ACTIVATION OF GEM-DIBORYLALKANES AND ALKENES TO EMCOPASS SELECTIVE C-C BOND FORMING REACTIONS

Oriol Salvadó Ruiz

UNIVERSITAT ROVIRA i VIRGILI

Activation of *gem*-diborylalkanes and alkenes to encompass selective C-C bond forming reactions

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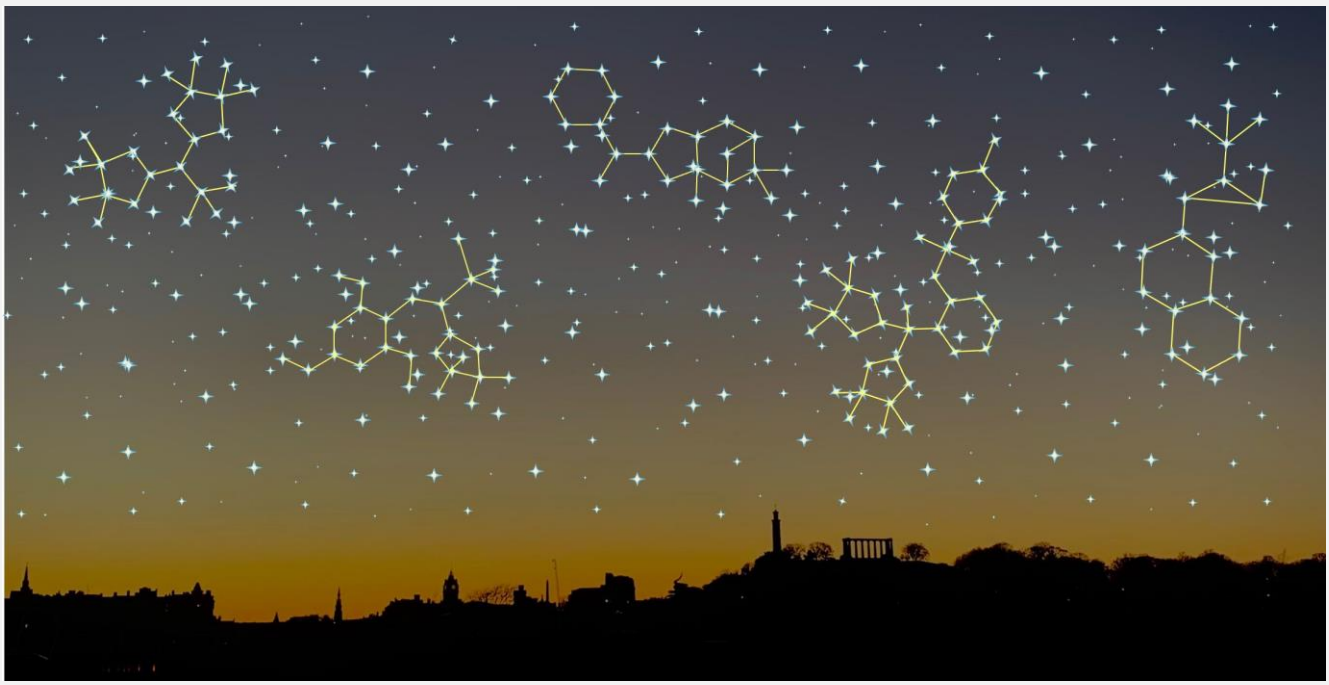

DOCTORAL THESIS

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Activation of *gem*-diborylalkanes and alkenes to encompass selective C-C bond forming reactions

PhD Thesis

Supervised by Prof. María Elena Fernández Gutiérrez

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DEPARTAMENT DE QUÍMICA
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Prof. María Elena Fernández Gutiérrez, professora catedràtica del Departament de Química Física i Inorgànica de la Universitat Rovira i Virgili,

FAIG CONSTAR que aquest treball, titulat:

"**Activation of *gem*-diborylalkanes and alkenes to encompass selective C-C bond forming reactions**"

que presenta Oriol Salvadó Ruiz per a l'obtenció del títol de Doctor, i que acompleix els requeriments per a poder optar a Menció Internacional, ha estat realitzat sota la meva direcció al Departament de Química Física i Inorgànica de la Universitat Rovira i Virgili.

Tarragona, 31 de gener de 2023

La directora de la tesi doctoral

Prof. María Elena Fernández Gutiérrez

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Agraïments

Estem al gener de 2023, miro enrere i em transporto a l'octubre de 2019. Veig aquell Oriol de 23 anys que decidia començar una aventura com la que suposa fer un doctorat en química. Un Oriol que tot just acabava un màster i que estava ple d'inseguretats i amb una gran incertesa de si estava donant el pas correcte en la seva vida. Tornant al present, puc assegurar que vaig prendre la millor decisió possible. Aquest temps ha estat una muntanya russa d'emocions i sentiments, un llarg viatge que va ser interromput per una pandèmia quan tan sols feia 5 mesos que havia començat, però també que m'ha fet créixer tant professional com personalment. I si una cosa tinc clara, és que no hauria sigut possible sense tots vosaltres.

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moment, per complicat que sembli té una solució i per tant, un costat positiu, només fa falta trobar-la.

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Gràcies a tots i totes!

"El sabio puede cambiar de opinión, el necio nunca"

Immanuel Kant

CONTENTS

Abbreviations list

12-crown-6	1,4,7,10-tetraoxacyclododecane
18-crown-6	1,4,7,10,13,16-hexaoxacyclooctadecane
acac	Acetylacetonate
AcOH	Acetic acid
b	Broad
Bhex	Hexylene glycolato boryl
Bpin	Pinacolato boryl
bpy	2,2′-bipyridine
CPME	Cyclopentyl methyl ether
d	Doublet
DCE	1,2-dichloroethane
DCM	Dichloromethane
DMAc	Dimethylacetamide
DMAE	*N*,*N*-dimethylaminoethanol
DME	1,2-dimethoxyethane
DMSO	Dimethyl sulfoxide
DPPB	1,4-(bis(diphenylphosphino)butane
dppf	1,1′-Ferrocenediyl-bis(diphenylphosphine)
dtbpy	4,4’-di-tert-butyl-2,2’-bipyridine

EDG	Electron donating group
equiv	Equivalents
Et_2O	Diethyl ether
EWG	Electron withdrawing group
hfacac	Hexafluoroacetylacetonate
KHMDS	Potassium bis(trimethylsilyl)amide
LDA	Lithium diisopropylamide
LiTMP	Lithium 2,2,6,6-tetramethylpiperidide
m	Multiplet
MeCN	Acetonitrile
MeOH	Methanol
MTBE	Methyl *tert*-butyl ether
MTBE	Methyl *tert*-butyl ether
MW	Microwaves
NBS	*N*-bromosuccinimide
NMM	*N*-methylmorpholine
Nu	Nucleoplile
PG	Protecting group
$PhCF_3$	Trifluorotoluene
Phth	Phthalimide

PMDTA	Pentamethyldiethylentriamine
q	Quartet
Ref	Reference
R_L	Large group
R_S	Small group
rt	Room temperature
s	Singlet
t	Triplet
TBAF	Tetra-*n*-butylammonium fluoride
TBDMS	*tert*-butyldimethyllsilyl
THF	Tetrahydrofuran
TMEDA	*N,N,N',N'*-Tetramethylethylenediamine
TMSDM	(trimethylsilyl)diazomethane
Tr	Trityl group (Triphenylmethyl)
Ts	Tosyl group (*p*-toluenesulfonyl)

CHAPTER 1

General introduction

1.1. Definition of *gem*-diboryl compounds

Organoboron compounds are useful building blocks in the organic synthetic field due to their low toxicity and their good functional group tolerance.[1] Especially, *gem*-diboron compounds have recently drawn the attention of the scientific community due to their emergence as a new type of bifunctional reagents for selective activation through deborylation or deprotonation and subsequent C-C bond formation.[2–4] In light of the increasing relevance of *gem*-diboron compounds, several synthetic approaches have been explored to facilitate their synthesis. In this context, *gem*-diboron compounds can be defined as bifunctional species containing two boryl moieties in *geminal* position and can be classified in two main groups: *gem*-diborylalkanes and *gem*-diborylalkenes (Figure 1.1).

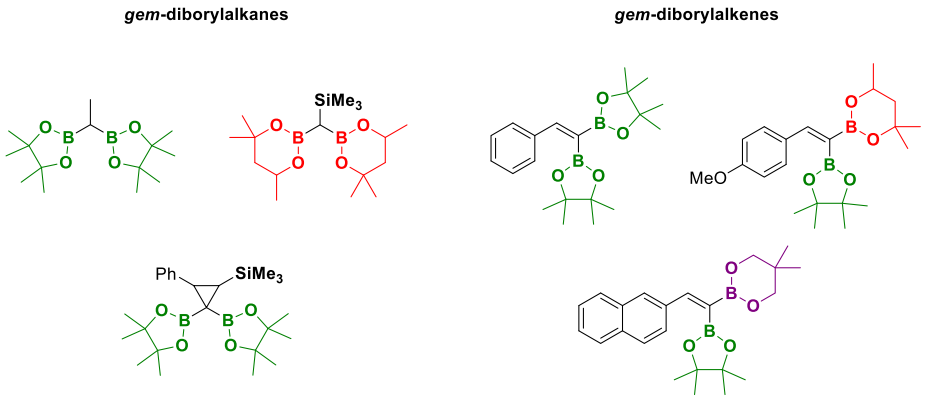


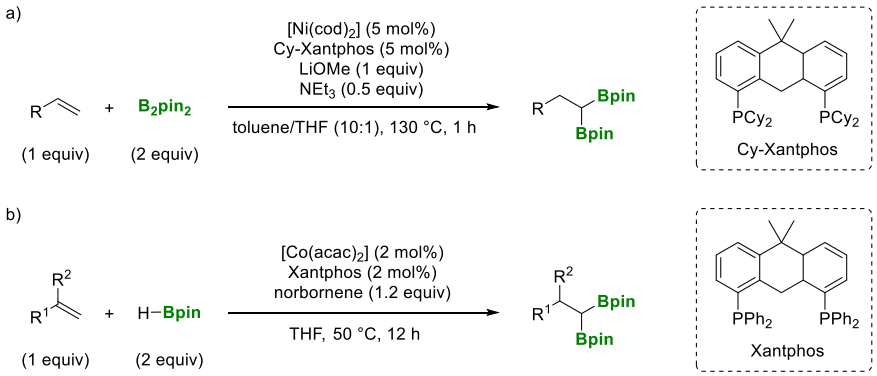
Figure 1.1 Representative examples of *gem*-diborylalkanes (left) and *gem*-diborylalkenes (right) with different boryl moieties.

This chapter describes the most relevant synthetic strategies to prepare *gem*-diborylalkanes and *gem*-diborylalkenes, as well as the most interesting stepwise functionalisation of the two boryl moieties.

1.2. Synthesis of *gem*-diborylalkanes

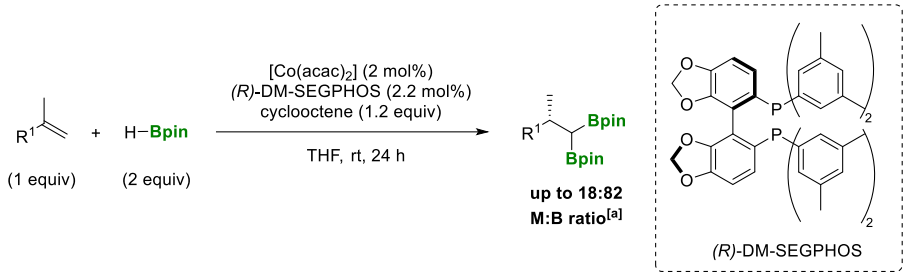
1.2.1. 1,1-Diborylation of alkenes

Diborylation of alkenes have been widely studied in the recent last years.[1] In this context, Fu and co-workers developed a nickel-catalysed 1,1-diborylation of terminal alkenes achieving good chemo- and regioselectivity.[5] The reaction proceeds with [Ni(cod)$_2$] and 4,5-bis(dicyclohexylphosphino)-9,9'-dimethylxanthene (Cy-Xantphos) as catalytic system and the presence of 2 equiv of bis(pinacolato)diboron (B_2pin_2), 1 equiv of LiOMe and 0.5 equiv of NEt_3 (Scheme 1.1a). The reaction is suitable for terminal alkenes such as styrenes or aliphatic alkenes, but has the limitation of sterically bulkier substrates, which are unreactive under these conditions. However, Ge and co-workers reported a cobalt-catalysed diborylation of 1,1-disubstituted alkenes to furnish a wide range of tetrasubstituted *gem*-diborylalkanes.[6] To conduct the former reactivity it was necessary the use of [Co(acac)]/Xantphos as catalylic system, as well as 1 equiv of norbornene, as hydrogen acceptor, and 2 equiv of pinacolborane (HBpin) as boron source (Scheme 1.1b).



Scheme 1.1 Synthestic approaches to *gem*-diborylalkanes through a) Ni-catalysed diborylation and b) Co-catalysed diborylation of terminal alkenes.

Additionally, the same authors studied the formation of enantioenriched 1,1-diborylkanes through a Co-catalysed 1,1-diborylation of terminal alkenes in the presence of chiral ligands. The reaction proceeds using [$Co(acac)_2$] and (*R*)-4,4'-bi-1,3-benzodioxole-5,5'-diylbis[bis(3,5-dimethylphenyl)phosphine] ((*R*)-DM-SEGPHOS), as catalytic system, and HBpin as borylating agent. In that case, cyclooctene was used as hydrogen acceptor[7] Nevertheless, the procedure shows a limitation since the monoborylalkane compounds are also observed as side products (Scheme 1.2).

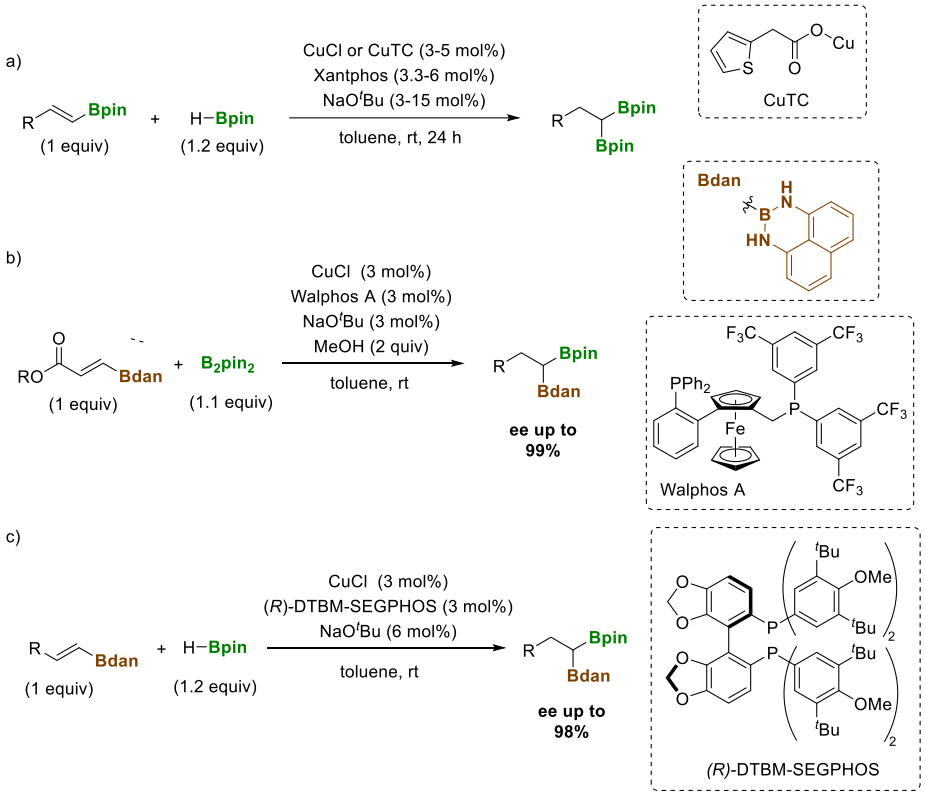


Scheme 1.2 Cobalt-catalysed enantioselective diborylation of 2-substituted propenes. [a] M:B ratio refers to monoboryl:bis(boryl) products ratio.

1.2.2. Borylation of alkenylboronates

Alkenylboronates have also been used as substrates to prepare *gem*-diborylalkanes. In this scenario, Yun and co-workers described the hydroboration of alkenylboronate compounds with HBpin in the presence of a catalytic system formed with copper(I) chloride (CuCl) or copper(I) thiophene-2-carboxylate (CuTC), Xantphos and NaO^{t}Bu (Scheme 1.3a).[8] Similarly, Hall and co-workers studied the viability of a copper-catalysed asymmetric conjugate borylation of β-boryl acrylates with B_2pin_2. The optimal catalytic conditions to prepare the enantioenriched 1,1-diborylalkanes are based on CuCl (3 mol%), Walphos-type ligand A (3 mol%), NaO^{t}Bu (3 mol%) and methanol (2 equiv) (Scheme 1.3b).[9] Additionally, Yun and co-workers developed a general and efficient method to prepare enantioenriched *gem*-diborylalkanes

through asymmetric hydroboration of alkenylboronates with HBpin using CuCl (3 mol%), (*R*)-DTMB-SEGPHOS (3 mol%) and NaO^{t}Bu (6 mol%), in toluene at room temperature (Scheme 1.3c).[10]

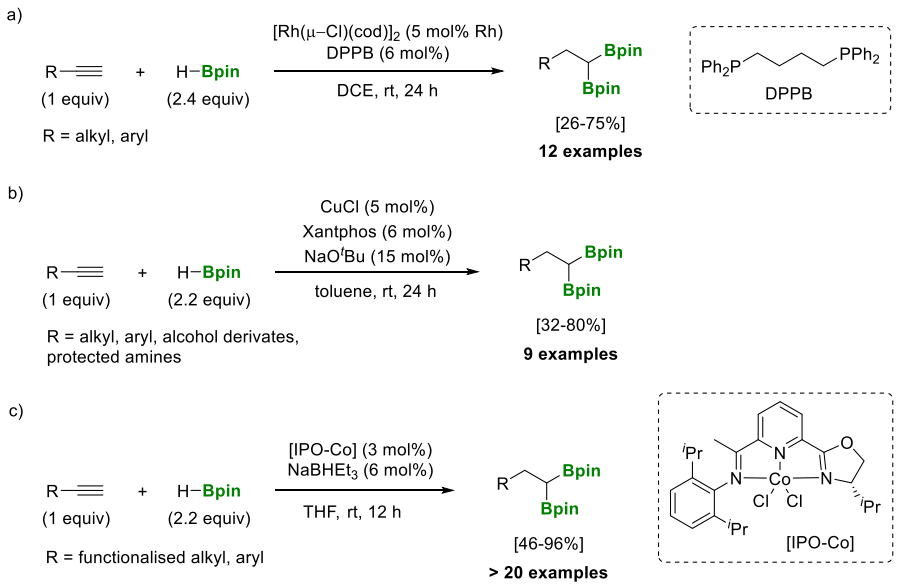


Scheme 1.3 a) Cu-catalysed hydroboration of alkenylboronates with HBpin, b) asymmetric Cu-catalysed hydroboration of β-boryl acrylates with B_2pin_2 and c) asymmetric Cu-catalysed hydroboration of alkenylboronates with HBpin.

