1.20 (s, 12 H), 1.06 (d, 3 H, J = 3 Hz), 1.01 (s, 3 H), 0.99-0.93 (m, 1 H), 0.86 (dd, 1 H + pentane, J = 3.2 Hz, 3.2 Hz), -0.06 (dd, 1 H, J = 8.8 Hz, 2 Hz); ^{13}C NMR (100 MHz, CDCl_3) δ 83.0, 24.9, 24.8, 20.6, 16.1, 14.3, 13.2.

Preparation of optically active 32 by asymmetric cyclopropanation

![reaction scheme](image)

A solution of Z-31 (7.98 g, 29.8 mmol) in 150 mL DCM and (+)-N,N,N',N'-tetramethyl-L-tartaramide (3.04 g, 14.9 mmol) in DCM was stirred for 2 h. In a separate 500 mL round-bottomed flask, a 0.2 M solution of diethyl zinc (9.15 mL, 89.3 mmol) was cooled to -78 °C in a dry/ice acetone cold bath. Diiodomethane (10.8 mL, 133.9 mmol) was added dropwise by syringe over about 5 minutes into the cold Et_2Zn solution. The reaction mixture stirred for 10 min before the Z-31/tartaramide solution was added via cannula, with rinsing with additional DCM. The reaction mixture stirred at -78 °C for 3 h. Sat. aqueous NH_4Cl was poured into the reaction mixture, which was then allowed to warm up to ambient temperature over 1 h. The aqueous phase was extracted 3x with DCM. The combined organic layers were dried with Na_2SO_4, filtered and the majority of solvent removed under reduced pressure. Pinacol (4.22 g, 35.7 mmol) was added to the crude reaction mixture, which stirred overnight under N_2. After concentration, most tartaramide was precipitated out with pentane and removed by filtration.
through a pad of Celite. The filtrate was concentrated and purified by column chromatography over silica gel (30:1 pentane/ether, \( R_f = 0.3 \)), affording 32 (5.52 g, 95%) as a colorless oil.

\[ ^1H \text{NMR (400 MHz, CDCl}_3) \delta 1.20 (s, 12 H), 1.06 (d, 3 H, J = 3 Hz), 1.01 (s, 3 H), 0.99-0.93 (m, 1 H), 0.86 (dd, 1 H, } J = 3.2 Hz, 3.2 Hz), -0.06 (dd, 1 H, } J = 8.8 Hz, 2 Hz); ^{13}C \text{NMR (100 MHz, CDCl}_3) \delta 83.0, 24.9, 24.8, 20.6, 16.1, 14.3, 13.2. \]

C. Homologation

Representative procedure for the homologation of cyclopropyl pinacol boronic esters (21, racemic and enantiopure 33)

A solution of cyclopropyl pinacol boronic ester 32 (2.96 g, 15.1 mmol) in and ICH\(_2\)Cl (4.00 g, 22.7 mmol) in 80 mL of THF in a 200 mL pear-shaped flask was cooled to -78 °C in a dry ice/acetone cold bath. \( n \)-BuLi (2.1 M in hexanes, 8.6 mL) was added by syringe pump over 20 min, dripping down the side of the flask to cool before reaching the THF solution. The mixture stirred at -78 °C for 20 min before warming to room temperature and stirring for an additional 2 h. The reaction was quenched with sat. aqueous NH\(_4\)Cl, and the aqueous phase extracted 3x with diethyl ether. The combined organic layers were dried with anhydrous MgSO\(_4\), filtered and concentrated. The crude oil was purified by flash chromatography over silica gel (30:1 pentane/ether, \( R_f = 0.3 \)), affording 33 (2.70 g, 85%) as colorless oil.
\[ \text{H NMR (400 MHz, CDCl}_3) \delta 1.24 (s, 12 H + pentane), 1.07 (s, 3 H), 0.86 (s, 2 H), 0.30 (t, 2 H, } J = 4.4 \text{ Hz), 0.24 (t, 2 H, } J = 4.2 \text{ Hz); }^{13}\text{C NMR (100 MHz, CDCl}_3) \delta 83.0, 25.0, 24.2, 24.0, 14.0, (C-B resonance missing due to boron broadening).} \]

\[ \text{H NMR (400 MHz, CDCl}_3) \delta 1.24 (s, 12 H), 1.04 (s, 3 H), 1.02 (d, 3 H, } J = 6.4 \text{ Hz), 0.79 (d, 2 H, } J = 9.6 \text{ Hz), 0.61-0.53 (m, 1 H), 0.44 (dd, 1 H, } J = 4 \text{ Hz, 4.4 Hz), -0.16(t, 1 H, } J = 4.8 \text{ Hz); }^{13}\text{C NMR (100 MHz, CDCl}_3) \delta 82.9, 25.0, 24.9, 21.2, 19.9, 18.5, 16.3, 14.3.} \]