1.2.3. Borylation of alkynes

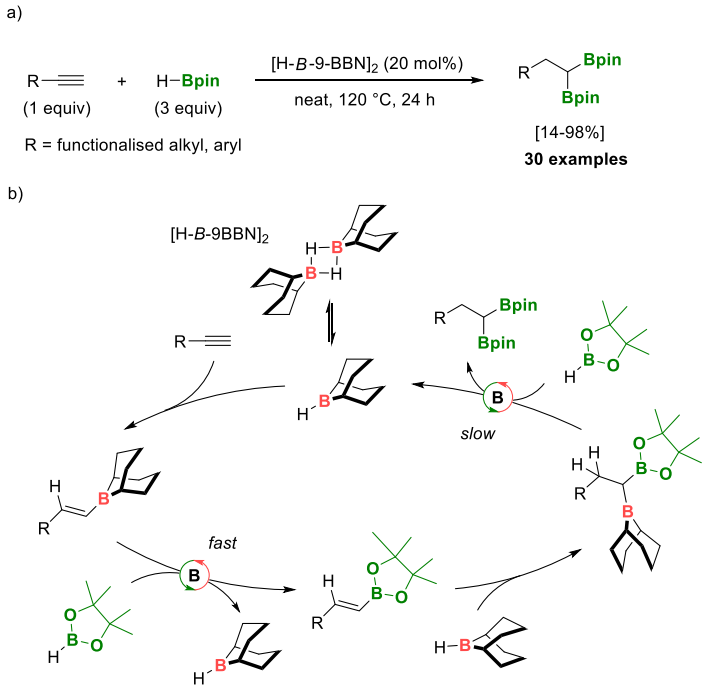
Sequential double hydroboration of terminal alkynes is one of the most feasible methodologies to prepare *gem*-diborylalkanes. Shibata and co-workers developed a sequential regioselective hydroboration of terminal alkynes to afford 1,1-diborylalkanes. [11] The reaction is carried out using pinacolborane (HBpin) in the presence of the catalyst chloro(cycloocta-1,5-diene)rhodium(I)

dimer (5 mol% Rh) and 1,4-(bis(diphenylphosphino)butane (DPPB, 6 mol%) as ligand (Scheme 1.4a). Additionally, a copper-catalysed double hydroboration of terminal alkynes with HBpin was reported by Yun and co-workers. The reaction allows the use of terminal alkynes containing various functional groups, such as protected propargyl amines, propargyl alcohol derivates and aliphatic or aromatic alkynes. The catalytic process is conducted using CuCl (5 mol%), Xantphos (6 mol%) and NaO^{t}Bu (15 mol%), in toluene at room temperature (Scheme 1.4b).[8] Analogously, Huang and co-workers focused on the synthesis of *gem*-diborylalkanes *via* cobalt-catalysed double hydrogenation of terminal alkynes.[12] This reactivity requires the use of 3 mol% of an iminopyridine-oxazoline cobalt complex (IPO-Co), as well as 6 mol % of $NaBHEt_3$, as catalyst activator and 2 equiv of HBpin (Scheme 1.4c). Different functional groups, such as, arenes (containing electron-donating and electron-withdrawing groups), chlorides, amides, ethers, esters and diphenylamines are tolerated.



Scheme 1.4 Regioselective double hydroboration of terminal alkynes with a) Rh complexes, b) Cu salt and c) Co complexes. Isolated yields in brackets.

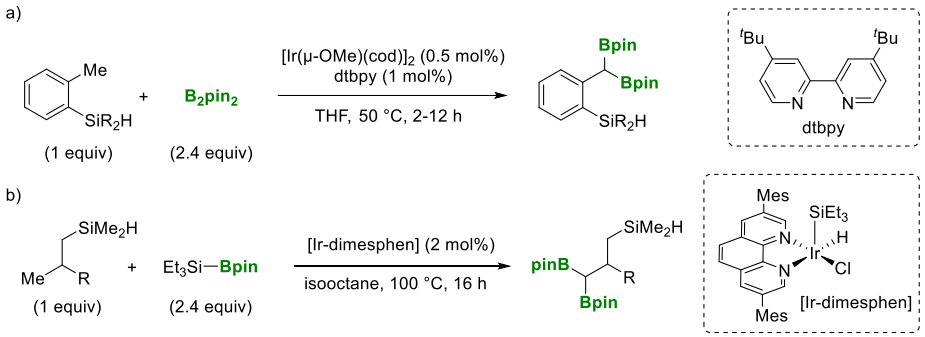
Alternatively, Thomas and co-workers studied a transition-metal-free double hydroboration of terminal alkynes.[13] The reaction is conducted using 9-borabicyclo[3.3.1]nonane (H-*B*-9-BBN), as catalytic agent, for the sequential double hydroboration of alkynes, in the presence of an excess of pinacolborane (Scheme 1.5a). This strategy is promoted by the C-B/B-H transborylation pathways, that occurs after each hydroboration step, which allows the free H-*B*-9-BBN to continue with the hydroboration reactions (Scheme 1.5b). This procedure shows to be efficient for functionalised alkyl and aryl groups, as well as chlorides, amines, ethers and esters among others groups.



Scheme 1.5 Transition-metal-free double hydroboration of terminal alkynes, with H-*B*-9-BBN, as catalyst, and HBpin, through a double transborylation, a) reaction scheme and b) proposed catalytic cycle.

1.2.4. Borylation of benzylic C-H bonds

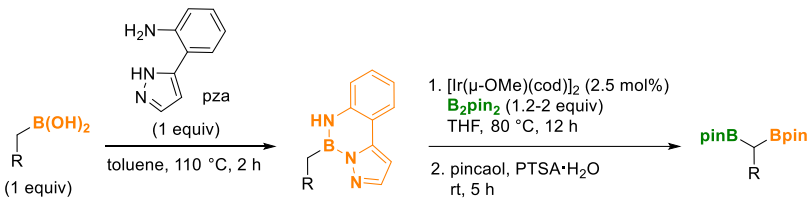
Transition-metal-catalysed C-H bond borylation has been studied during the last decades.[14–17] In the context of the synthesis of *gem*-diborylalkanes, Hartwig and co-workers developed a methodology to afford the former compounds through a regioselective diborylation of primary benzylic C-H bonds. This reaction is catalysed by $[Ir(\mu\text{-}OMe)(cod)]_2$ (0.5 mol%) and 4,4-di-tert-butyl-2,20-bipyridine (dtbpy) (1 mol%), in the presence of 2 equiv of B_2pin_2. In this particular case, a hydrosilane group on the *ortho* position of the aryl group is needed as potencial directing group (Scheme 1.6a).[18] The same group developed an alternative silyl-directed borylation in non-benzylic C-H bonds of alkyl(dimethyl)silanes. The reaction is conducted with 2 mol% of an iridium(III)-phenanthroline type complex ([Ir-dimesphen]) and 2 equiv of triethyl(pinacolboryl)silane (Et_3Si-Bpin), in isooctane at 100 °C, to afford to corresponding *gem*-diborylalkane (Scheme 1.6b).[19]



Scheme 1.6 Hydrosilane-directed Ir-catalysed C-H bond borylation of a) benzylic C-H bonds and b) alkylic C-H bonds.

Similarly, Suginome and co-workers established a boryl-directed iridium-catalysed C(sp^3)-H borylation of alkylboronic acids to prepare polyborylalkanes, including *gem*-diborylalkanes. This methodology uses a pyrazolaniline (pza), as a temporary directing group attached to the boron atom

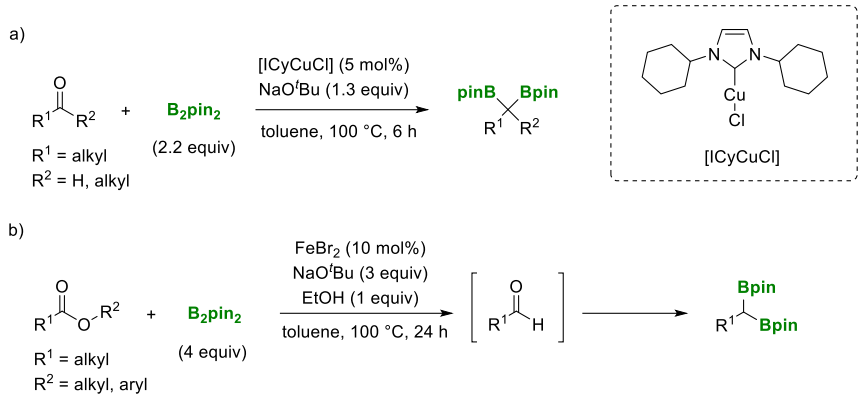
of alkylboronic acids and $[Ir(\mu\text{-OMe})(cod)]_2$ as catalyst, being B_2pin_2 the borylating agent. Further treatment with pinacol and *p*-toluensulfonic acid monohydratated ($PTSA{\cdot}H_2O$) seems to be required to remove the pyrazolaniline moiety in order to obtain the *gem*-bis(pinacolboryl)alkanes (Scheme 1.7).[20] The reaction does not proceed towards the C-H borylation with alkyl pinacolboronates. Nevertheless, if the alkylboronic acid has a $C(sp^3)$-H bond at either the β- or γ-position, multiple polyborated products are obtained.



Scheme 1.7 Boryl-directed Ir-catalysed C-H bond borylation of alkylboronic acids using a pyrazolaniline (pza) fragment as temporary directing group.

1.2.5. Diborylation of carbonylic compounds

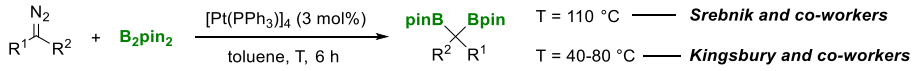
A copper-catalysed deoxygenative *gem*-diborylation of aldehydes and ketones was described by Liu and co-workers. The reaction undergoes a copper-catalysed borylation of aldehydes and ketones followed by a base-promoted C-OBpin borylation. The optimised reaction conditions are based on 5 mol% of an N-heterocyclic carbene-copper complex ([ICyCuCl]), 2.2 equiv of B_2pin_2 and 1.3 equiv of NaO^tBu (Scheme 1.8a).[21] Additionally, the same group reported a synthetic strategy to afford *gem*-diborylalkanes from carboxylic esters through an iron-catalysed sequential hydrogenation of the ester followed by a diborylation of the generated aldehyde intermediate. The reaction undergoes towards the formation of *gem*-diborylalkanes using catalytic $FeBr_2$ (10 mol%), B_2pin_2 (4 equiv), NaO^tBu (3 equiv) and EtOH (1 equiv) (Scheme 1.8b).[22]



Scheme 1.8 a) Cu-catalysed deoxygenative diborylation of aldehydes and ketones, and b) Fe-catalysed hydrogenation/diborylation of carboxylic esters.

1.2.6. Carbene insertion into diboron compounds

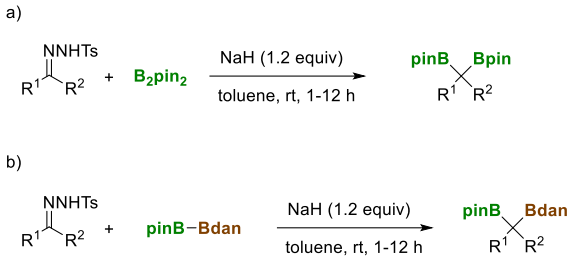
The synthesis of *gem*-diborylalkanes through carbene insertion into diboron compounds has been widely explored in the recent years, focusing on the use of diazo compounds as carbene precursors.[23–27] In this context, Srebnik and co-workers developed a platinum-catalysed carbene insertion into B_2pin_2, using $[Pt(PPh_3)_4]$ as catalyst, to prepare few examples of *gem*-diborylalkanes (Scheme 1.9).[23] Subsequently, Kingsbury and co-workers studied the same methodology in order to improve the scope of diazo compounds, as well as lowering the reaction temperature (Scheme 1.9).[24]



Scheme 1.9 Pt-catalysed diborylation of diazo compounds *via* carbene insertion into bis(pinacolato)diboron.

Alternatively, Wang and co-workers established a transition-metal-free cross-coupling reaction between *N*-tosylhydrazones, as diazo compound precursors,

and B_2pin_2. This methodology uses *N*-tosylhydrazones, that are generated from the corresponding aldehydes and cyclic ketones, B_2pin_2 (1.2 equiv) and a base (1.2 equiv).[25,26] The use of sodium hydride (NaH), as base, is fundamental for this reaction because it allows the hydrogen release when the proton is abstracted from the *N*-tosylhydrazone, avoiding a protodeboronation step of the generated *gem*-diborylalkanes (Scheme 1.10a). Similarly, Cuenca, Fernández, Carbó and co-workers studied the viability of using unsymmetrical diboron reagents, as pinB-Bdan, to synthesise the corresponding non-symmetrical *gem*-diborylalkanes. (Scheme 1.10b).[27]



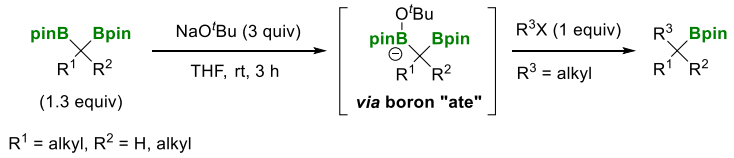
Scheme 1.10 Transition-metal-free diborylation of *N*-tosylhydrazones with a) symmetrical B_2pin_2 and b) unsymmetrical pinB-Bdan.

1.3. Applications of *gem*-diborylalkanes

Several applications of *gem*-diborylalkanes have been deeply studied, allowing multiple strategies to generate new C-C bonds. The most representative activations and reactivities of *gem*-diborylalkanes are shown in this section.

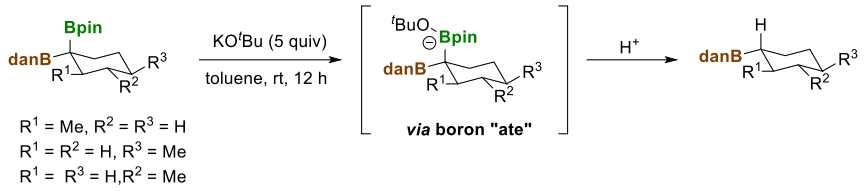
1.3.1. Deborylation with alkoxy bases

Reactivity of α-boryl carbanion, obtained *via* deborylation of *gem*-diborylalkanes with alkoxy bases, was studied by Morken and co-workers.[28] The use of an excess of NaO^{t}Bu (3 equiv) with 1,1-bis(pinacolboryl)alkanes generates a boron "ate" intermediate that can proceed through a nucleophilic substitution with alkyl halides enabling the new C-C bond formation (Scheme 1.11).



Scheme 1.11 Cross-coupling reaction between *gem*-diborylalkanes and alkyl halides *via* boron "ate" intermediate.

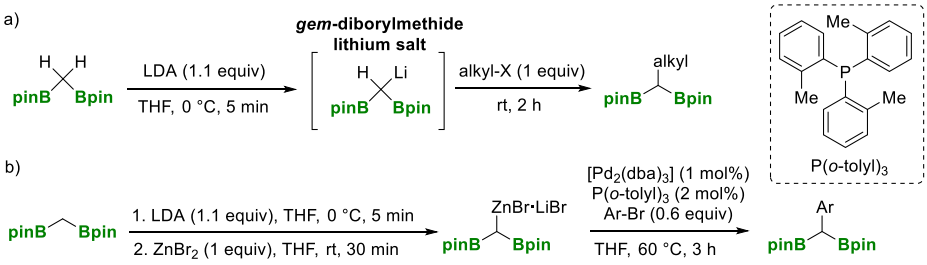
In the case of unsymmetrical *gem*-diborylalkanes, Cuenca, Fernández, Carbó and co-workers studied the selective activation of the boron moieties with alkoxy bases. Focusing on the case of *gem*-diborylalkanes with Bpin/Bdan moieties, taking $(CH_3)(H)C(Bpin)(Bdan)$ as example, the formation of the boron "ate" intermediate depends on the Lewis acidity of the boryl groups. The addition of 5 equiv of KO^{t}Bu to 1-Bpin-1-Bdan-diborylalkanes promotes the protodeboronation of the Bpin moiety, due to the higher stabilisation of the generated negative charge, with the remaining Bdan moiety (Scheme 1.12).[27]



Scheme 1.12 Alkoxy-assisted protodeboronation of unsymmetrical *gem*-diborylalkanes containing Bpin/Bdan moieties *via* boron "ate" intermediate.

1.3.2. Reactivity of α,α-diborylcarbanions

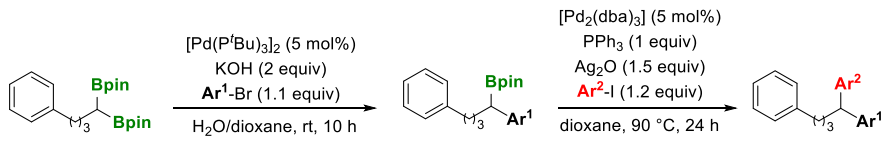
Gem-diborylalkanes can also be activated through a deprotonation pathway in the presence of organolithium bases such as lithium 2,2,6,6-tetramethylpiperidide (LiTMP) or lithium diisopropylamide (LDA) to generate an α,α-diborylcarbanion. Fu and co-workers used this strategy to functionalise the simplest bis(pinacolboryl)methane in the presence of 1.1 equiv of LDA and alkyl halides to afford alkyl-substituted *gem*-diborylalkanes (Scheme 1.13a).[29] Alternatively, Cho and co-workers studied the formation of (diborylmethyl)zinc(II), from *gem*-diborylmethide lithium salt, to conduct a palladium-catalysed Negishi cross-coupling with aryl halides using [$Pd_2(dba)_3$] (1 mol%) and tri(2-tolyl)phosphine (2 mol%) as catalytic system. The former methodology allows the formation of aryl-substituted *gem*-diborylalkanes (Scheme 1.13b).[30]



Scheme 1.13 a) Deprotonation of bis(pinacolboryl)methane with LDA and subsequent coupling with alkyl halides and b) Pd-catalysed coupling with bis(pinacolboryl)methylzinc bromide.

1.3.3. Selective deborylative cross-coupling reaction

Stepwise cross-coupling reactions with *gem*-diborylalkanes to functionalise the two boryl moieties selectively has been explored in the last decades. Wang and co-workers, and more recently Huang and co-workers, studied the chemoselective monoarylation and stepwise diarylation of *gem*-diborylalkanes using different palladium complexes.[25] The *gem*-diborylalkane, containing a phenylpropyl group, undergoes the first cross coupling reaction using [Pd(P^tBu_3)$_2$] (5 mol%), as catalytic system and KOH, as base, in H_2O/dioxane as solvent mixture. These reaction conditions were previously described by Shibata and co-workers, highlighting that the reaction proceeds at room temperature.[11] Even diverse aryl bromides are successfully used as coupling partners, which includes O- and S-containing heterocyclics bromides (Scheme 1.14). The use of *p*-CF_3-substituted aryl bromide and 4-bromo-2-methylpyridine proceed towards the formation of cross-coupling products with protodeboronation of the remaining boryl moiety. The second cross-coupling reaction is conducted in the presence of catalytic [$Pd_2(dba)_3$] and PPh_3, and 1.5 equiv of Ag_2O to afford the formation of 1,1-diarylated products (Scheme 1.14).

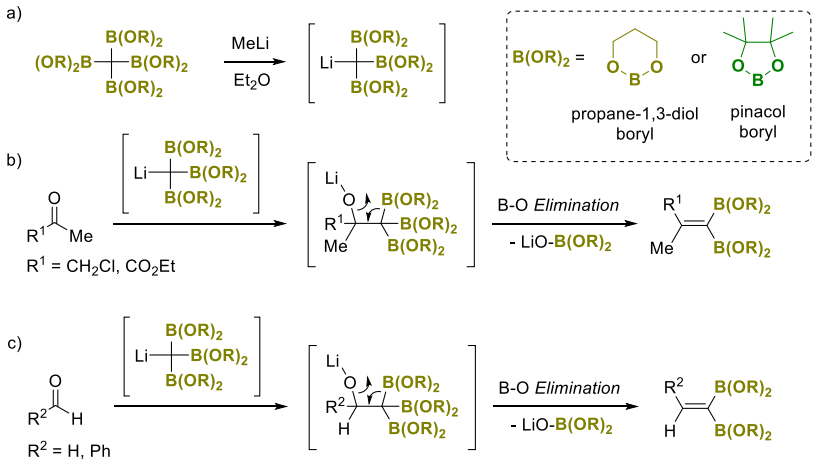


Scheme 1.14 Pd-catalysed stepwise functionalisation of *gem*-diborylalkanes to afford 1,1-diarylated products.

1.4. Synthesis of *gem*-diborylalkenes

1.4.1. Condensation of α,α,α-triborylcarbanion with aldehydes and ketones

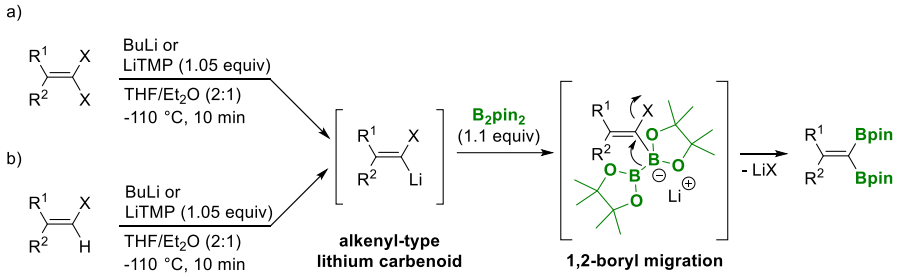
Matteson firstly described the generation of triborylmethide lithium salts, from tretraborylmethane in the presence of methyllithium (MeLi) (Scheme 1.15a), and its reactivity with aldehydes and ketones towards the formation of *gem*-diborylalkenes *via* B-O elimination.[31] The reactivity was studied using either propane-1,3-diol and pinacol boryl moieties. The use of ketones as coupling partners tolerates functional groups such as, α-chloroalkyls and esters (Scheme 1.15b). Benzaldehyde and formaldehyde also undergo the condensation reaction, towards trisubstituted *gem*-diborylalkenes. (Scheme 1.15c).



Scheme 1.15 a) Generation of triborylmethide lithium salts and its condensation with b) ketones and c) aldehydes towards the formation of *gem*-diborylalkenes.

1.4.2. Diborylation of 1,1-dihalo and 1-haloalkenes

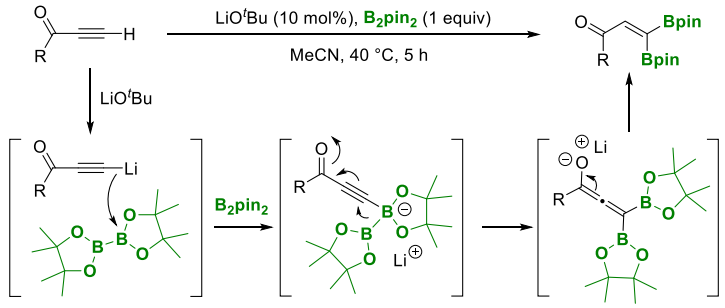
Hiyama and co-workers developed a synthetic strategy to afford *gem*-diborylalkenes from 1,1-dihaloalkenes. The reaction proceeds through aklylidene-type lithium carbenoid intermediates that can be formed from 1,1-dihaloalkenes in the presence of BuLi or LiTMP (1.05 equiv). Subsequent addition of B_2pin_2 (1.1 equiv) to the generated lithium carbenoid resulted in the formation of the corresponding *gem*-diborylalkenes (Scheme 1.16a).[32,33] Additionally, in the same group it was reported the *gem*-diborylation of 1-haloalkenes following a similar strategy through lithium carbenoid species (Scheme 1.16b).[32,33]



Scheme 1.16 Geminal diborylation of a) 1,1-dihaloalkenes and b) 1-haloalkenes, through alkenyl-type lithium carbenoid intermediates and subsequent 1,2-boryl migration.

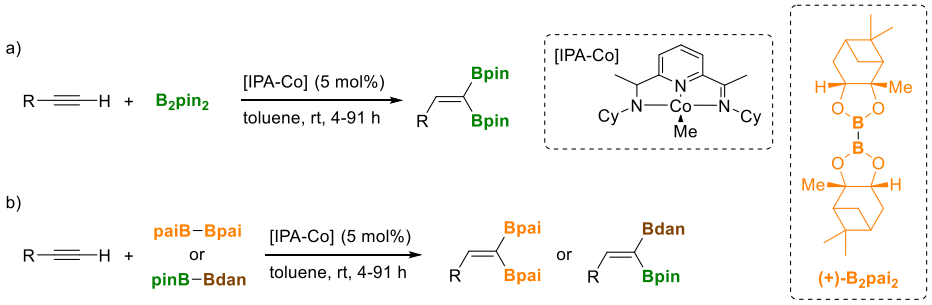
1.4.3. Diborylation of terminal alkynes

Sawamura and co-workers studied the *gem*-diborylation of terminal alkynes with B_2pin_2. The reaction proceeds with propargyl esters, amides and imidazole-type compounds in the presence of LiO^tBu (10 mol%) and B_2pin_2 (1 equiv) suggesting the formation of 1,1-diboryallenes which isomerise to afford the final *gem*-diborylalkene (Scheme 1.17).[34]



Scheme 1.17 Transition-metal-free diborylation of terminal alkynes in the presence of catalytic LiO^{t}Bu to afford *gem*-diborylalkenes.

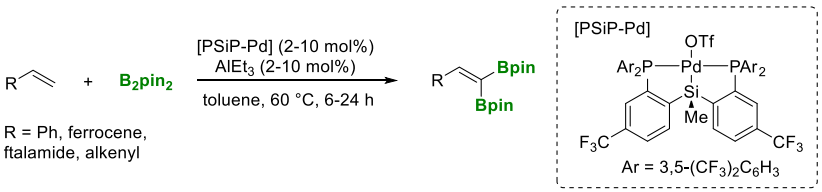
Additionally, Chirik and co-workers established a cobalt-catalysed diborylation of terminal alkynes with B_2pin_2. The optimised conditions involve 5 mol% of an iminopyridineamine-cobalt complex ([IPA-Co]) and 1 equiv of B_2pin_2. Functional group tolerance of the reaction includes the use of different motifs such as *tert*-buthyldimethylsilyl ether (TBDMS), acetal, ester, phthalimide, nitrile and secondary amide, as well as terminal double bond, which is unreactive under the reaction conditions (Scheme 1.18a). The reaction can be also conducted with bis[(+)-pinanediolato]diboron and pinB-Bdan as diboron reagents, obtaining the corresponding *gem*-diborylalkenes (Scheme 1.18b).[35]



Scheme 1.18 Co-catalysed 1,1-diborylation of terminal alkynes with a) B_2pin_2 and b) (+)-B_2pai_2 or pinB-Bdan.

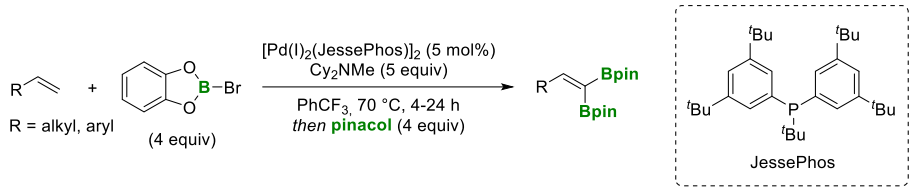
1.4.4. Dehydrogenative borylation of alkenes

A palladium-catalysed double dehydrogenative borylation was explored by Iwasawa and co-workers. The reaction of alkenes with B_2pin_2, in the presence of a catalytic palladium complex with a PSiP-pincer-type ligand ([PSiP-Pd]) and $AlEt_3$ (5 mol%), proceeds towards the formation of 1,1- and 1,2-diborylalkenes. The use of terminal alkenes bearing electronically activated bulky groups and 2 equiv of bis(pinacolato)diboron leads to the obtention of *gem*-diborylalkenes (Scheme 1.19).[36,37]



Scheme 1.19 Pd-catalysed double dehydrogenative borylation of terminal alkenes bearing electronically activated bulky substituents.

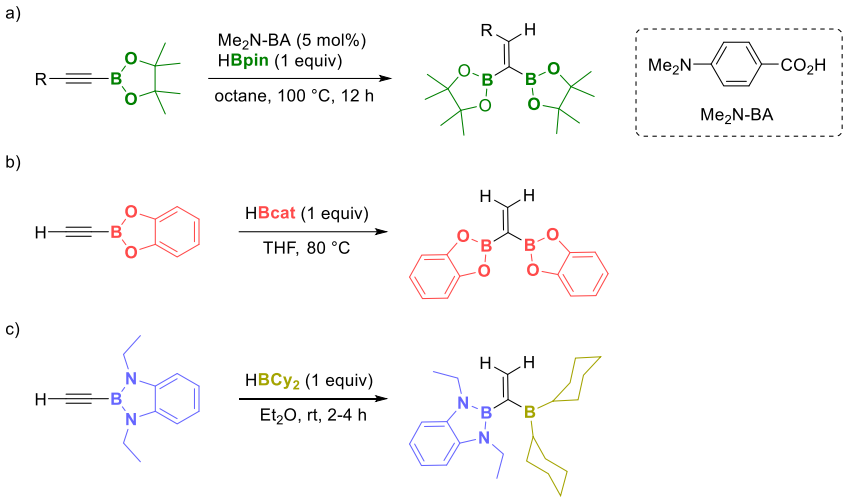
Alternatively, Watson and co-workers explored the synthesis of 1,1-diborylalkenes through a palladium-catalysed boryl-Heck reaction of terminal alkenes. The reported reaction is capable of using aliphatic alkenes containing a variety of functional groups, such as halides, alkylsilanes, ethers and silyl ethers. Similarly, aromatic alkenes with electron donating or electron withdrawing groups undergo boryl-Heck reaction to furnish the corresponding *gem*-diborylalkenes. The optimised reaction conditions involve $[Pd(I)_2(JessePhos)]_2$ as catalyst (5 mol%), 4 equiv of *B*-bromocatecholborane (catBBr) and 5 equiv of *N*,*N*-dicyclohexyl-methylamine (Cy_2NMe), in trifluorotoluene ($PhCF_3$). Further treatment of the reaction mixture with 4 equiv of pinacol is necessary to generate the two Bpin moieties of the afforded *gem*-diborylalkenes (Scheme 1.20).[38]



Scheme 1.20 Pd-catalysed boryl-Heck reaction of aromatic and aliphatic terminal alkenes to generate *gem*-diborylalkenes.

1.4.5. Hydroboration of alkynylboronates

Jin and co-workers studied the carboxylic acid-catalysed hydroboration of alkynylboronates in the presence of HBpin. The use of *ortho*-substituted benzoic acid (Me_2N-BA, 5 mol%) and HBpin (5 equiv), in octane at 100 °C resulted to be the optimised conditions for the desired hydroboration reaction. Both aliphatic and aromatic alkynylboronates undergo the hydroboration pathway efficiently generating various *gem*-diborylalkenes (Scheme 1.21a).[39] Alternatively, some methodologies were established to obtain *gem*-diborylalkenes through non-catalysed hydroboration of alkynylboronates.[40,41] Siebert and co-workers established the non-catalysed hydroboration of ethynyl(catechol)boronate with 1 equiv of catecholborane (HBcat), generating the corresponding 1,1-di(catecholboryl)ethene (Scheme 1.21b).[42] Additionally, Weber and co-workers explored the hydroboration of alkynylboronates containing 1,3,2-benzodiazaborole moieties with 1 equiv dicyclohexylborane ($HBCy_2$) to afford unsymmetrical *gem*-diborylalkenes (Scheme 1.21c)[43]



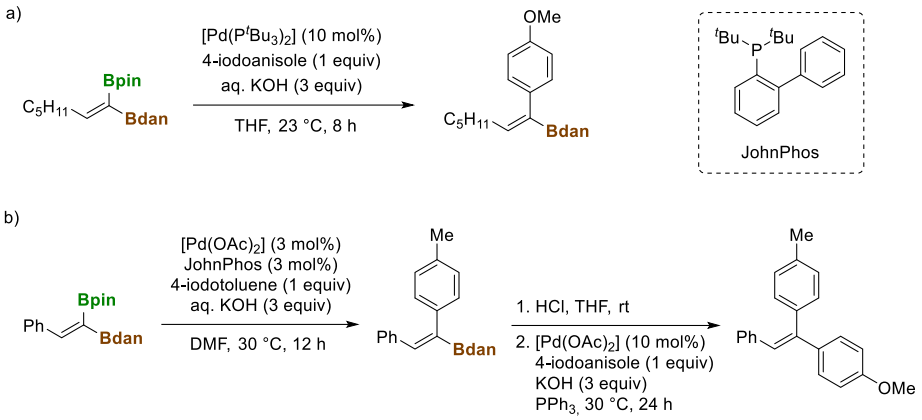
Scheme 1.21 Hydroboration of alkynylboronates through a) carboxylic-acid-catalysed path with HBpin, b) non-catalysed reaction with HBcat and c) non-catalysed reaction with $HBCy_2$.

1.5. Applications of *gem*-diborylalkenes

The presence of two boryl moieties in *geminal* position in alkenes has led several studies to develop strategic methodologies to functionalise them in a stepwise manner. Geminal boryl groups can be differentiated under the optimised reaction conditions as well as depending on the substituents on the alkene, that can assist the selective boryl activation.

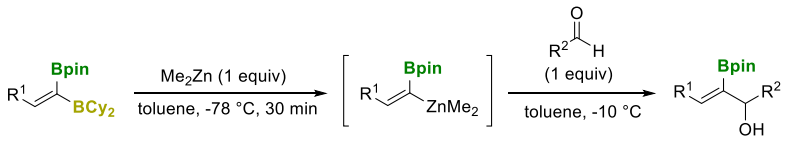
1.5.1. Reactivity of non-symmetrical *gem*-diborylalkenes

Chirik and co-workers reported the selective Suzuki-Miyaura cross-coupling of 1,1-diborylheptene containing Bpin and Bdan moieties with 4-iodoanisole. The generated cross-coupling product through the Bpin moiety occurs due to the higher reactivity over the Bdan moiety, affording the desired substituted borylalkene, bearing the remaining Bdan group (Scheme 1.22a).[35] Similarly, Engle and co-workers described the sequential cross-coupling reaction of *gem*-diborylalkenes bearing Bpin/Bdan moieties.[44] The use of [$Pd(OAc)_2$]/JohnPhos, as catalytic system and 4-iodotoluene, as coupling partner, in the presence of KOH resulted in the selective Suzuki-Miyaura coupling reaction at the Bpin moiety (Scheme 1.22b). The sequentially addition of hydrochloric acid, followed by a catalytic amount of [$Pd(OAc)_2$] and PPh_3, 4-iodoanisole and KOH leads the second cross-coupling reaction at Bdan moiety (Scheme 1.22b).



Scheme 1.22 a) Selective cross-coupling reaction of unsymmetrical *gem*-diborylalkenes at Bpin moiety and b) selective sequential cross coupling of *gem*-diborylalkenes throghout stepwise functionalisation.

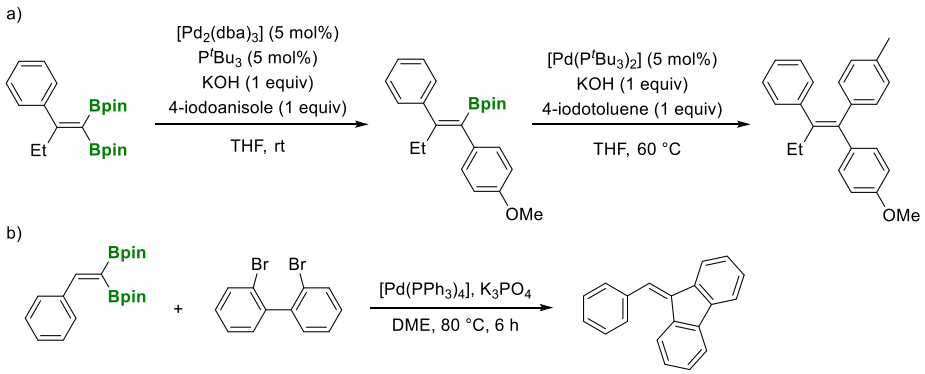
Transmetallation of *gem*-diborylalkenes containing Bpin and BCy_2 groups with dimethylzinc was studied by Walsh and co-workers. The higher Lewis acidity of BCy_2 moiety favoured the transmetallation over the Bpin moiety, which remains untouched. Concomitant reaction of the generated heterobimetallic boron/zinc specie with aldehydes provides the corresponding allylic alcohol product (Scheme 1.23).[40]



Scheme 1.23 Synthesis of allylic alcohols from *gem*-diborylalkenes bearing Bpin/BCy_2 moieties through boron/zinc heterobimetallic intermediate.

1.5.2. Reactivity of symmetrical *gem*-diborylalkenes

Selective cross-coupling reactions of *gem*-diborylalkenes bearing two Bpin moieties has been widely explored.[45] Different methodologies have been developed depending on the substituents of the *gem*-diborylalkenes and the nature of the coupling partners. Hiyama and co-workers established a sequential cross-coupling of *gem*-diborylalkenes with aryl iodides towards the formation of 1,1,2-triaryl-1-alkenes. The use of $[Pd_2(dba)_3]/P^tBu_3$, as catalytic system, KOH (1 equiv), as base, and 4-iodoanisole (1 equiv), as coupling partner, proceeds at room temperature through Suzuki-Miyaura cross-coupling at the boron placed *trans* to the bulkier phenyl group. The subsequent second cross-coupling reaction occurs with $[Pd(P^tBu_3)_2]$, KOH and 4-iodotoluene and needs to be heated at 60 °C, suggesting a higher energy barrier for the second cross-coupling reaction (Scheme 1.24a).[46] Additionally, Jin and co-workers explored the annulative double Suzuki-Miyaura cross-coupling reaction of *gem*-diborylalkenes with 2,2'-dibromo-1,1'-biphenyl coupling partner in the presence of $[Pd(PPh_3)_4]$ and K_3PO_4 at 80 °C, to afford 9-benzylidene-9*H*-fluorene type products (Scheme 1.24 b).[39]



Scheme 1.24 a) Stereoselective sequential cross-coupling of *gem*-diborylalkenes generating triarylated alkenes with different aryl moieties and b) annulative double cross-coupling of *gem*-diborylalkenes to afford 9-benzylidene-9*H*-fluorene type products.

1.6. References

[1] a) E. Fernández, A. Whiting, Eds., *Synthesis and Application of Organoboron Compounds*, Springer International Publishing, **2015**.

b) E. Fernández, Eds., *Advances in Organoboron Chemistry towards Organic Synthesis*, Georg Thieme Verlag KG, **2020**

[2] N. Miralles, R. J. Maza, E. Fernández, *Adv. Synth. Catal.* **2018**, *360*, 1306–1327.

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CHAPTER 2

General objectives

The present doctoral thesis has been conducted with the main purpose of developing chemical methodologies through new reactivities and applications of *gem*-diborylalkanes and *gem*-diborylalkenes.

The specific objectives of each chapter are outlined below:

Chapter 3 is focused on the study and development of a boron-Wittig reaction between aromatic and aliphatic aldehydes and diborylsilylmethide lithium salts. The main challenge of this chapter is the control of the stereochemistry on the 1,1-silylborylated trisubstituted alkene products. We want to apply the new methodology to the preparation of 1,1-silylborylated conjugated dienes and enynes.

Chapter 4 is centred on the reactivity of diborylalkyl lithium salts with vinyl aziridines through nucleophilic ring-opening reaction with particular attention on the regioselectivity of the diborylalkylation/ring-opening process. We are committed to apply this new methodology to synthesise homoallyldiboronate species.

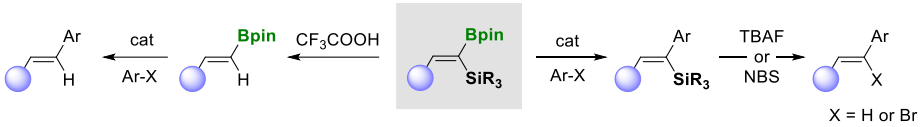
Chapter 5 is aimed to explore the palladium-catalysed insertion of (trimethylsilyl)diazomethane into *gem*-diborylalkenes with a particular emphasis on the stereoselectivity of the cyclopropanation reaction. We focus on applying this methodology to the synthesis of polyfunctional cyclopropyl alcohols.

CHAPTER 3

Diborylsilylalkylation / olefination of aliphatic, aromatic and α,ß-unsaturated aldehydes

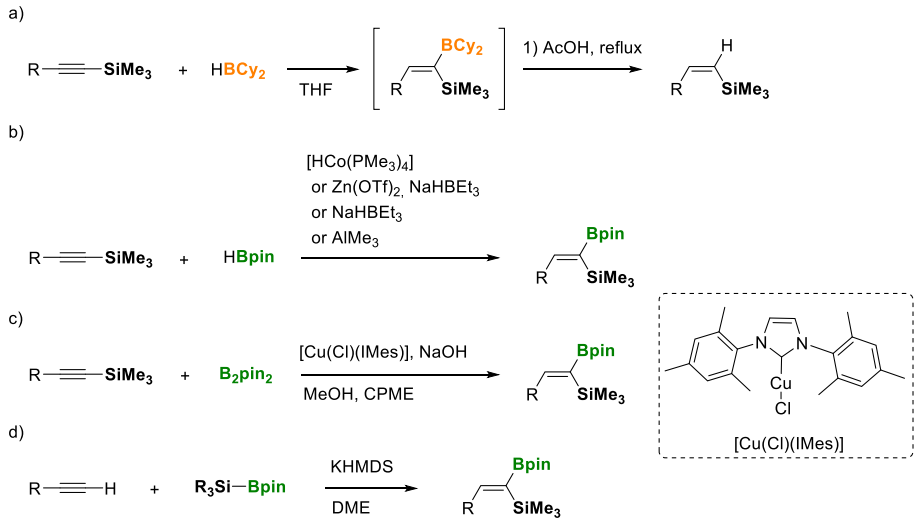
3.1. State of the art

The stereoselective synthesis of densely functionalised olefins represents a challenge in preparative organic chemistry.[1] One of the synthetic strategies to achieve polysubstituted alkenes is by using 1,1-silylborylalkenes, as substrates, due to the versatility of both C-Si and C-B bonds to be selectively functionalised at later stages (Scheme 3.1).[2–5]



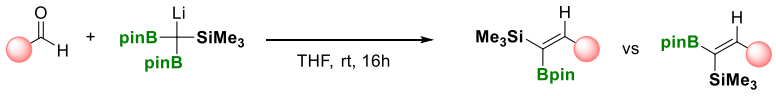
Scheme 3.1 Complementary functionalisation of 1,1-silylborylalkenes.