**D. Diol exchanges involving oxidation of boronic esters to boronic acids**

Preparation of methylcyclopropylcarbinyl propanediol boronic ester 19

NaIO\(_4\) (15.1 g, 70.2 mmol) was dissolved in 4:1 THF/H\(_2\)O (40 mL THF and 10 mL H\(_2\)O). The solution was poured into a 100 mL round-bottomed flask containing 18 (4.59 g, 23.4 mmol). After 30 min of stirring, HCl (1 M, 15.6 mL) was poured into the mixture, which then stirred overnight under N\(_2\). After 16 h, the reaction was filtered to remove undissolved NaIO\(_4\) and extracted 3x with ether. 1,3-propanediol (1.68 mL, 23.4 mmol) was added to an Erlenmeyer flask containing the combined organic layers. Anhydrous MgSO\(_4\) was added once water drops were visible on the flask walls. After stirring for 1.5 h, the reaction mixture was filtered and concentrated into a 10 mL flask. The oil was degassed in 3 freeze-pump-thaw cycles with liquid
N₂, then vacuum transferred through a distillation apparatus at 15 torr (30 °C water bath), leaving any excess propanediol behind. The product was collected as a colorless oil (2.9 g, 84%).

\[ 1 \text{H NMR (400 MHz, CDCl}_3 \text{)} \delta 4.00 (t, 4 \text{ H, } J = 5.6 \text{ Hz}), 1.94 (p, 2 \text{ H, } J = 5.6 \text{ Hz}), 1.06 (s, 3 \text{ H}), 0.73 (s, 2 \text{ H}), 0.25 (t, 2 \text{ H, } J = 2.4 \text{ Hz}), 0.22 (s, \text{ H, } J = 2.4 \text{ Hz}); \]

\[ 13 \text{C NMR (100 MHz, CDCl}_3 \text{)} \delta 61.7, 27.6, 25.8, 14.0, 12.7. \]

Preparation of Z-31 by oxidation and diol exchange of Z-30

A modified version of Aue et al.'s procedure⁷c was followed for oxidation to the boronic acid. NaIO₄ (5.94 g, 27.7 mmol) and NH₄OAc (3.43 g, 44.4 mmol) were dissolved in a 2.5:1 (26 mL/11 mL) solution of acetone and water. The cloudy mixture was poured into a 50 mL round-bottomed flask containing Z-30 (1.01 g, 5.5 mmol) and then stirred under N₂ for 2 d, or until the pinacol boronate had been consumed, as visualized by TLC (15% EtOAc in hexanes, I₂ stain, Rₜ = 0.8). The acetone was removed by rotary evaporation, and the aqueous material extracted 3x with ether. The combined organic layers were washed 2x with brine to remove any NaIO₄, and then concentrated almost to dryness. The solid boronic acid was quickly redissolved in enough DCM to also dissolve (+)-N,N,N',N'-tetramethyl-L-tartaramide (1.13 g, 5.5 mmol). Anhydrous MgSO₄ and an excess of dry K₂CO₃ were added, and the mixture stirred in the atmosphere for 1 d. The solids were filtered off, and the filtrate concentrated. Any remaining acetic acid should be removed after the boronic acid has completely reacted with the diol by azeotropically
concentrating 5x with toluene and then concentrating *in vacuo* (3 torr) overnight, giving Z-31 as a viscous yellow oil (1.41 g, 95%).

\[
\text{Z-31}
\]

\(^1\text{H NMR} (400 \text{ MHz, CDCl}_3) \delta 6.49 (qd, 1 \text{ H}, J = 2 \text{ Hz, } 4.4 \text{ Hz}), 5.58 (s, 2 \text{ H}), 3.23 (s, 3 \text{ H}), 2.99 (s, 3 \text{ H}), 1.71 (d, 3 \text{ H}, J = 6.4 \text{ Hz}), 1.67 (s, 3 \text{ H}); ^{13}\text{C NMR} (100 \text{ MHz, CDCl}_3) \delta 76.1, 37.3, 37.1, 36.1, 14.5, 13.5.