The first synthesis of 1,1-silylborylalkenes was conducted by Reichenbach and co-workers, based on the hydroboration of 1-trimethylsilyl-1-hexyne with dicyclohexylborane ($HBCy_2$). The 1,1-silylborylalkene generated was transformed into the corresponding (*Z*)-silylalkene *via* protodeboronation (Scheme 3.2a).[6] Subsequent studies were conducted to extend the use of hydroboration of alkynylsilanes exploring the compatibility of different substituents on the alkynes, as well as on the alkylborane source.[7–9] The convenient use of alkoxyboranes consolidated the synthesis of 1,1-silylborylalkenes, first with catecholborane (HBcat),[10] and subsequently with pinacolborane (HBpin). The reaction can be conducted in the presence of catalytic amounts of complexes or additives such as $[HCo(PMe_3)_4]$,[5] $Zn(OTf)_2/NaHBEt_3$,[11] $NaHBEt_3$[12] or $AlMe_3$[13] (Scheme 3.2b). Diboron reagents have been used as alternative reagents for hydroboration with copper catalysts, since Cu-B species are efficiently formed from σ-bond metathesis between CuOR and B_2pin_2 (Scheme 3.2c).[14] More recently, silylboranes (R_3Si-Bpin) have demonstrated their utility in a base-catalysed 1,1-silylborylation of terminal alkynes towards the synthesis of 1,1-silylborylalkenes in a stereoselective way (Scheme 3.2d).[4]



Scheme 3.2 Synthesis of 1,1-silylborylalkenes with (a) alkylboranes, (b) alkoxyboranes, (c) diboranes and (d) silylboranes.

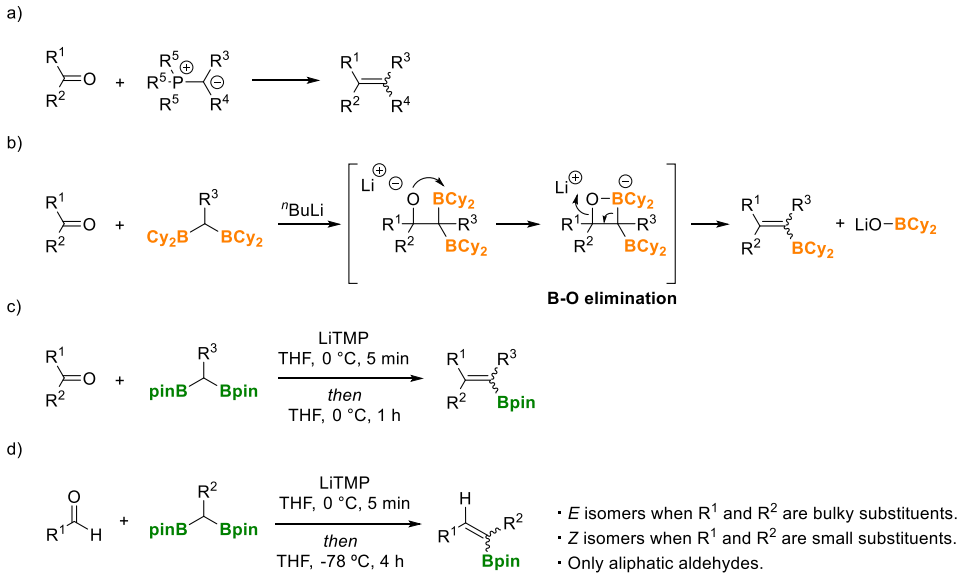
The synthetic routes described in Scheme 3.2 generated, principally, the *Z* stereoisomer. In this chapter it has been proposed an alternative way to synthesise 1,1-silylborylalkenes through a boron-Wittig[15] reaction using aldehydes and diborylsilylmethide lithium salts (Scheme 3.3). The viability of the reaction and the stereoselectivity are fundamental challenges in this study.



Scheme 3.3 Boron-Wittig reaction between aldehydes and diborylsilylmethide lithium salts.

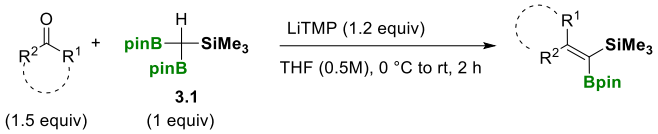
3.2. Context of the work

Wittig and co-workers discovered an olefination reaction in which aldehydes and ketones react with a phosphonium ylide to efficiently generate a broad scope of olefines (Scheme 3.4a).[16] Zubiani and co-workers described the boron-Wittig reaction[17], that takes place between aldehydes or ketones and α-boryl carbanions (Scheme 3.4b). Shibata and co-workers firmly consolidated the renaissance of the boron-Wittig reaction and the benefits of this type of condensation reactions using stable pinacolboryl moieties in the α-boryl carbanions, but also controlling the stereoselectivity of the alkenes formed through the *syn* B-O elimination (Scheme 3.4c).[18] Focusing on the boron-Wittig reaction with aldehydes and diborylalkanes, Morken and co-workers explored this reactivity with aliphatic aldehydes observing that the stereoselectivity of the reaction outcome depends on the steric properties of substituents on aldehydes and diborylalkanes (Scheme 3.4d).[19]



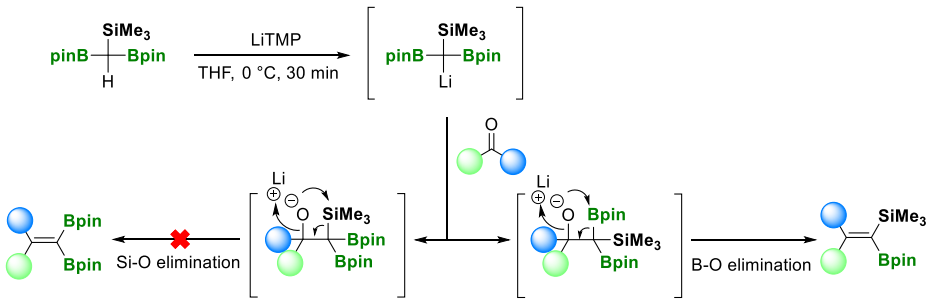
Scheme 3.4. Representative examples of: a) Wittig olefination, b) boron-Wittig olefination with R^3-CH(BCy_2)$_2$, c) boron-Wittig olefination with R^3-CH(Bpin)$_2$ and d) boron-Wittig olefination of aldehydes.

Recently, in previous studies conducted in our group, Fernández and co-workers developed an opportune *gem*-silylborylation of symmetric and non-symmetric ketones, introducing a new olefination reagent $HC(Bpin)_2(SiMe_3)$ (**3.1**). This protocol opened the door to the stereoselective preparation of tetrasubstituted 1,1-silylborylalkenes (Scheme 3.5).[20]



Scheme 3.5 Boron-Wittig olefination between ketones and $HC(Bpin)_2(SiMe_3)$.

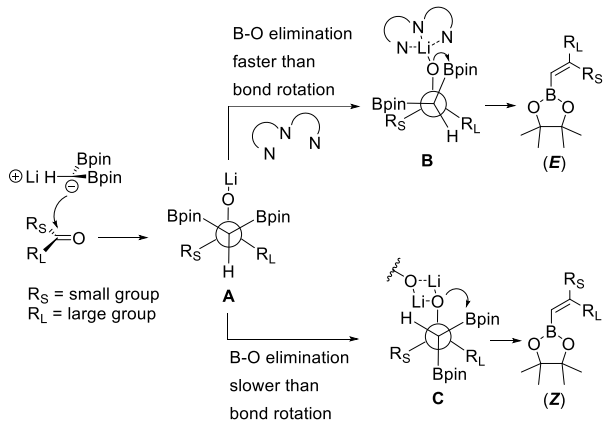
The first step of the reaction requires the deprotonation of **3.1** with LiTMP in THF at 0 °C for 30 minutes (Scheme 3.6, top). Subsequently, the corresponding ketone is added to the solution containing the diborylsilylmethide lithium salt and at that point, the next step could proceed through a Petterson-type Si-O elimination to afford a *gem*-diborylalkene (Scheme 3.6, left) or through the B-O elimination to access *gem*-silylborylalkenes (Scheme 3.6, right). Interestingly, the silylborylation of symmetric and non-symmetric ketones resulted chemoselective towards the exclusive B-O elimination. [20]



Scheme 3.6 Selective B-O elimination (right) *versus* Si-O elimination (left).

Complementarily, Morken and co-workers promoted the use of additives to control the stereoselectivity in the boron-Wittig olefination between ketones

and *gem*-diborylmethane in the presence of LiTMP.[21] They observed that the addition of triamines such as pentamethyldiethylentriamine (PMDTA) or 1,4,7-trimethyl-1,4,7-triazacyclononane (TMTAN), contributed to enhance the stereoselectivity. As shown in Scheme 3.7, the addition of the lithium bis(pinacolboryl)methide to the ketone might proceed lying the smallest group of the nucleophile (H in this case) between the carbonyl substituents thus providing intermediate **A**. Considering that B-O elimination is faster than bond rotation, the evolution to intermediate **B** that minimise the steric interactions with the resting Bpin fragment should be favoured and the (*E*)-alkene might be obtained. Alternatively, when B-O elimination is slow, bond rotation may allow conversion of **A** into **C** where H is sited proximal to the stabilised Li-O dimeric species. From intermediate **C**, B-O elimination would give the (*Z*)-alkene. The authors assumed that the use of triamines such as PMDTA and TMTAN might favour the formation of species **B**, in agreement with previous studies about higher lithiated complexes.[22]



Scheme 3.7 Proposed origin of the stereoselectivity when triamines are used in the boron-Wittig reaction with diborylmethane and ketones in the presence of LiTMP.

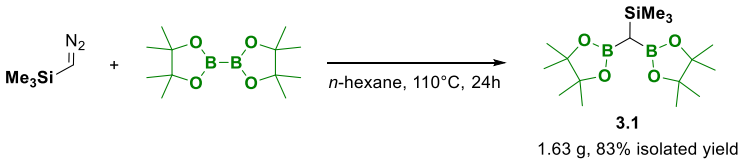
3.3. Specific objectives

The main goal of the chapter is the development of a boron-Wittig reaction between aromatic or aliphatic aldehydes and diborylsilylmethide salts to obtain 1,1-silylborylalkenes. The specific objectives are:

1. Search of the optimisation reaction conditions.
2. Control of the stereoselectivity in the olefination reaction.
3. Study of the reaction with sterically hindered aromatic aldehydes and aliphatic aldehydes.
4. Extension of the reaction to α,β-unsaturated aldehydes.

3.4. Results and discussion

To perform the boron-Wittig reaction planned in this chapter, we had to prepare the reagent $HC(Bpin)_2(SiMe_3)$ (**3.1**). We proceeded through a methodology previously described in our group.[20] The diborylsilylmethane synthesis could be efficiently conducted on gram scale simply by mixing B_2pin_2 and 2 equivalents of (trimethylsilyl)diazomethane (2M in hexane solution) and stirring the mixture at 110 °C for 24 h (1.63 g, 83% of yield, Scheme 3.8).

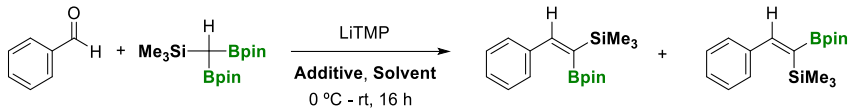


Scheme 3.8 Synthesis of diborylsilylmethane in a gram scale.

To search the viability of the reaction, the reagent $HC(Bpin)_2(SiMe_3)$ (**3.1**) was deprotonated in the presence of LiTMP (1.2 equiv) to form *in situ* a diborylsilyl carbanion at 0 °C. We used the model substrate benzaldehyde (0.8 equiv), which was added to the generated lithium salt $LiC(Bpin)_2(SiMe_3)$ in THF (0.12M) at 0 °C. The reaction was warmed to room temperature and stirred for 16 h to accomplish the formation of the 1,1-silylborylated trisubstituted alkene **3.2** in 82% of conversion, proving that under these conditions, the B-O elimination is favoured *versus* the Si-O Peterson elimination. The conversion was calculated from ^{1}H NMR spectra using naphthalene as internal standard (Table 3.1, entry 1). The selectivity observed shows a preference for the *E* stereoisomer (**3.2** *E:Z* = 70:30) with the Bpin moiety *syn* to the aryl group. The use of alternative solvents such as cyclopentyl methyl ether (CPME) and 1,4-dioxane were considered for the optimisation reaction. When CMPE was used, although the conversion increased slightly to 84%, the stereoselectivity diminished significantly (Table 3.1, entry 2). The use of 1,4-dioxane provided

lower conversion and selectivity data (Table 3.1, entry 3). The influence of adding pentamethyldiethylenetriamine (PMDTA) and two crown ethers such as 1,4,7,10,13,16-hexaoxacyclooctadecane (18-crown-6) and 1,4,7,10-tetraoxacyclododecane (12-crown-4), in THF, was also studied. It was observed that the addition of PMDTA resulted in very low conversion and similar stereoselectivity (Table 3.1, entry 4). The reactivity with 18-crown-6 and 12-crown-4 provided moderate and good conversions and comparable stereoselectivity (Table 3.1, entries 5 and 6). We concluded that the use of additives did not influence on the stereoselectivity of the olefination, suggesting that the B-O elimination was not affected by the presence of Li interaction with the additives.

Table 3.1 Optimisation of the reaction conditions for the Boron-Wittig olefination.[a]



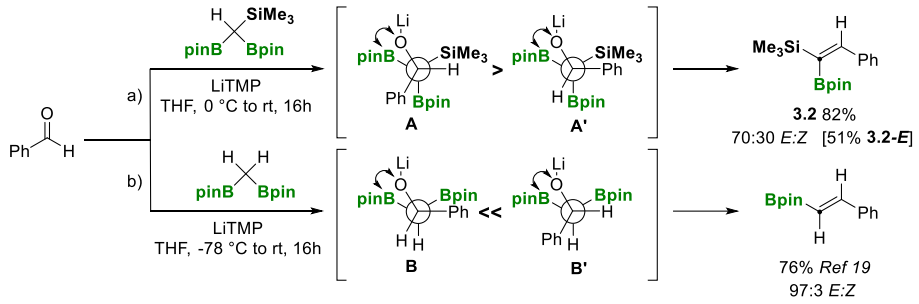
3.1 3.2-*E* 3.2-*Z*

Entry	Solvent	Additives	Conversion (%)[b]	3.2(*E:Z*)
1	THF	---	82	70:30
2	CPME	---	84	54:46
3	1,4-dioxane	---	66	58:42
4	THF	PMDTA	13	69:31
5	THF	18-crown-6	44	68:32
6	THF	12-crown-4	72	68:32

[a] Reactions were performed with 0.24 mmol (0.8 equiv) of model substrate benzaldehyde, 0.3 mmol (1 equiv) of $HC(Bpin)_2(SiMe_3)$, 0.36 mmol (1.2 equiv) of LiTMP and 0.24 mmol (0.8 equiv) of the additive in 2 mL of the solvent, at 0 °C for 30 min and then at rt for 16 h. [b] Conversions were calculated from the ^1H NMR using naphthalene as internal standard.

As it was observed, the olefination reaction showed a preference for the *E* isomer maintaining the Bpin moiety and the aryl group in a relative *syn* position. To justify this fact, we suggest a favoured intermediate **A** versus **A'**

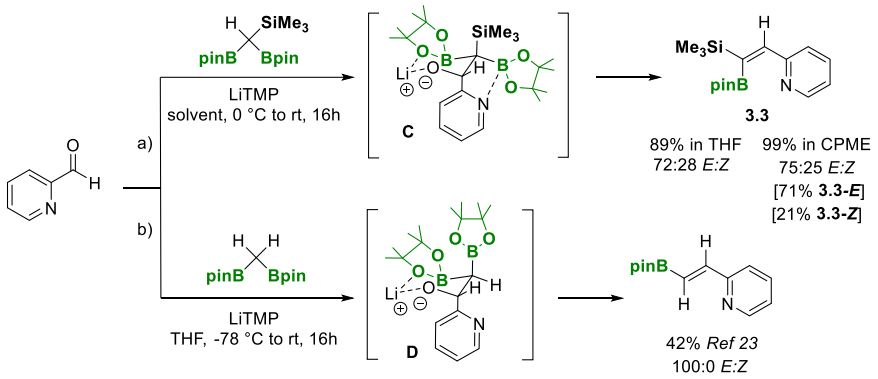
during the B-O elimination (Scheme 3.9a). This preference contrasts with the trend observed by Morken and co-workers in the boron-Wittig reaction between bis(pinacolboryl)methane and aldehydes in which they obtained *trans*-vinylboronic esters through a plausible **B'** intermediate (Scheme 3.9b).[19] Despite the fact that the *E:Z* ratio for product **3.2** is modest, it is noticeable to mention that the **3.2-*E*** isomer has never been isolated before. As it was mentioned, previous synthetic attempts, based on the hybrodoration of 1-phenyl-2-trimethylsilylacetylene, provided only the **3.2-*Z*** isomer as an expected B-H *syn* addition to the triple bond.[5,13]



Scheme 3.9 Comparison of boron-Wittig olefination between benzaldehyde and a) $LiC(Bpin)_2(SiMe_3)$ and b) $LiCH(Bpin)_2$. Reaction conditions for the olefination: 0.24 mmol (0.8 equiv) of aldehyde, 0.3 mmol (1 equiv) of $HC(Bpin)_2(SiMe_3)$, 0.36 mmol (1.2 equiv) of LiTMP and in 2 mL of THF were stirred at 0 °C for 30 min and then at rt for 16 h. Isolated yield shown in brackets.

We next explored the condensation of picolinaldehyde with the *in situ* formed $LiC(Bpin)_2(SiMe_3)$ and the conversion on olefin **3.3** was 89%, in THF, with a *E:Z* ratio = 72:28. When the reaction was conducted in CPME as solvent, the conversion was quantitative and the *E:Z* ratio = 75:25, being the major product isolated in 71% (Scheme 3.10a). The stereocontrol of the reaction contrasts with the one observed using $LiCH(Bpin)_2$ since the *trans*-vinylboronic ester is generated exclusively in 42% yield (Scheme 3.10b).[23] To justify this fact, we have suggested for our reaction a plausible chair-like intermediate **C** in which the steric hindered $SiMe_3$ group might promote an intramolecular interaction

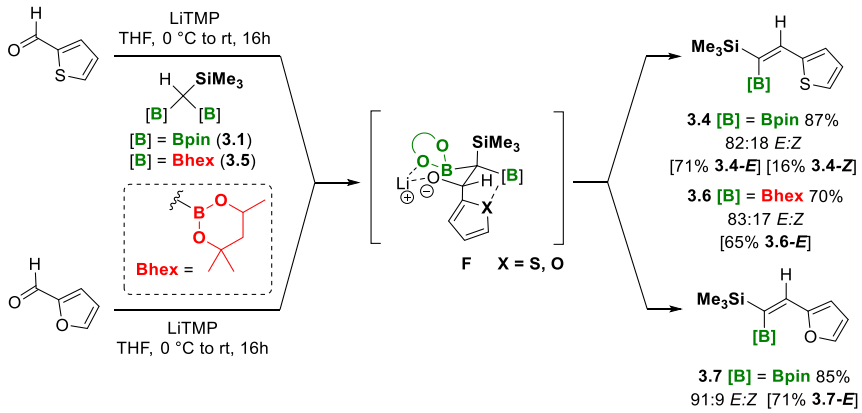
between the nitrogen and one of the Bpin groups, forming a five membered ring that might explain the observed enriched selectivity on **3.3-*E*** (Scheme 3.10a). This is in agreement with the fact that product **3.3-*Z*** shows a characteristic ^{11}B NMR signal at 32.5 ppm whereas in the isomer **3.3-*E*** this ^{11}B NMR signal is observed at 27.6 ppm, as consequence of a subtle N-B intramolecular interaction. In the absence of chelation control the intermediate **D** might predict the expected *trans*-vinylboronic ester formation (Scheme 3.10b).



Scheme 3.10 Boron-Wittig reaction between picolinaldehyde and a) $LiC(Bpin)_2(SiMe_3)$ and b) $LiCH(Bpin)_2$ for comparison. Reaction conditions for the olefination: 0.24 mmol (0.8 equiv) of aldehyde, 0.3 mmol (1 equiv) of $HC(Bpin)_2(SiMe_3)$, 0.36 mmol (1.2 equiv) of LiTMP and in 2 mL of THF were stirred at 0 °C for 30 min and then at rt for 16 h. Isolated yields shown in brackets.