Preparation of enantiopure and racemic 28

\[
\text{33} \rightarrow \text{1) NH}_4\text{OAc, NaIO}_4 \text{ Acetone/H}_2\text{O, 2d} \rightarrow \text{2) 1,3-propanediol MgSO}_4, \text{Et}_2\text{O, 1d} \rightarrow \text{28}
\]

A modified version of Aue et al. ’s procedure\(^7c\) was followed for oxidation to the boronic acid. NaIO\(_4\) (18.07 g, 84.6 mmol) and NH\(_4\)OAc (10.42 g, 135.3 mmol) were dissolved in a 2.5:1 (48 mL/19 mL) solution of acetone and water. The cloudy mixture was poured into a 100 mL round-bottomed flask containing enantiopure or racemic 33 (3.55 g, 16.9 mmol), and then was stirred in N\(_2\) for 2 d, or until the pinacol boronate had been consumed, as visualized by TLC (15% EtOAc in hexanes, I\(_2\) stain, \(R_f = 0.8\)). The acetone was removed by rotary evaporation, and the aqueous material extracted 3x with ether. The combined organic layers were washed 2x with brine to remove any NaIO\(_4\), and then concentrated to about half the original volume. 1,3-propanediol (1.22 mL, 16.9 mmol), anhydrous MgSO\(_4\) and an excess of dry K\(_2\)CO\(_3\) were added, and the mixture stirred in the atmosphere for 1 d. The solids were filtered off, and the filtrate concentrated into a 15 mL flask. The oil was degassed in 3 freeze-pump-thaw cycles with liquid
N₂, then purified by distillation (58 °C at 3 torr). The product 28 was collected as a colorless oil (2.35 g, 83%).

\[
\begin{align*}
\text{racemic and optically active 28} & \quad ^1H \text{ NMR } (400 \text{ MHz, CDCl}_3) \delta 3.98 \ (t, \ 4 \ H, \ J = 5.6 \text{ Hz}), 1.93 \ (p, \ 2 \ H, \ J = 5.6 \text{ Hz}), 1.02 \ (d, \ 3 \ H, \ J = 2 \text{ Hz}), 1.01 \ (s, \ 3 \ H), 0.68 \ (s, \ 2 \ H), 0.55-0.47 \ (m, \ 1 \ H), \\
& \quad 0.40 \ (dd, \ 1 \ H, \ J = 4 \text{ Hz}, \ 4 \text{ Hz}), -0.20 \ (t, \ 1 \ H, \ J = 3.6 \text{ Hz}); ^{13}C \text{ NMR } (100 \text{ MHz, CDCl}_3) \delta 68.5, 27.6, 21.1, 19.8, 18.6, 16.5, 14.4.
\end{align*}
\]

E. Grignard reactions

Preparation of Z-/E-31 by Grignard reaction

A solution of B(OMe)₃ (0.53 mL, 4.8 mmol) in 50 mL of THF in a 200 mL round-bottomed flask was cooled to -78 °C in a dry ice/acetone bath. 1-methyl-1-propenylmagnesium bromide (10 mL, 0.5 M in THF) was added by syringe pump over 20 minutes. The reaction mixture was allowed to warm back to room temperature and stirred overnight. The mixture was then cooled to 0 °C and quenched with 1 M HCl, and stirred at 0 °C for 30 min. NaOH (3M) was added to the quench until the mixture reached pH 12, and then washed 2x with ether. The aqueous phase was acidified back to pH 2 with 1 M HCl, and extracted 4x with ether. The combined organic layers were concentrated to dryness and redissolved in DCM. (±)-N,N,N’,N’-tetramethyl-L-tartaramide (0.97 g, 4.8 mmol) was added. Anhydrous MgSO₄ was added after 1 h of stirring,
and then the mixture stirred overnight. $^1$H NMR spectroscopy showed a 1:1 mix of $Z$ and $E$ alkene peaks.

$$\text{Z-31}$$

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 6.49 (qd, 1 H, $J = 2$ Hz, 4.4 Hz), 5.58 (s, 2 H), 3.23 (s, 3 H), 2.99 (s, 3 H), 1.71 (d, 3 H, $J = 6.4$ Hz), 1.67 (s, 3 H); $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 76.1, 37.3, 37.1, 36.1, 14.5, 13.5.

$$\text{E-31}$$

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 6.24 (qd, 1 H, $J = 2$ Hz, 4.8 Hz), 5.62 (s, 2 H), 3.24 (s, 3 H), 3.00 (s, 3 H), 1.88 (dq, 3 H, $J = 2$ Hz, 8 Hz), 1.75 (t, 3 H, $J = 2$ Hz).

**F. Homomethallylation and homomethcrotylation**

All reactions were performed using 50 mg of boronates 19 or 28, according to the same procedure as in our previous report. The combined organic layers after extraction were dried with Na$_2$SO$_4$ before concentration. Reactions at 0 °C were cooled in an ice bath before addition of boronate, Lewis acid or aldehyde. Reactions at 40 °C were set up at room temperature in 25 mL sealed tubes before heating to the desired temperature.