With these precedents in mind, we next performed the reaction with two alternative heterocyclic aldehydes, such as thiophene-2-carbaldehyde and furan-2-carbaldehyde. The olefination of thiophene-2-carbaldehyde with the *in situ* formed $LiC(Bpin)_2(SiMe_3)$ generated the corresponding trisubstituted alkene **3.4** in 87% conversion and showed an improved *E:Z* ratio of 82:18 (Scheme 3.11). To the best of our knowledge, **3.4-*E*** was synthesised for the first time in this work whereas **3.4-*Z*** had been prepared via hydroboration of trimethyl(thiophen-2-ylethynyl)silane in 50% yield.[24] Alternatively, we studied the influence of hexylene glycolato boryl moiety (Bhex) in the

olefination of thiophene-2-carbaldehyde, using $LiC(Bhex)_2(SiMe_3)$, which was generated *in situ* from $HC(Bhex)_2(SiMe_3)$ (**3.5**) and LiTMP. The reagent **3.5** was synthesised throughout the same synthetic pathway used to synthesise **3.1** but using bis(hexylene glicolato)diboron (B_2hex_2) as diboron source. The olefination of thiophene-2-carbaldehyde, with the *in situ* formed $LiC(Bhex)_2(SiMe_3)$ generated the olefin **3.6** in 70% conversion within a *E:Z* ratio up to 83:17, showing similar stereoselectivity but a slight decrease in conversion in comparison with the $LiC(Bpin)_2(SiMe_3)$ reagent, probably due to the steric hindrance associated to the Bhex moiety (Scheme 3.11). The ^{11}B NMR signal at 28.9 ppm for **3.6-*E*** might correlate with a subtle B-S intramolecular interaction. Alternatively, furan-2-carbaldehyde reacted with **3.1**/LiTMP providing a similar reaction outcome towards the trisubstituted alkene **3.7** (85% conversion) with a notably increased *E:Z* ratio up to 91:1, using both THF or CPME as the solvent (Scheme 3.11). The intermediate **F** has been suggested to justify the enhanced stereoselectivity observed in this reaction, through a plausible intramolecular X-B interaction (X = O, S). Compound **3.7** has been prepared for the first time in this work.

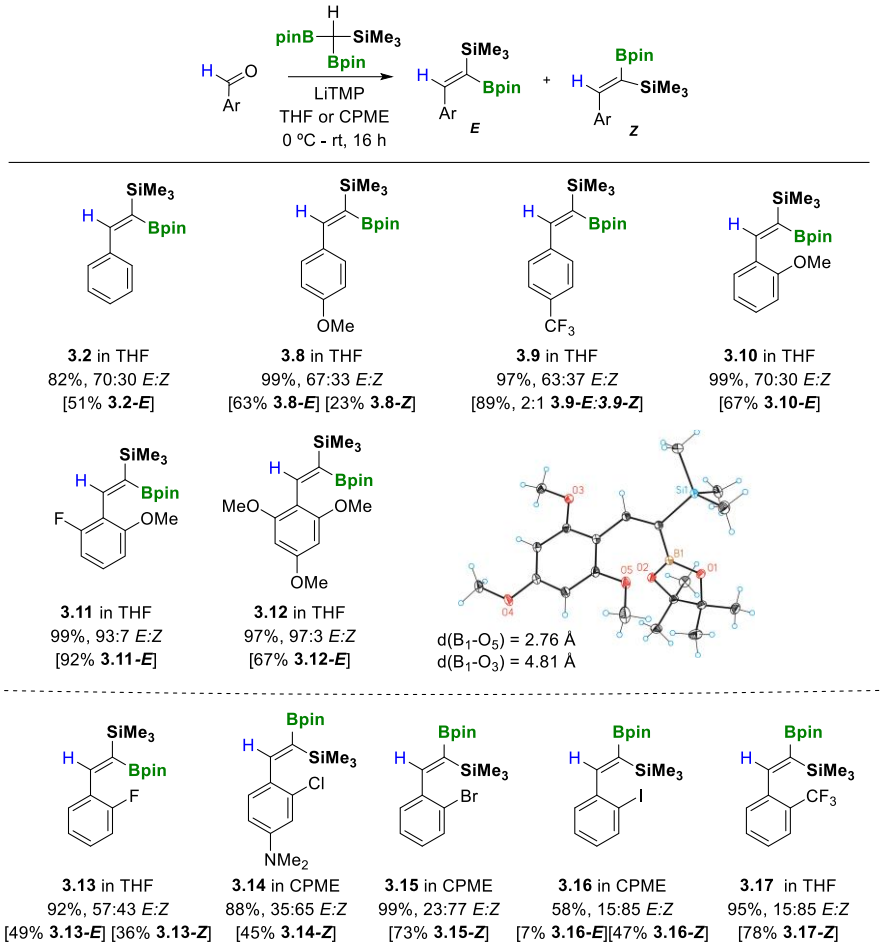


Scheme 3.11 Boron-Wittig reaction between thiophene-2-carbaldehyde or furan-2-carbaldehyde with $LiC(Bpin)_2(SiMe_3)$ or $LiC(Bhex)_2(SiMe_3)$. Reaction conditions for the olefination: 0.24 mmol (0.8 equiv) of aldehyde, 0.3 mmol (1 equiv) of $HC[B]_2(SiMe_3)$, 0.36 mmol (1.2 equiv) of LiTMP and in 2 mL of THF were stirred at 0 °C for 30 min and then at rt for 16 h.

Our next study was orientated to demonstrate that steric and electronic modifications on aromatic aldehyde substrates contributed not only to obtain the exclusive formation of stereoisomer *E*, but also to reverse the stereocontrol toward formation of stereoisomer *Z*, depending on the substituents present in the aryl group. The introduction of electron donating (OMe) or electron withdrawing (CF_3) groups in the *para* position of the aryl moiety of the aromatic aldehydes, did not change the olefination outcome, either in conversion (almost quantitative) or stereoselectivity, having a modest preference for the products **3.8-*E*** and **3.9-*E*** (Scheme 3.12). Both products were synthesised for the first time in this work, since only **3.8-*Z*** and **3.19-*Z*** were already known.[5,25] When the methoxy group was located at the *ortho* position of the aryl moiety, both conversion and stereoselectivity was not altered (see product **3.10** in Scheme 3.12). However, higher stereoselectivity in favour of the *E*-stereoisomer was achieved when both *ortho* positions were occupied. The use of 2-fluoro-6-methoxybenzaldehyde or 2,4,6-trimethoxybenzaldehyde in the olefination reaction generated the corresponding trisubstituted alkenes **3.11** and **3.12** in high yields (99% and 97%, respectively) and high preference on the *E*-stereoisomer, 93:7 *E:Z* ratio for **3.11** and 97:3 *E:Z* ratio for **3.12** (Scheme 3.12). X-ray diffraction of **3.12-*E*** shows a short B_1-O_5 length distance (2.76 Å) compared to B_1-O_3 (4.81 Å), which suggests an attractive interaction between B_1-O_5 since the covalent bond lengths B_1-O_1 is 1.3796(8) Å and B_1-O_2 is 1.3794(8) Å (Scheme 3.12). This situation forces a torsion angle C-C=C-C about 12.02º. It has to be mentioned that none of these polyfunctionalised products with *ortho* substituents have been prepared before.

Interestingly, when the reaction was performed with F, Cl, Br, I and CF_3 groups in *ortho* position of the aromatic aldehydes, we observed a change in the trend of the stereoselectivity along the olefination reaction. Whereas substrates with *ortho* substituents F or Cl provided the olefins **3.13** and **3.14** in high yield and poor stereoselectivity, the presence of Br, I or CF_3 imposed a remarkable change in the stereoselectivity since the formation of the *Z*-stereoisomer was

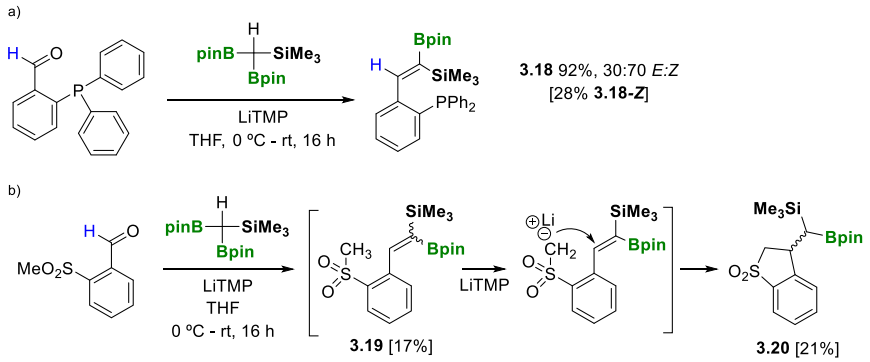
favoured up to 15:85 *E:Z* ratio for **3.16** and **3.17** (Scheme 3.12). The reversed trend might be correlated with steric effects of the silyl group that controls the B-O elimination towards the preferred *Z*-stereoisomer for **3.16** and **3.17**.



Scheme 3.12 Substrate scope of aromatic aldehydes for stereoselective boron-Wittig reaction with $HC(Bpin)_2(SiMe_3)$ and LiTMP. Reaction conditions for olefination: 0.24 mmol (0.8 equiv) of aldehyde, 0.3 mmol (1 equiv) of $HC(Bpin)_2(SiMe_3)$, 0.36 mmol (1.2 equiv) of LiTMP in 2 mL of the solvent, at 0 °C for 30 min and then at rt for 16 h. Isolated yields shown in brackets.

Alternative aldehydes with sterically hindered functional groups at the *ortho* position were also tested. The corresponding olefination reaction of 2-(diphenylphosphino)benzaldehyde with **3.1**/LiTMP allowed the formation of

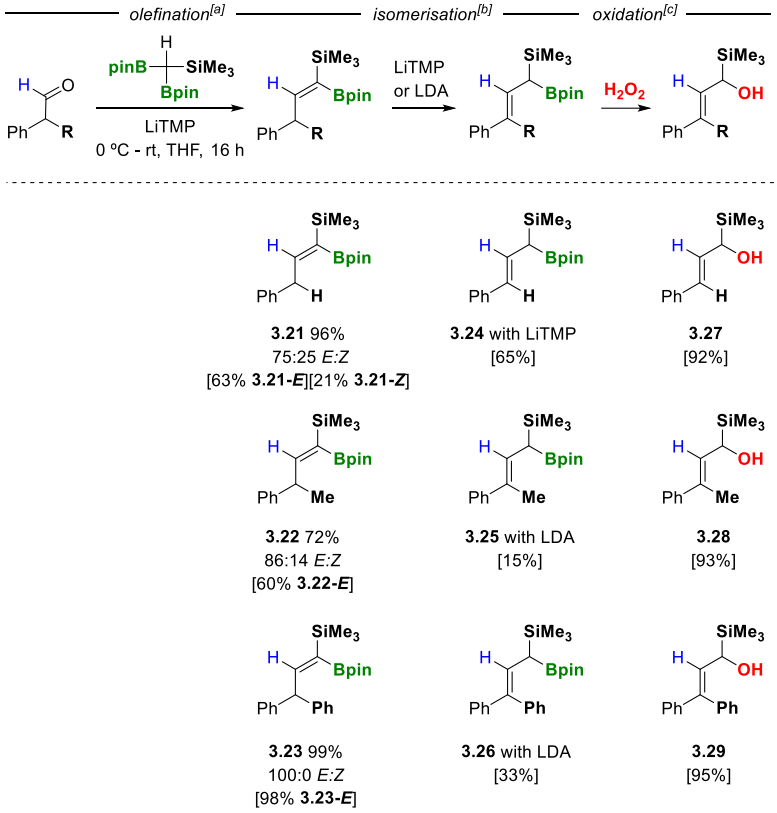
the trisubstituted olefin **3.18** in high conversion and a preference for the *Z*-stereoisomer with *E:Z* = 30:70 ratio (Scheme 3.13a). Surprisingly, when 2-(methylsulfonyl)benzaldehyde reacted with the diborylsilylmethide lithium salt, the expected trisubstituted alkene **3.19** was scarcely isolated (17%, **3.19-*E***), and instead, the cyclic system **3.20** was detected and isolated (Scheme 3.13b). Its formation might be postulated throughout the formation of (phenylsulfonyl)methylene lithium intermediate (via deprotonation of the aryl sulfonyl group with the excess of LiTMP)[26] which interacts intramolecularly with the alkene to form the saturated cyclic compound **3.20**. This kind of benzothiophene 1,1-dioxides had been prepared before through catalysed hydrogenation of the corresponding unsaturated cyclic compounds.[27,28]



Scheme 3.13 Boron-Wittig reaction between sterically hindered *ortho* substituted aryl aldehydes and $HC(Bpin)_2(SiMe_3)$ and LiTMP. Reaction conditions for the olefination: 0.24 mmol (0.8 equiv) of aldehyde, 0.3 mmol (1 equiv) of $HC(Bpin)_2(SiMe_3)$ and 0.36 mmol (1.2 equiv) of LiTMP in 2 mL of THF were stirred at 0 °C for 30 min and then at rt for 16 h. Isolated yields shown in brackets.

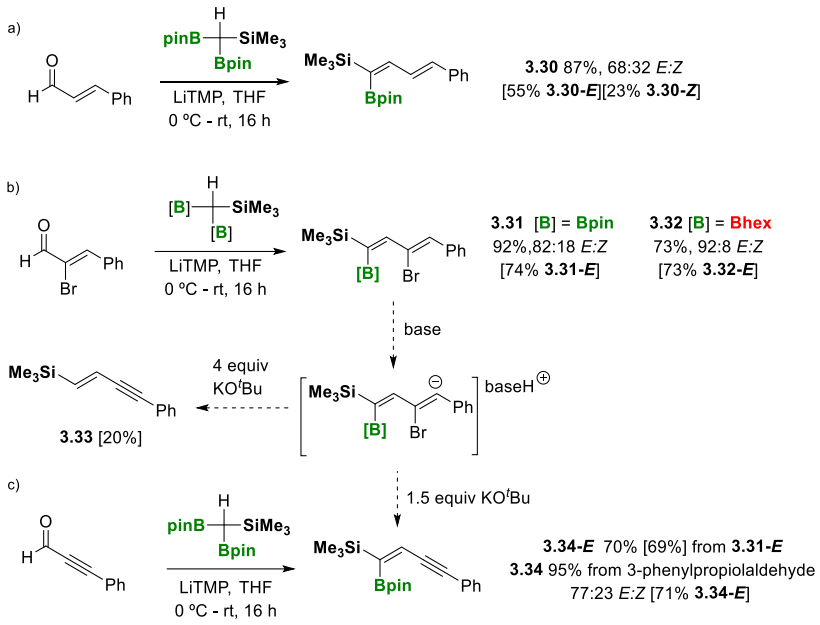
The scope of this methodology was extended to study the olefination with aliphatic aldehydes, demonstrating that steric factors might also influence the stereoselectivity of the reaction outcome in non-aromatic aldehydes. Whereas the boron-Wittig of 2-phenylacetaldehyde generates the corresponding trisubstituted alkene **3.21** in 75:25 *E:Z* ratio, the olefination of 2-phenylpropanal shows an increment of the stereoselectivity up to 86:14 *E:Z*

ratio in product **3.22**. Moreover, the most sterically hindered aldehyde (2,2-diphenylacetaldehyde), is transformed exclusively into alkene **3.23-*E*** (Scheme 3.14). All these products could be converted into valuable allylic 1,1-borylsilylalkanes by proton abstraction/isomerisation in the presence of LiTMP or LDA. The allylic compounds **3.24**-**3.26** could be isolated in moderate yields with exclusively *E* stereoselectivity and efficiently oxidised towards α-(hydroxyallyl)silanes **3.27**-**3.29** (Scheme 3.14).



Scheme 3.14 Boron-Wittig reaction of aliphatic aldehydes with $HC(Bpin)_2(SiMe_3)$ /LiTMP and subsequent proton abstraction/isomerisation and eventual oxidation. [a] Reaction conditions for the olefination: 0.24 mmol (0.8 equiv) of aldehyde, 0.3 mmol (1 equiv) of $HC(Bpin)_2(SiMe_3)$, 0.36 mmol (1.2 equiv) of LiTMP in 2 mL of THF were stirred at 0 °C for 30 min and then at rt for 16 h. [b] Reaction conditions for isomerisation: 0.3 mmol (1 equiv) of 1.1-silylborylalkene, 0.36 mmol (1.2 equiv) of LiTMP or LDA and 2 mL of THF were stirred at 0 °C for 30 min and then at rt for 16 h. [c] Reaction conditions for the oxidation: 0.2 mmol (1 equiv) of *gem*-silylborylated compound, 0.4 mmol (2 equiv) of $NaBO_3 \cdot H_2O$ and 1 mL of THF/H_2O (*v/v* = 1/1) were stirred at rt for 16h. Isolated yields shown in brackets.

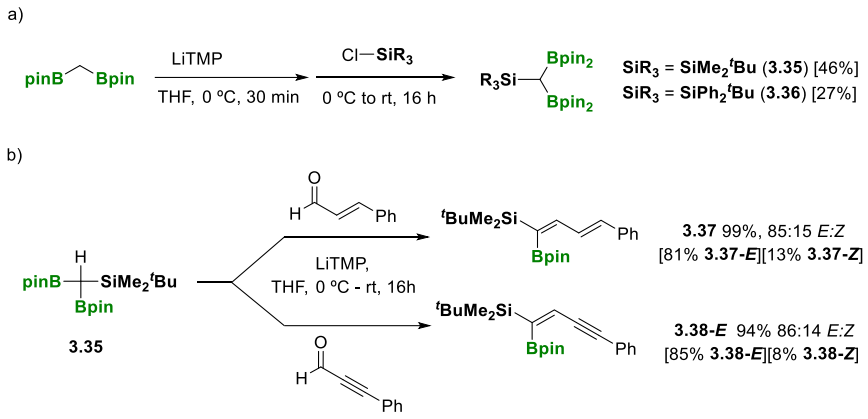
Finally, the olefination of α,β-unsaturated aldehydes with the corresponding diborylsilylmethide lithium salt was explored. Chemoselectivity became a matter of concern because the nucleophilic attack of the diborylsilylcarbanion can take place on the aldehyde functionality or on the conjugated β position. To test this challenge, the reaction of cinnamaldehyde with $LiC(Bpin)_2(SiMe_3)$ was studied and to our delight the trisubstituted conjugated dienyl compound **3.30** was exclusively formed in a 68:32 *E:Z* ratio (Scheme 3.15a). Interestingly, the analogue substrate 2-bromo-3-phenylacrylaldehyde conducted the boron-Wittig reaction with $LiC(Bpin)_2(SiMe_3)$ towards the substituted diene **3.31** in high yield and enhanced 82:18 *E:Z* ratio (Scheme 3.15b). Even higher stereoselectivity could be achieved using the analogue lithium salt with Bhex moieties instead of Bpin, $HC(Bhex)_2(SiMe_3)$/LiTMP, generating the product **3.32** in a 92:8 *E:Z* ratio (Scheme 3.15b). However, the addition of 1.5 equivalents of KO^tBu to the isolated stereoisomer **3.31-*E*** promoted the HBr elimination and subsequent enyne **3.34-*E*** formation with exclusive stereoselectivity (Scheme 3.15b). The addition of an excess of base to the previuously isolated product **3.32-*E***, resulted in a complete protodeboronation process with the subsequent formation of (*E*)-trimethyl(4-phenylbut-1-en-3-yn-1-yl)silane (**3.33-*E***) in moderate yield (Scheme 3.15b). To have a complete picture of the olefination of α,β-unsaturated aldehydes, we conducted the boron-Wittig reaction with 3-phenylpropiolaldehyde and reagent **3.1**. As Scheme 3.15c shows, the formation of product **3.34** could be obtained although with lower stereoselectivity (77:23 *E:Z* ratio), in comparison with the same product obtained from **3.31** (Scheme 3.16c).



Scheme 3.15 Boron-Wittig olefination of α,β-unsaturated aldehydes with $LiC(Bpin)_2(SiMe_3)$. Reaction conditions for the olefination: 0.24 mmol (0.8 equiv) of aldehyde, 0.3 mmol (1 equiv) of $HC(Bpin)_2(SiMe_3)$, 0.36 mmol (1.2 equiv) of LiTMP in 2 mL of THF were stirred at 0 °C for 30 min and then at rt for 16 h. Isolated yields shown in brackets.

Eventually, we investigated the substituent effect of the silane group on the stereoselectivity of the olefination reaction. For this reason, the reagents $HC(Bin)_2[Si]$ (**3.35**, ([Si]=$SiMe_2{}^tBu$)) and **3.36**, ([Si]=$SiPh_2{}^tBu$) had to be synthesised mixing bis(pinacolboryl))methane/LiTMP in 3 mL of THF at 0 °C for 30 minutes followed by the addition of 1.2 equivalents of the corresponding chlorosilane ($ClSiMe_2{}^tBu$ for **3.35** and $ClSiPh_2{}^tBu$ for **3.36**) in 1 mL of THF.[29] Both reaction were warmed to room temperature and stirred for 16 hours (Scheme 3.16a). To test the suitability of reagents **3.35** and **3.36**, in the boron-Wittig reaction, two substrates (cinnamaldehyde and 3-phenylpropiolaldehyde) were tested. It was observed that the stereoselectivity on the *E* stereoisomer is favoured when the more sterically hindered reagent **3.35** is involved (Scheme 3.16b). The resulting products **3.37** and **3.38** were obtained in 85:15 *E:Z* ratio and 86:14 *E:Z* ratio, respectively than the corresponding analogues with the

$SiMe_3$ moiety (products **3.30** and **3.34**, see Scheme 3.15). On the other hand, when the reactivity was tested with the reagent **3.36**, conversions on the corresponding diene and enyne were very low, probably, due to the highly congested diborylsilylmethane $HC(Bpin)_2SiPh_2{}^tBu$ involved.