*Homomethallylation*
Eluted with 12% EtOAC in hexanes. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 4.72 (s, 2 H), $\delta$ 3.65-3.57 (m, 1 H), 2.16-2.04 (m, 2 H), 1.74 (s, 3 H), 1.65-1.54 (m, 3 H + water), 1.47-1.40 (b, 4 H), 1.35-1.21 (b, 8 H), 0.88 (t, 3 H, $J$ = 7.2 Hz); $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 133.8, 127.1, 110.2, 72.0, 62.1, 37.7, 35.3, 34.2, 29.8, 29.4, 27.6, 25.8, 22.6.

Eluted with 12% EtOAC in hexanes. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 3.88-3.80 (m, 1 H), 1.73-1.57 (m, 3 H), 1.51-1.40 (b, 4 H), 1.37-1.23 (b, 8 H), 1.13-1.02 (m, 3H), 1.08 (s, 3 H), 0.88 (t, 3 H, $J$ = 6.4 Hz), 0.44-0.38 (m, 1 H), 0.35-0.30 (m, 1 H), 0.28-0.21 (m, 2 H); $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 70.6, 46.7, 37.8, 32.0, 29.8, 29.5, 25.8, 22.9, 22.8, 14.3, 13.11, 12.2.

Homomethcrotylation

Eluted with 10% EtOAc in hexanes. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.38-7.24 (m, 5H + CDCl$_3$), 4.80 (d, 2 H, $J$ = 7.8 Hz), 4.67-4.63 (m, 1 H), 2.49 (q, 1 H, $J$ = 7.5 Hz), 1.86 (d, 1 H, $J$ = 3.5 Hz), 1.75 (dd, 2 H, $J$ = 6 Hz, 8 Hz), 1.70 (s, 3 H), 1.06 (d, 3 H, $J$ = 7 Hz); $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 145.3, 128.6, 127.6, 125.9, 125.8, 110.8, 72.6, 44.4, 38.2, 20.3, 18.6.
8 mg, 37% yield after flash column chromatography, eluted with 12% EtOAc in hexanes. >95% ee after benzylation (Daicel Chiralpak OD-H, 100% hexanes, 1 mL/min, 220 nm), tR (major) = 21.6, tR (minor) = 30.5 min.

$^1$H NMR (400 MHz, CDCl$_3$) δ 7.30-7.16 (m, 5 H + CDCl$_3$), δ 4.75 (d, 2 H, $J = 10.4$ Hz), 3.66-3.58 (m, 1 H), 2.83-2.75 (m, 1 H), 2.69-2.61 (m, 1 H), 2.53-2.44 (m, 1 H), 1.78-1.71 (m, 3 H), 1.66 (s, 3 H), 1.60-1.57 (m, 2 H + water), 1.48-1.41 (m, 1 H), 1.03 (d, 3 H, $J = 7.2$ Hz); $^{13}$C NMR (100 MHz, CDCl$_3$) δ 149.5, 142.1, 128.2, 125.6, 110.28, 69.4, 42.1, 39.3, 37.7, 32.0, 20.2, 18.2; $[\alpha]_D^{20} = +2.7$ (c 0.22, DCM).

Eluted with 6% EtOAc in hexanes.$^1$H NMR (400 MHz, CDCl$_3$): δ 4.88 (d, 2 H, $J = 5.4$ Hz), 3.46 (d, 2 H, $J = 10.4$ Hz), 1.75 (s, 3 H), 1.68-1.57 (m, 2 H), 1.51-1.39 (m, 2 H), 1.36-1.21 (br s, 8 H), 1.04 (s, 3 H), 1.00 (s, 3 H); 0.88 (t, 3 H, $J = 6.8$ Hz + hexanes) $^{13}$C NMR (100 MHz, CDCl$_3$) δ 151.3, 112.1, 75.7, 43.9, 32.0, 31.7, 29.3, 29.5, 27.6, 22.8, 22.7, 21.8, 19.9, 14.3.

**G. Known compounds**

The following are known compounds and were characterized by comparison to spectra reported in literature.
23a. Eluted with 6% EtOAc in hexanes.\textsuperscript{7g}

23b. Eluted with 12% EtOAc in hexanes.\textsuperscript{7h}

24b. Eluted with 12% EtOAc in hexanes.\textsuperscript{5d}

anti-25. Eluted with 12% EtOAc in hexanes.\textsuperscript{7i}

syn-25. Eluted with 12% EtOAc in hexanes. Isolated as a 1:1 mixture with an unknown alkene.\textsuperscript{7i}

35a. Eluted with 10% EtOAc in hexanes.\textsuperscript{7j}
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I. HPLC Chromatograms

![HPLC Chromatogram](image)

36b was prepared by benzoylation of 34b.
References


(8) Due to quadrupole broadening, the NMR signal for carbon directly attached to boron is often too weak to be observed. See: Wrackmeyer, B. *Prog. Nucl. Magn. Reson. Spectrosc.* **1979**, *12*, 227-259.