Scheme 3.16 a) Synthesis of **3.35** and **3.36** and b) subsequent use in the boron-Wittig reaction with cinnamaldehyde and 3-phenylpropiolaldehyde. Reaction conditions for the olefination: 0.24 mmol (0.8 equiv) of aldehyde, 0.3 mmol (1 equiv) of $HC(Bpin)_2$[Si], 0.36 mmol (1.2 equiv) of LiTMP in 2 mL of THF were stirred at 0 °C for 30 min and then at rt for 16 h. Isolated yields shown in brackets.

3.5. Conclusions

Summarising this chapter, we have conducted the olefination reaction between aromatic or aliphatic aldehydes and diborylsilylmethide lithium salts with a special focus on the challenging stereocontrol on the 1,1-silylborylated trisubstituted alkenes. We have found that heterocyclic aldehydes could be involved in the stereodetermining intermediates *via* intramolecular interaction of N, O or S with B. Also, depending on the substituents at *ortho* position of aryl aldehydes, a divergent stereocontrol has been observed. Whereas OMe group favours the *E* stereosiomer during the olefination reaction, the bulky halides favoured the *Z* stereoisomer formation. Finally, the boron-Wittig olefination of α,β-unsaturated aldehydes, with diborylsilylmethide lithium salts, allows access to 1,1-silylborylated conjugated dienes and enynes. Mostly of the *E* stereoisomeric products synthesised in this Chapter have been prepared for the first time, complementing the alternative existing methodologies for the preparation of the corresponding *Z* stereoisomeric trisubstituted 1,1-borylsilyl alkenes.

3.6. References

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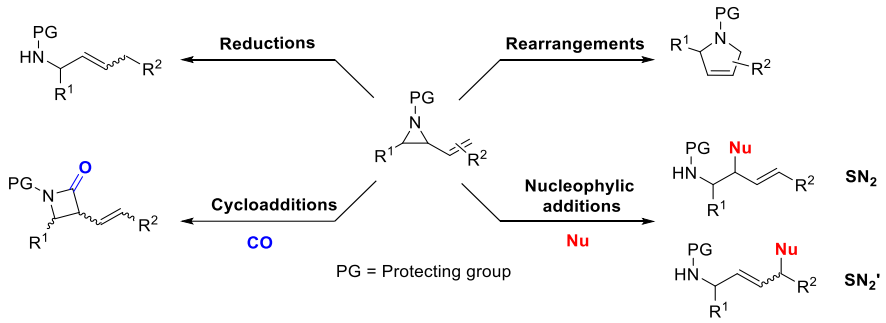
CHAPTER 4

Diborylalkylation / ring-opening of substituted vinyl aziridines

4.1. State of the art

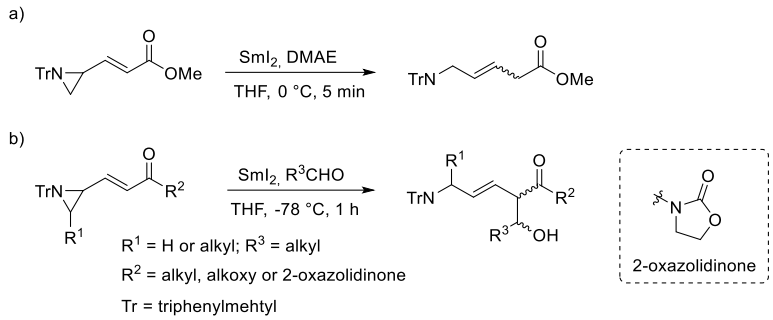
Among the diversely functionalised aziridines, vinyl aziridines have reached a significant interest as building blocks in organic synthesis.[1] These compounds are of particularly synthetic value because they show a remarkable reactivity trend due to the high strain associated with the three-membered ring, as well as the electron-withdrawing nature of the nitrogen atom. In addition, vinyl aziridines enhance their reactivity due to presence of the pending carbon-carbon double bond. Some of the most important transformations, from the synthetic point of view, include reduction reactions, rearrangements, cycloaddition reactions, and nucleophilic additions *via* S_N2 and S_N2' (Scheme 4.1).[2]



Scheme 4.1 Strategic transformations of vinyl aziridines

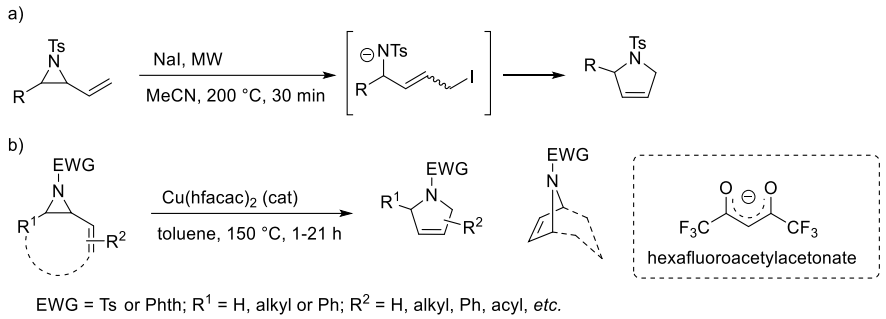
Reductive ring-opening reactions are promoted by electron transfer to vinyl aziridines affording allylamine compounds. Stengel and co-workers established the reactivity of acrylic aziridines with samarium (II) iodide, in presence of *N,N*-dimethylaminoethanol (DMAE) as proton source, to obtain the corresponding allylamine in diastereomeric mixtures (Scheme 4.2a).[3] Moreover, Mukaiama and co-workers studied the diastereoselectivity of this particular reaction using diverse substituents and acyl groups on the vinyl aziridines, as well as the subsequent aldol reaction of *in situ* generated samarium enolates with aldehydes. The use of a chiral oxazolidinone, as acyl

group, resulted in excellent diastereoselectivity in the asymmetric aldol addition (Scheme 4.2b).[4,5]



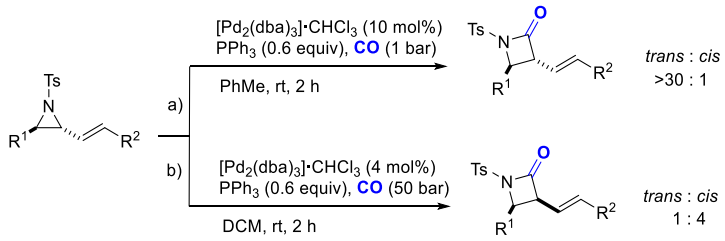
Scheme 4.2 Ring-opening of vinyl aziridines promoted by SmI_2.

Reactions of vinyl aziridines include rearrangements that allow the formation of pyrrolines and pyrroles assisted by heating. Somfai and co-workers established the formation of 3-pyrrolines from simple *N*-tosyl vinyl aziridines through consecutive ring-opening/ring-closing reactions, promoted by NaI at 200 °C under microwave irradiation (Scheme 4.3a).[6] Alternatively, transition-metal-catalysed reactions can afford the synthesis of 3-pyrrolines starting from the appropriate vinyl aziridines. Njardarson and co-workers reported a copper(II)-catalysed ring-expansion from functionalised vinyl aziridines, using the commercially available $[Cu(hfacac)_2]$ (hfacac = hexafluoroacetylacetonate) catalyst, providing access to a broad range of 3-pyrrolines including bicyclic pyrrolines. (Scheme 4.3b).[7]



Scheme 4.3 Rearrangements of vinyl aziridines to 3-pyrrolines with a) NaI and b) copper(II) complexes.

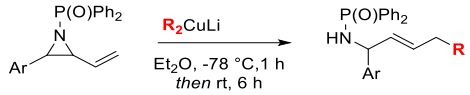
Vinyl aziridines can also undergo cycloaddition reactions in the presence of carbon monoxide to reach β-lactams. Aggarwal and co-workers studied the palladium-catalysed carbonylation of vinyl aziridines, controlling the diastereoselectivity of the reaction by adjusting reaction parameters, such as, CO pressure. When the ring-expansion reaction is carried out with 10 mol% of]$Pd_2(dba)_3$]·$CHCl_3$ and CO (1 bar), the reaction in conducted to form *trans* β-propiolactam (Scheme 4.4a). On the contrary, if 4 mol% of [$Pd_2(dba)_3$]·$CHCl_3$ and 50 bars of CO are present, the lactam is formed showing a preference for the *cis* isomer (Scheme 4.4b).[8]



Scheme 4.4 Palladium(0)-catalysed carbonylative ring-expansion of vinyl aziridines to obtain β-lactams in a diastereoselective way using a) [$Pd_2(dba)_3$]·$CHCl_3$ (10 mol%) and CO (1 bar) and b) [$Pd_2(dba)_3$]·$CHCl_3$ (4 mol%) and CO (50 bar).

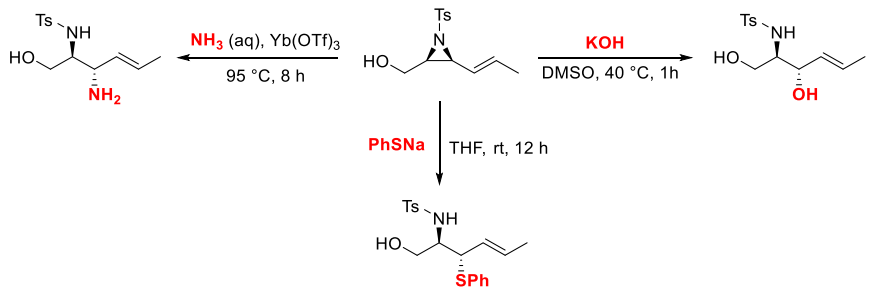
Vinyl aziridines can undergo nucleophilic addition with concomitant ring-opening reactions, with a variety of carbon- and heteroatom-based nucleophiles

producing a variety of functionalised amines with excellent stereoselectivity. The reaction of vinyl aziridines containing terminal C=C double bonds with organocopper reagents, such as Gilman-type reagents (R_2CuLi), generates the corresponding *E*-allylamines. The ring-opening proceeds through a nucleophilic pathway, in which the organocopper reagent reacts with the terminal carbon of the vinyl group, *via* S_N2' reaction type, forming a new C-C bond (Scheme 4.5).[9]



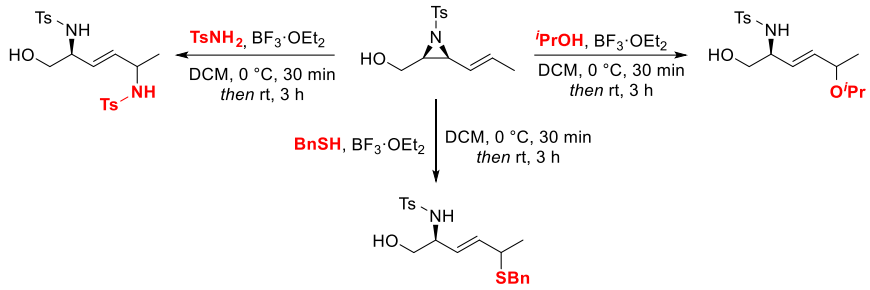
Scheme 4.5 Ring-opening reaction with Gilman organocopper reagents to give *E*-allylamines.

Pérez and co-workers studied the nucleophilic ring-opening reaction of vinyl aziridines with oxygen, nitrogen or sulphur based nucleophiles, demonstrating the feasibility of the reaction through S_N2. The use of KOH as nucleophilic oxygen source, with DMSO as solvent, resulted in the corresponding amino diol product through a nucleophilic ring-opening at the allylic position (Scheme 4.6, right). Similarly, aqueous ammonia solution in the presence of $Yb(OTf)_3$ reacts with vinyl aziridines to obtain the 1-hydroxy-2,3-diamino derivative (Scheme 4.6, left). Consequently, it was also demonstrated that vinyl aziridines undergo S_N2 reaction with sodium thiophenolate salt (PhSNa), in THF, to reach the 1-hydoxy-2-amino-3-thio substituted product (Scheme 4.6, bottom).[10]



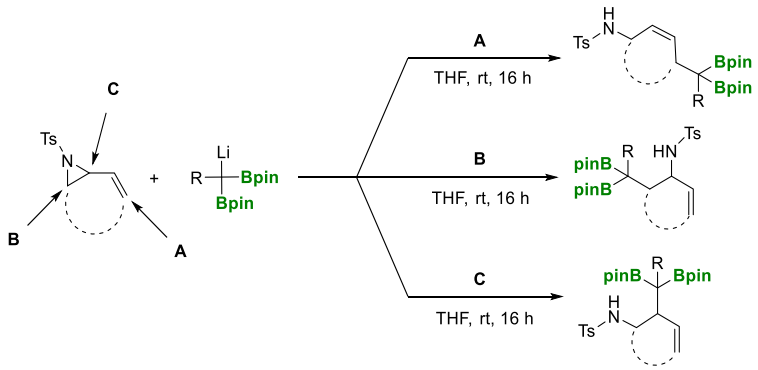
Scheme 4.6 Nucleophilic ring-opening reaction of vinyl aziridines *via* S_N2 with oxygen (right), nitrogen (left) and sulphur (bottom) based nucleophiles.

Moreover, the addition of Lewis acids, such as $BF_3{\cdot}OEt_2$, in the reaction media combined with the use of more steric hindered nucleophiles, such as isopropanol (^{i}PrOH), *p*-toluenesulfonamide ($TsNH_2$) and benzyl mercaptan (BnSH) provides the corresponding S_N2' ring-opening products (Scheme 4.7).



Scheme 4.7 Nucleophilic ring-opening reaction of vinyl aziridines *via* S_N2' with oxygen (right), nitrogen (left) and sulphur (bottom) based nucleophiles.

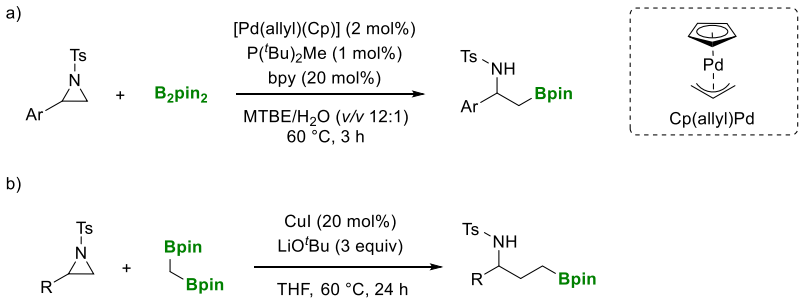
Within those precedents, we designed in this chapter a new strategy to perform nucleophilic ring-opening reactions of *N*-tosyl vinyl aziridines with 1,1-diborylmethide lithium salts (Scheme 4.8). The regioselectivity, as well as the stereoselectivity, were essential challenges in this study.



Scheme 4.8 Nucleophilic ring-opening reaction between cyclic and non-cyclic vinyl aziridines and diborylmethide lithium salts.

4.2. Context of the work

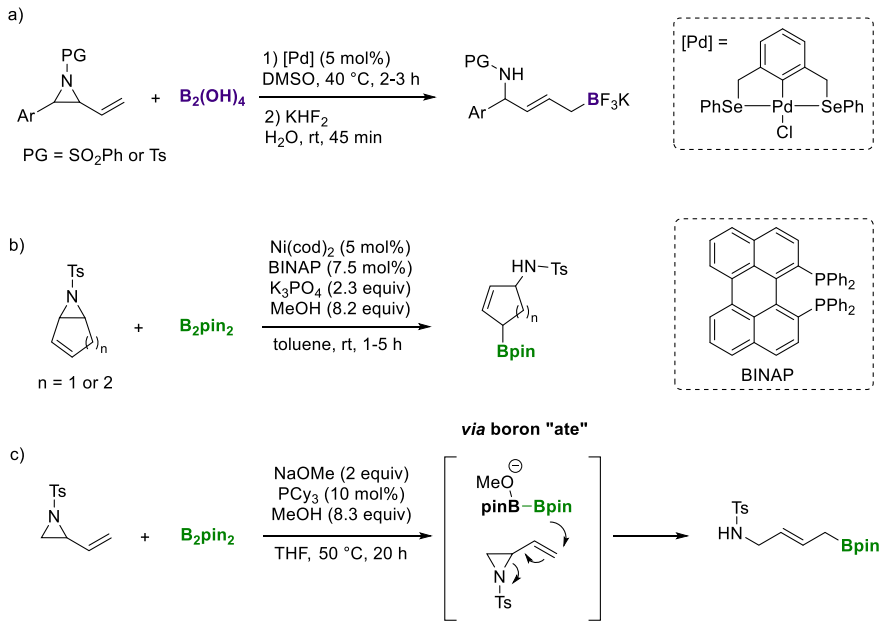
Nucleophilic ring-opening reactions of aziridines with organoboron reagents provide a useful method for constructing non-cyclic organoboron compounds with the selective control of the ring cleavage within high atom economy parameters.[11] Minakata and co-workers developed a Pd-catalysed regioselective borylative ring-opening reaction of substituted 2-arylaziridines affording β-aminoalkylboronates.[12] The reaction occurs only with monosubstituted 2-arylaziridines *via* S_N2 pathway under very specific conditions, using as catalytic systems [Pd(allyl)Cp], P(^{t}Bu)$_2$Me and 2,2′-bipyridine (bpy), and B_2pin_2 as borylative agent (Scheme 4.9a). Moreover, Fu and co-workers promoted the use of *gem*-diborylmethane, instead of diboron reagents, affording γ-aminoboronic esters, through a copper-catalysed ring-opening reaction with the concomitant C-C bond formation. The borylmethylation of substituted 2-alkylaziridines is furnished under mild conditions with CuI and the presence of 3 equiv of LiO^{t}Bu as base (Scheme 4.9b).[13]



Scheme 4.9 Convenient S_N2 ring-opening reaction with a) Pd-catalysed borylation and b) Cu-catalysed borylmethylation.

Szabó and co-workers established the reactivity of vinyl aziridines with diboron reagents in a Pd-catalysed borylative ring-opening reaction. The substituted 2-aryl-3-vinyl aziridines react with tetrahydroxydiboron ($B_2(OH)_4$) in the presence of a Pd-pincer complex as catalyst, affording the corresponding

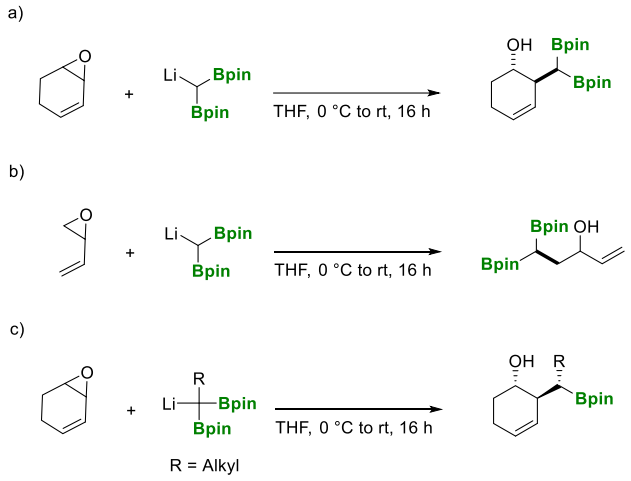
potassium trifluoroallylborates after being treated *in situ* with KHF_2 (Scheme 4.10a).[14] Furthermore, studies of the Ni-catalysed ring-opening reaction of cyclic and non-cyclic vinyl aziridines were conducted by Pineschi and co-workers. The use of [Ni(cod)$_2$], in combination with racemic BINAP, methanol, anhydrous, K_3PO_4 and B_2pin_2, was necessary to perform the borylative ring-opening of cyclic vinyl aziridines (Scheme 4.10b).[15] Fernández and co-workers studied the viability of conducting the borylative ring-opening reaction of vinyl aziridines, in a transition-metal-free context. The reaction was suggested to occur with the formation of a boron 'ate' complex that undergoes a nucleophilic ring-opening reaction *via* S_N2' to reach the corresponding allylboronates (Scheme 4.10c).[16]



Scheme 4.10 Borylative ring-opening reaction of vinyl aziridines with a) Pd-complexes, b) Ni complexes and c) transition metal-free version.

Recently in our group, Fernández and co-workers studied the reactivity of the analogous vinyl epoxides with diborylmethide lithium salts, LiCH(Bpin)$_2$. The reaction proceeds throughout an exclusive S_N2 diborylmethylation/ring-

opening reaction, in a regioselective way, depending on the nature of the substrates. While the nucleophilic ring-opening on 3,4-epoxy-1-cyclohexene takes place exclusively on the allylic position (Scheme 4.11a), the diborylmethide lithium salt reacts with 3,4-epoxy-1-butene at the homoallylic position (Scheme 4.11b). However, when substituted *gem*-diborymethide lithium salts, $LiC(Bpin)_2(R)$, react with 3,4-epoxy-1-cyclohexene, the corresponding diborylated product suffers from protodeboronation due to the plausible high steric factors. Interestingly, this protodeboronation proceeds in a diastereoselective manner when the 1,1-diboron reagent is bearing an alkyl group (Scheme 4.11c).[17]



Scheme 4.11 Diborylmethylation/ring-opening of a) 2,3-epoxy-1-cyclohexene with $LiCH(Bpin)_2$, b) 3,4-epoxy-1-butene with $LiCH(Bpin)_2$ and c) 2,3-epoxy-1-cyclohexene with $LiC(R)(Bpin)_2$.

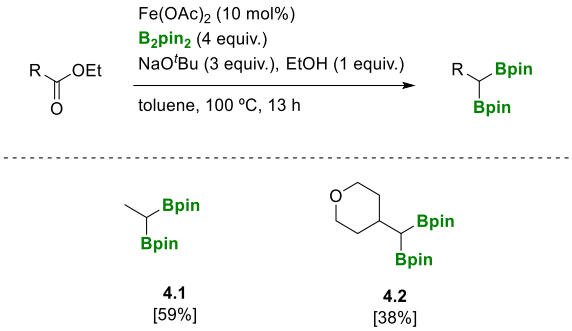
4.3. Specific objectives

The leading target of the chapter is to study the nucleophilic ring-opening reaction of cyclic and non-cyclic vinyl aziridines with substituted 1,1-diborylmethide lithium salts. The specific objectives are:

1. Control the regioselectivity of the diborylalkylation/ring-opening reaction.
2. Explore the reaction with substituted and unsubstituted vinyl aziridines.
3. Extension of the reaction to the cyclic 2,3-epoxy-1-cyclohexene.
4. Application of the reaction conditions to 2-vinyloxirane.

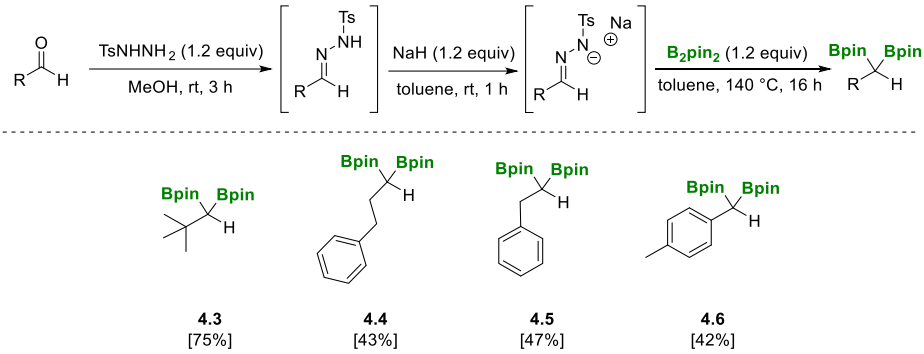
4.4. Results and discussion

To conduct the arranged study, it was necessary to synthesise the *gem*-diborylalkanes as well as the *N*-tosyl vinyl aziridines. We proceeded through different synthetic strategies depending on the feasibility of each methodology for the desired substituted 1,1-diborylalkanes. The corresponding diborylalkane reagents bearing a methyl group (**4.1**) and tetrahydropyran group (**4.2**) were synthesised following a methodology described by Liu and co-workers that proceeds through an iron-catalysed hydrodiborylation of carboxylic esters (Scheme 4.12).[18]



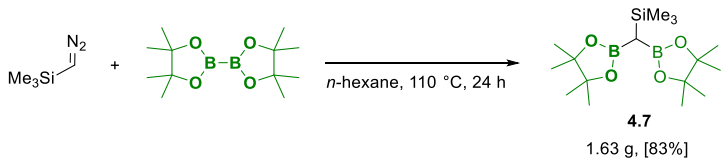
Scheme 4.12 Synthesis of 1,1-diborylalkanes **4.1** and **4.2**. Reaction conditions: 4 mmol (4 equiv) of B_2pin_2, 3 mmol (3 equiv) of NaO^tBu, 0.1 mmol (10 mol%) of $Fe(OAc)_2$ and 7 mL of dry toluene were stirred at 100 °C for 1 h. Then 1 mmol (1 equiv) of the carboxyclic ester and 1 mmol (1 equiv) of EtOH were added and the reaction mixture was stirred at 100 °C for 12 h. Isolated yields in brackets.

Furthermore, other *gem*-diborylalkanes with alkyl and aryl substituents were afforded from the corresponding aldehydes following a synthetic strategy previously reported by Wang and co-workers, introducing some modifications.[19] The aldehyde was first treated with *p*-toluenesulfonyl hydrazide ($TsNHNH_2$) in MeOH to form the corresponding tosyl hydrazone that, after the removal of the solvent, reacted with sodium hydride (NaH) in toluene at room temperature, deprotonating the hydrazone. Finally, B_2pin_2 was added to the reaction mixture with additional toluene to afford the *gem*-diborylalkanes **4.3 - 4.6** under 140 °C for 16 h (Scheme 4.13).



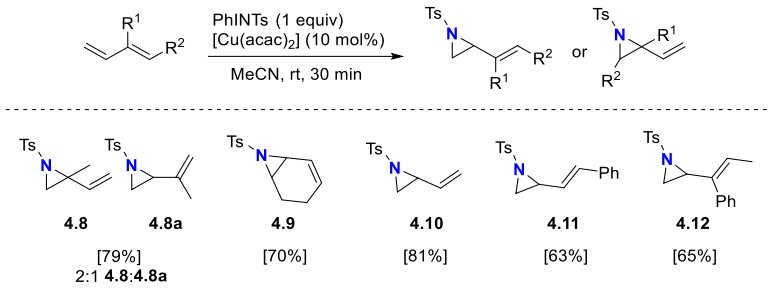
Scheme 4.13 Synthesis of 1,1-diborylalkanes with alkyl and aryl substituents. Reaction conditions: 12 mmol (1 equiv) of the aldehyde, and 14.4 mmol (1.2 equiv) of $TsNHNH_2$ in 30 mL of MeOH were stirred at rt for 3h. Then 14.4 mmol (1.2 equiv) of NaOH and 80 mL of toluene were added and stirred at rt for 1h. Finally, 14.4 mmol (1.2 equiv) of B_2pin_2 and 5 mL extra of toluene were added and stirred at 110 °C for 16 h. Isolated yields in brackets.

Additionally, the *gem*-diborylalkane **4.7**, containing a trimethylsilyl group (previously described in Chapter 3 of this thesis), was also synthesised using the same methodology reported by Fernández and co-workers (Scheme 4.14). [20]



Scheme 4.14 Synthesis of diborylsilylmethane **4.7** in gram scale. Isolated yield in brackets.

On the other hand, the *N*-tosyl vinyl aziridines were synthesised following a procedure established by Knight and co-workers, based on the reactivity between conjugated dienes and the nitrene source 4-methyl-*N*-(phenyl-λ^3-iodaneylidene)benzenesulfonamide (PhINTs) in the presence of $[Cu(acac)_2]$. The desired *N*-tosyl vinyl aziridines were obtained after the nitrene insertion into the conjugated diene in good yields.[21]

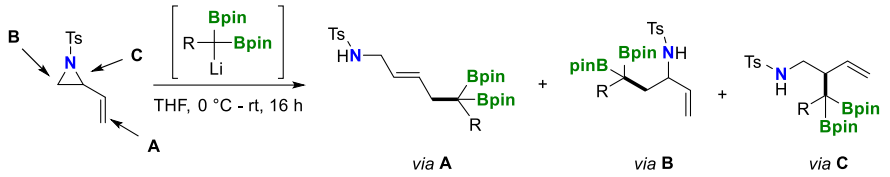


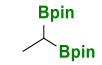
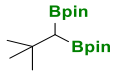
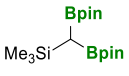
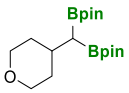
Scheme 4.15 Synthesis of *N*-tosyl vinyl aziridines from conjugated 1,3-dienes. Reaction conditions for the aziridination: 5 mmol (1 equiv) of the 1,3-diene, 5 mmol (1 equiv) of PhINTs, 0.5 mmol (10 mol%) of $Cu(acac)_2$ and 10 mL of acetonitrile (MeCN) were stirred at rt for 30 minutes.

To study the viability of our work, 1-tosyl-2-vinylaziridine (**4.10**) was selected as model substrate to react with *gem*-diborylalkanes in the presence of a base. To conduct the study, 1 equiv of bis(pinacolboryl)ethane (**4.1**) was deprotonated with 1.2 equiv of LiTMP, in THF at 0 °C (for 30 min), to form *in situ* the substituted 1,1-diborylmethide lithium salt with a molecular formula of $LiC(Bpin)_2(CH_3)$. The addition of 0.8 equiv of the aziridine **4.10** was performed at 0 °C and the mixture was stirred initially for 10 minutes followed by 16 h at rt. After this reaction time, the substrate was quantitatively transformed into two different products. The major product (**4.14**) was isolated in 64% yield, suggesting a ring-opening nucleophilic attack on the less sterically hindered position, *via* S_N2 (Table 4.1, entry 1). Nevertheless, the *E*-homoallylboronate product **4.13** was also obtained and isolated in 35% due to the S_N2' ring opening reaction (Table 4.1, entry 1). Similarly, the *tert*-butyl and trimethylsilyl substituted *gem*-diborylalkanes $HC(Bpin)_2(^tBu)$ (**4.3**) and $HC(Bpin)_2(SiMe_3)$ (**4.7**) showed a favoured reactivity on the less sterically hindered position *via* S_N2 ring-opening reaction to afford products **4.16** and **4.18**, respectively (Table 4.1, entries 2 and 3). Moreover, both diboryl reagents also reacted *via* S_N2' with the aziridine **4.10** obtaining the *E*-homoallylboronates **4.15** and **4.17**, respectively (Table 4.1, entries 2 and 3). Interestingly, when 2,2'(tetrahydro-2*H*-pyran-4-yl)methylenebis(pinacolboronate) (**4.2**) was employed as *gem*-

diborylalkane reagent, the reaction outcome with substrate **4.10** was conducted exclusively *via* S_N2 ring-opening/C-C coupling. The product of the nucleophilic attack was isolated on the less sterically hindered position, providing 63% of product **4.19** (Table 4.1, entry 4). The minor product **4.20** was simultaneously formed by the nucleophilic ring opening reaction on the allylic position (Table 4.1, entry 4).

Table 4.1 Diborylalkylation / ring-opening reaction of 1-tosyl-2-vinylaziridine.[a]

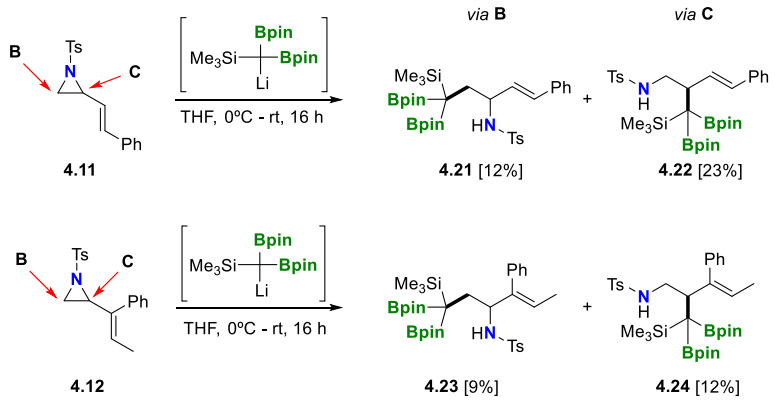


Entry	*gem*-diborylalkane	Products [IY%][b]		
		via **A**	*via* **B**	*via* **C**
1	 **4.1**	**4.13** [35%]	**4.14** [64%]	---
2	 **4.3**	**4.15** [38%]	**4.16** [53%]	---
3	 **4.7**	**4.17** [25%]	**4.18** [56%]	---
4	 **4.2**	---	**4.19** [63%]	**4.20** [36%]

[a] Reaction conditions for the ring-opening reaction: 0.5 mmol (1 equiv) of *gem*-diborylalkane and 0.6 mmol (1.2 equiv) of LiTMP in 2 mL of THF were stirred at 0 °C for 30 min. Then 0.4 mmol (0.8 equiv) of vinyl aziridine and 1 mL of THF were added and the mixture was stirred at 0 °C for 10 min followed by 16 h at rt. [b] [IY%] = Isolated yields in %.

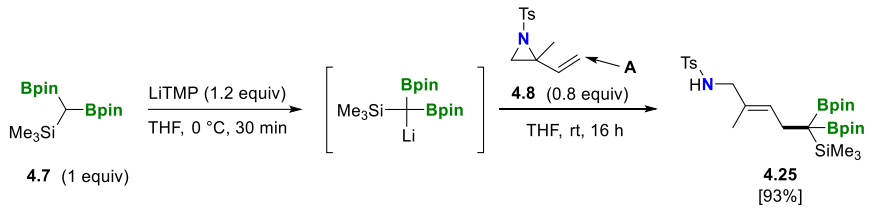
We next studied the reactivity between (*E*)-2-styryl-1-tosylaziridine (**4.11**) and the diborylsilymethide lithium salt formed from the corresponding *gem*-diborylalkane **4.7** by deprotonation with LiTMP. The generated products **4.21** and **4.22** suggested a suppression of the S_N2' ring-opening reaction pathway **A**,

favouring the nucleophilic attack on the more congested position of the aziridine **4.11** (Scheme 4.16, top). The analogous (*E*)-2-(1-phenylprop-1-en-1-yl)-1-tosylaziridine (**4.12**) undergoes S_N2 ring-opening reaction on both position of the aziridine group obtaining the products **4.23** and **4.24** (Scheme 4.16, bottom). Low yields were afforded suggesting a certain instability of the electronically conjugated products, during the purification protocol.



Scheme 4.16 Diborylalkylation / ring-opening reaction between substituted vinyl aziridines **4.11** and **4.12**, and $LiC(Bpin)_2(SiMe_3)$. Reaction conditions for the ring-opening reaction: 0.5 mmol (1 equiv) of *gem*-diborylalkane and 0.6 mmol (1.2 equiv) of LiTMP in 2 mL of THF were stirred at 0 °C for 30 min. Then 0.4 mmol (0.8 equiv) of vinyl aziridine and 1 mL of THF were added and the mixture was stirred at 0 °C for 10 min followed by 16 h at rt.

To our delight, when 2-methyl-1-tosyl-2-vinylaziridine (**4.8**) was explored for diborylalkylation ring-opening reaction with $HC(Bpin)_2(SiMe_3)$ (**4.7**) and LiTMP, it could be observed the exclusive formation of the allylic amine/homoallylic boronate product **4.25** resulting from the regioselective S_N2' ring-opening reaction (Scheme 4.17). The reaction occurred with complete stereocontrol towards the formation of the *E*-stereoisomer.



Scheme 4.17 Regioselective S_N2' diborylalkylation/ring-opening reaction of vinyl aziridine **4.8** with $LiC(Bpin)_2(SiMe_3)$. Reaction conditions for the ring-opening reaction: 0.5 mmol (1 equiv) of *gem*-diborylalkane and 0.6 mmol (1.2 equiv) of LiTMP in 2 mL of THF were stirred at 0 °C for 30 min. Then 0.4 mmol (0.8 equiv) of vinyl aziridine and 1 mL of THF were added and the mixture was stirred at 0 °C for 10 min followed by 16 h at rt. Isolated yield in brackets.

To confirm the absolute configuration of the exclusive stereoisomers afforded in the S_N2' ring-opening reaction of vinyl aziridine **4.8** with **4.7** and LiTMP, one-dimensional Nuclear Overhauser Effect (1D NOE) experiments of the product **4.25** were conducted. To deeply analyse these experiments, it was necessary to assign every signal in the ^1H NMR (Figure 4.1a).

The aromatic protons of the tosyl group (H_h and H_i) were assigned at 7.29 ppm and 7.73 ppm, as well as the olefinic proton (H_c) that can be observed at 5.40 ppm. The amino proton H_g was assigned at 4.17 ppm, whereas the allylic protons H_a and methyl moiety of the tosyl group seem to appear at 3.34 ppm and at 2.42 ppm, respectively. The allylic protons H_d were assigned at 2.22 ppm as well as the protons of olefinic methyl group (H_b) that were assigned at 1.55 ppm. Finally, the protons of the Bpin moiety (H_e) and the trimethylsilyl protons (H_f) can be observed at 1.16 ppm and 0.05 ppm, respectively (Figure 4.1a).

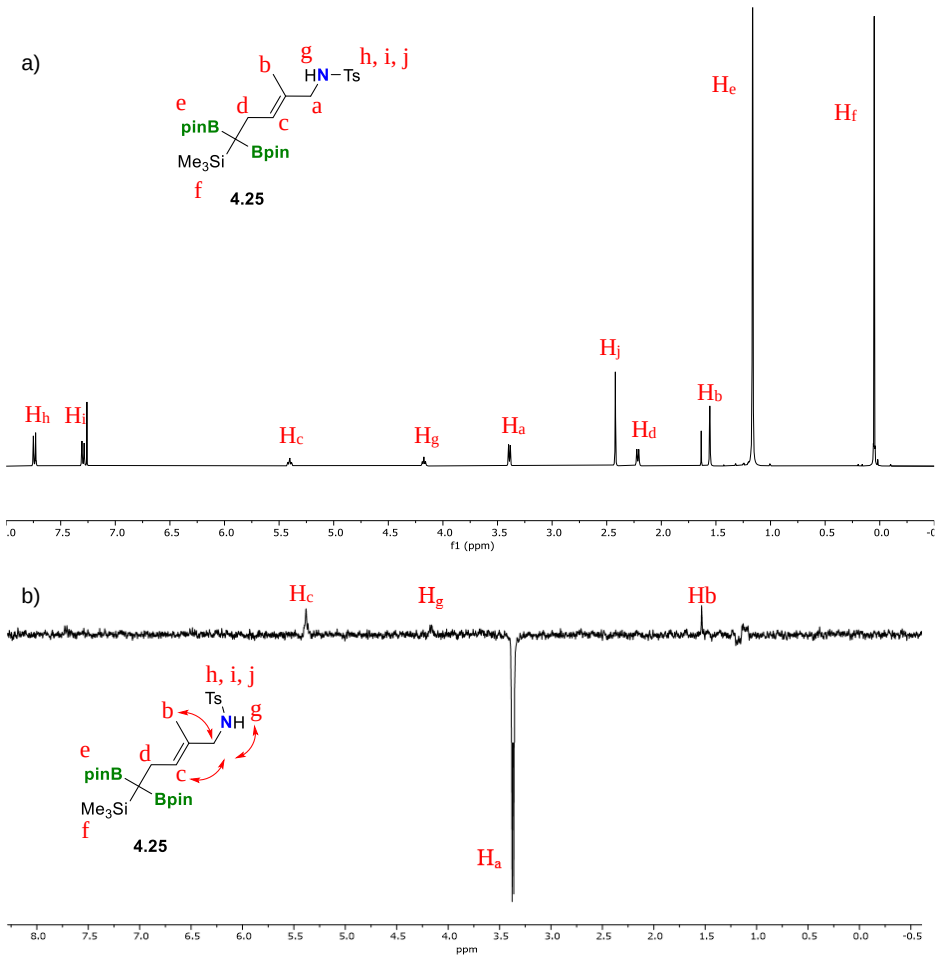


Figure 4.1 For comparison, ^{1}H NMR and 1D NOE experiment irradiating at 3.34 ppm (H_a) of product **4.25**.

To conduct the 1D NOE experiment of product **4.25**, the allylic protons H_a were selected to be irradiated in order to justify the absolute stereoselectivity. The irradiated protons at 3.34 ppm disclosed three main signals in the experiment corresponding to the vinylic proton H_c (5.36 ppm), the amino proton H_g (4.12 ppm) and the olefinic methyl protons H_b (1.51 ppm) (Figure 4.1b). This fact was in accordance with the assignment of the *E*-stereoisomer. On the contrary, if the afforded product was the *Z*-stereoisomer, the allylic protons H_d should have had response on the 1D NOE experiment instead of H_c (Figure 4.2).

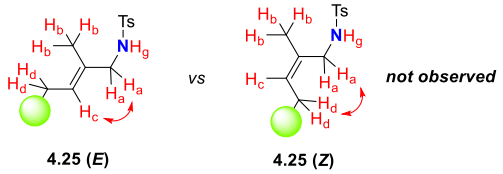
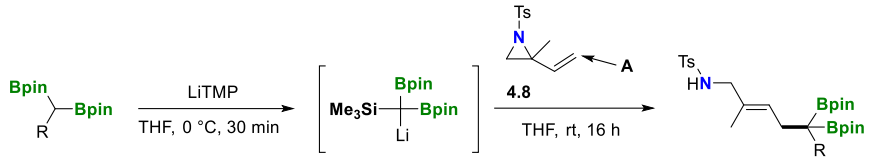
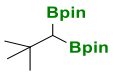
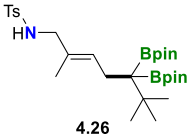
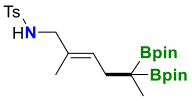
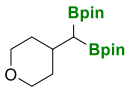
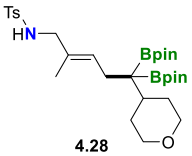
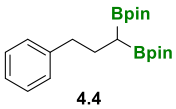
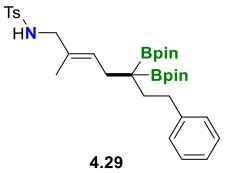
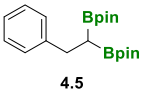
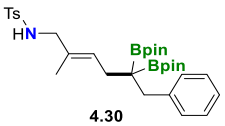
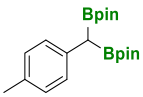
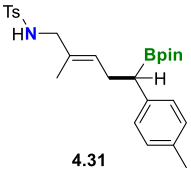


Figure 4.2 Expected differences of NOE effect of the *E*/*Z* isomers of product **4.25**.

When the *gem*-diborylalkanes **4.1**, **4.2** and **4.3** (containing primary, secondary and tertiary C_β substituents) were involved in the reaction with aziridine **4.8**, it was observed that quantitative isolated yields on the desired products (**4.26**, **4.27** and **4.28**) were isolated, suggesting a favoured S_N2' mechanism (Table 4.2, entries 1-3). Nevertheless, the *gem*-diborylalkanes, bearing 1-phenyl-ethyl (**4.4**) and benzyl (**4.5**) substituents, undergo the ring-opening reaction *via* S_N2' in moderate isolated yields (Table 4.2, entries 4 and 5). This fact can be justified due to the lack of stability of the products during the purification process since no other byproducts were observed in the reaction media. However, the use of 2,2'-(*p*-tolylmethylene)bispinacolboronate **4.6** proceeded as expected *via* S_N2' ring-opening/C-C bond formation, but protodeboronation occurred affording the product **4.31** containing only one boryl moiety (Table 4.2, entry 6). It is suggested that the inner reactivity of the benzylic boron group in the α-diborylbenzyl carbanion might justify the favoured protodeborations under basic conditions, as it was observed in previous studies.[22,23]

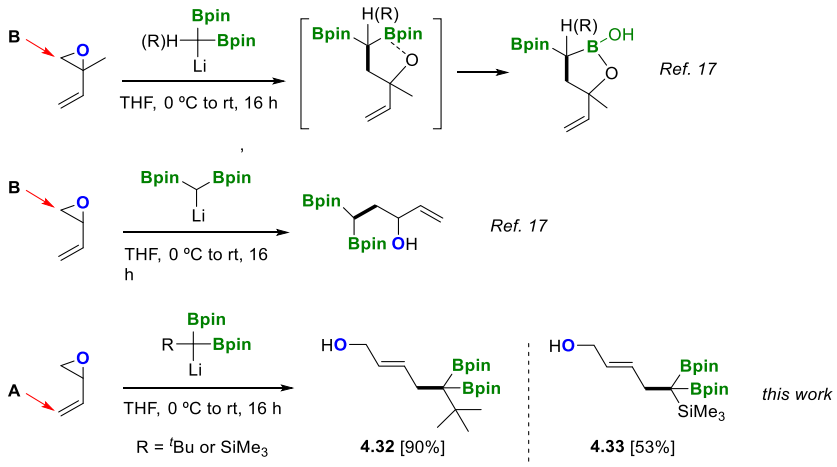
Table 4.2 Regioselective S_N2' diborylalkylation/ring-opening reaction of vinyl aziridine **4.8**.[a]



Entry	*gem*-diborylalkane	Product	[IY%][b]
1	 4.3	 4.26	[96%]
1	 4.1	 4.27	[98%]
3	 4.2	 4.28	[99%]
4	 4.4	 4.29	[50%]
5	 4.5	 4.30	[75%]
6	 4.6	 4.31	[65%]

[a] Reaction conditions for the ring-opening reaction: 0.5 mmol (1 equiv) of *gem*-diborylalkane and 0.6 mmol (1.2 equiv) of LiTMP in 2 mL of THF were stirred at 0 °C for 30 min. Then 0.4 mmol (0.8 equiv) of vinyl aziridine **4.8** and 1 mL of THF were added and the mixture was stirred at 0 °C for 10 min followed by 16 h at rt. [b] [IY%] = Isolated yields in %.

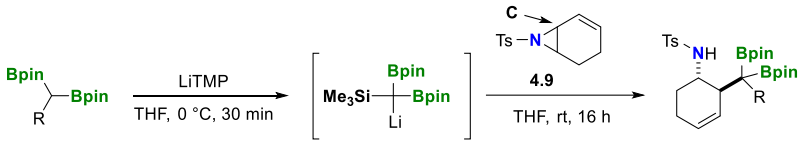
For comparison, the favoured regioselectivity observed on the diborylmethylation of the vinyl aziridines **4.8** and **4.10** was opposite to the reactivity observed in the analogous vinyl epoxides, under the same reaction conditions (Scheme 4.18). Nucleophilic attack of diborylalkyl lithium salts occurred exclusively on the less steric hindered position of 2-methyl-2-vinyloxirane *via* S_N2 mechanism with concomitant intramolecular cyclisation affording the substituted 3-borylated-1,2-oxaborolan-2-ol product. (Scheme 4.18, top).[17] In the case of 2-vinyloxirane, the reaction also proceeded through a ring-opening reaction on the homoallylic position with 1,1-diborylmethide lithium salt, obtaining the corresponding allylic alcohol (Scheme 4.18, centre).[17] Interestingly, when we conducted the reaction with 2-vinyloxirane and substituted *gem*-diborylmethide lithium salts, the S_N2'ring-opening reaction was exclusively observed (Scheme 4.18, bottom).

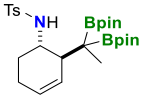
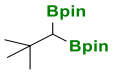
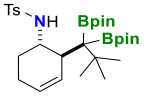
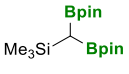
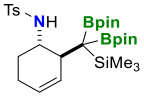
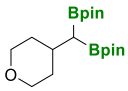
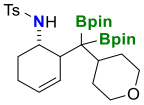
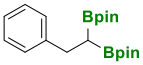
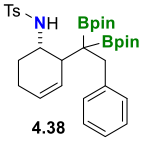
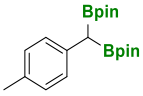
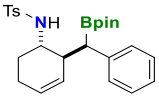


Scheme 4.18 For comparison, see the regioselective diborylalkylation/ring-opening reaction of 2-methyl-2-vinyloxirane and 2-vinyloxirane with substituted and non-substiuted *gem*-diborylalkyl lithium salts.

The reactivity between the cyclic 7-tosyl-7-azabicyclo[4.1.0]hept-2-ene (**4.9**) and different *gem*-diborylalkyl lithium salts was also explored and, in contrast to the favoured S_N2' ring-opening reaction of non-cyclic vinyl aziridine **4.8**, it was observed that **4.9** suffered an exclusive S_N2 nucleophilic attack at the allylic position with the subsequent aziridine ring-opening (Table 4.3).

Table 4.3 Regioselective S_N2 diborylalkylation/ring-opening reaction of vinyl aziridine **4.9**.[a]

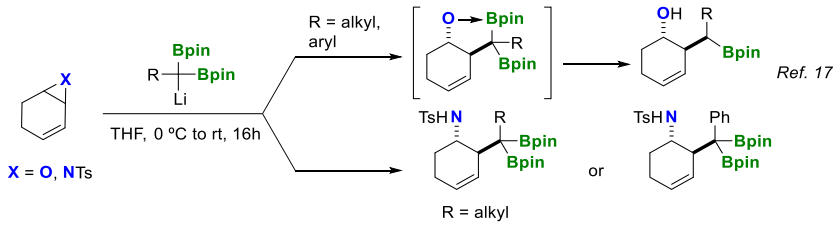


Entry	*gem*-diborylalkane	Product	[IY%][b]
1	 **4.1**	 **4.34**	[98%]
2	 **4.3**	 **4.35**	[98%]
3	 **4.7**	 **4.36**	[99%]
4	 **4.2**	 **4.37**	[96%]
5	 **4.5**	 **4.38**	[51%]
6	 **4.6**	 **4.39**	[66%]

[a] Reaction conditions for the ring-opening reaction: 0.5 mmol (1 equiv) of *gem*-diborylalkane and 0.6 mmol (1.2 equiv) of LiTMP in 2 mL of THF were stirred at 0 °C for 30 min. Then 0.4 mmol (0.8 equiv) of vinyl aziridine **4.9** and 1 mL of THF were added and the mixture was stirred at 0 °C for 10 min followed by 16 h at rt. [b] [IY%] = Isolated yields in %.

The reaction was completely stereoselective forming exclusively homoallyldiboronate compounds with *trans* disposition of the NHTs and $C(Bpin)_2R$ groups, maintaining the two boron moieties unaltered in the final product. Substituted *gem*-diborylalkanes **4.1**, **4.2**, **4.3** and **4.7** containing primary, secondary and tertiary C_β substituents and a TMS group, proceeded through a regioselective S_N2 ring-opening reaction affording the desired homoallyldiboronate products **4.34**-**4.37** in quantitative isolated yields (Table 4.3, entries 1-4). Reagent **4.5**, bearing a benzyl group, also allowed the formation of the homoallyldiboronate **4.38** in moderate isolated yield (Table 4.3, entry 5). Nevertheless, when the tolyl substituted *gem*-diborylalkane **4.6** is involved in the reaction, it can be observed that the obtained ring-opening product **4.39** retained only one boryl moiety, suggesting a protodeboronation pathway as a consequence of the steric hindrance of the α-diboryltolyl carbanion (Table 2, entry 6). Both entries 5 and 6 provided quantitative conversion on the desired products without any observed byproduct formation, but isolated yields were only modest, suggesting an instability of the products during purification.

Similar protodeboronation sequence was observed in the diborylalkylation of the analogous cyclic vinyl epoxide 3,4-epoxy-1-cyclohexene, providing the homoallylboronate products with only one boron moiety remaining at the final products. This fact was completely independent of which substituents were bearing the *gem*-diborylalkane (Scheme 4.19, top).[17]



Scheme 4.19 Comparative diborylalkylation ring-opening reaction with substituted *gem*-diborylalkyl lithium salts and cyclic vinyl epoxide (top) and cyclic vinyl aziridine (bottom).

It suggested an intramolecular interaction of the hydorxy group with one of the boron moieties favouring the protodeboronation in the sterically hindered tetrasubstituted carbon. In comparison with that study, in the case of the aziridine, two boron moieties were maintained in the final product, when R = alkyl groups, suggesting that this N-B interaction is not favoured (Scheme 4.19, bottom), except for the synthesis of product **4.39**, when R = Ph.

4.5. Conclusions

Summarising this chapter, we have conducted the regioselective ring-opening reaction on different vinyl aziridines with diborylalkyl lithium salts. It has been observed a preferred S_N2 ring-opening/C-C bond formation reaction on the less sterically hindered position of 1-tosyl-2-vinylaziridine in contrast to the favoured S_N2' diborylalkylation on 2-methyl-1-tosyl-2-vinylaziridine. Additionally, α-diboryl carbanions reacted with the cylcic 7-tosyl-7-azabicyclo[4.1.0]hept-2-ene *via* S_N2 ring-opening reaction on the allylic position affording exclusively homoallyldiboronate species with *trans* disposition of the amine and the diborylmethyl moiety. Despite the fact that the regioselectivity depends on the nature of the vinyl aziridines, the resulting products maintained the two boryl moieties unaltered except for those reactions where aryl substituted *gem*-diborylalkanes were involved, suggesting that protodeboronation seems to proceed due to steric hindrance around the tetrasubstituted carbon. All of the diborylalkylation/ring-opening products synthesised in this chapter have been prepared for the first time.

4.6. References

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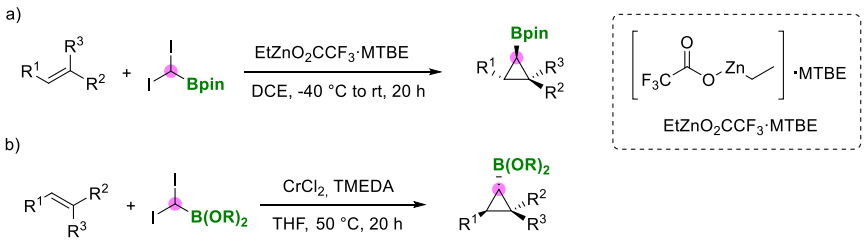
CHAPTER 5

Cyclopropanation of 1,1-diborylalkenes with (trimethylsilyl)diazomethane.

5.1. State of the art

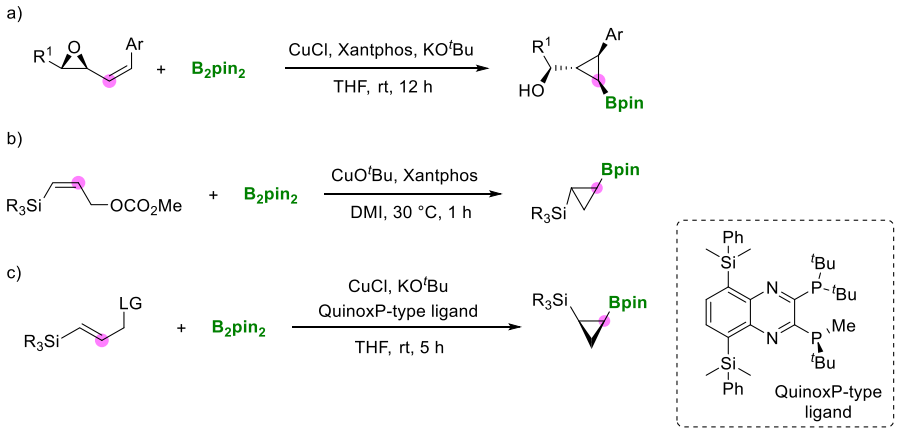
The presence of boryl substituents in cyclopropane rings is a growing area of interest to the scientific community, since it provides the chance to transform the cyclopropyl structure into more complex molecules.[1] Nevertheless, direct access to cyclopropylboronates, with high levels of diastereoselectivity, is still a challenge.[2]

The known Simmons-Smith reaction has been considered one of the strategic methodologies to achieve borylcyclopropanes. In this context, Charette and co-workers established a borylmethyl-cyclopropanation of substituted olefines using a borylmethylzinc carbenoids. The reaction proceeds with the olefin substrate, the reagent $I_2CH(Bpin)$ as borylmethyl source and $EtZnO_2CCF_3$·MTBE in 1,2-dichloroethane (DCE), affording the corresponding borylcyclopropanes with excellent stereocontrol of the reaction (Scheme 5.1a).[3] Additionally, Takai and co-workers studied the reactivity of unactivated alkenes with diiodomethyl boronic esters in the presence of a large excess of $CrCl_2$ and tetramethylethylenediamine (TMEDA). It was observed that the reaction can be performed under mild reaction conditions and with good stereoselectivity depending exclusively on the steric effects of the alkene (Scheme 5.2b).[4]



Scheme 5.1 Strategic synthesis of borylcyclopropanes through Simmons-Smith reaction catalysed by a) $EtZnO_2CCF_3$·MTBE anb b) $CrCl_2$/TMEDA.

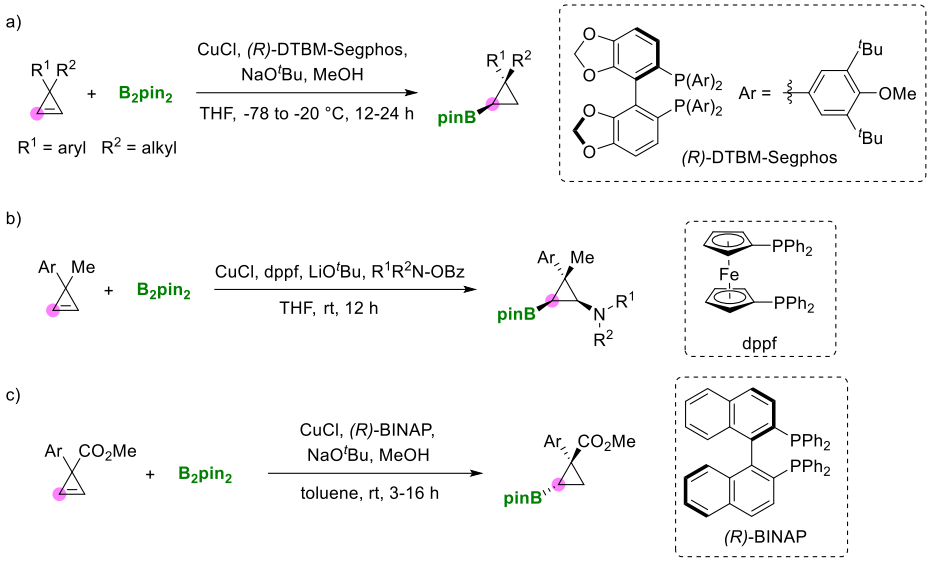
Alternatively, Tortosa and co-workers developed a ring-opening/ring-closing reaction of readily available allylic epoxides using inexpensive Cu(I) source as CuCl, and Xantphos as ligand, in the presence of B_2pin_2 and KO^{t}Bu. The reaction takes place through a borylcupration of the alkene moiety with the concomitant intramolecular S_N2 reaction to afford the corresponding borylcyclopropanes (Scheme 5.2a).[5] Ito and co-workers deeply studied the Cu-catalysed borylative ring-closing of allyl compounds, assisted by a base, using different conditions depending on the nature of the allyl substrates. The reactivity of substituted *Z*-vinylsilanes with Cu-O^{t}Bu, Xantphos and B_2pin_2 in 1,3-dimethyl-2-imidazolidinone (DMI) undergoes *trans*-borylsilylcyclopropanes with complete stereocontrol of the reaction (Scheme 5.2b).[6] The stereoselective ring-closing of substituted *E*-vinylsilanes was performed, by the same group, with B_2pin_2, KO^{t}Bu, in the presence of CuCl and a modified chiral QuinoxP-type ligand, generating the corresponding *cis*-borylsilylcyclopropanes (Scheme 5.2c).[7]



Scheme 5.2 Synthesis of borylcyclopropanes *via* ring-closing reactions from a) vinyl epoxides, b) *Z*-vinylsilanes and c) *E*-vinylsilanes.

Additionally, desymmetrisation of cyclopropenes has been established as an alternative synthetic strategy to generate cyclopropylboronates. In this context,

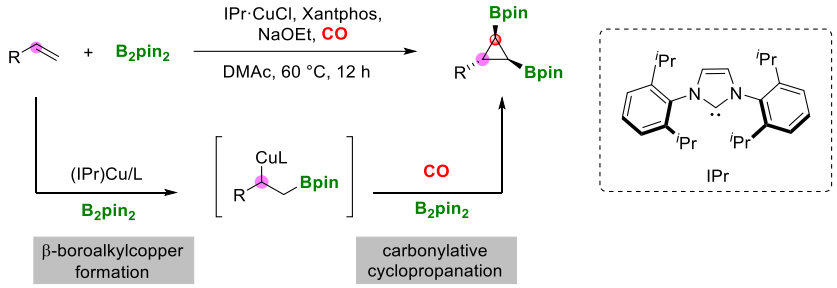
Tortosa and co-workers studied the diastereo- and enantioselective Cu-catalysed hydroboration of cyclopropenes. This methodology allows the formation of cyclopropylboronates using CuCl as catalyst, (*R*)-DTBM-Segphos as ligand, and B_2pin_2 as hydroboration agent in the presence of NaO^{t}Bu and a large excess of MeOH (Scheme 5.3a).[8] In the same work, the electrophilic trapping of cyclopropylboronate with electrophilic amines (*O*-benzoyl-*N*,*N*-dialkylhydroxylamines) was also explored using a CuCl/dppf catalyst system, LiO^{t}Bu and B_2pin_2 (Scheme 5.3b).[8] Alternatively, Lin and co-workers established a copper-catalysed asymmetric hydroboration reaction of 3-aryl-3-methylester substituted cyclopropenes with the use of CuCl/(*R*)-BINAP catalytic system, B_2pin_2, NaO^{t}Bu and MeOH (Scheme 5.3c).[9]



Scheme 5.3 Desymmetrisation of 3,3-disubstituted cyclopropenes with a) CuCl/(*R*)-DTBM-Segphos, b) CuCl/dppf and c) CuCl/(*R*)-BINAP catalytic systems.

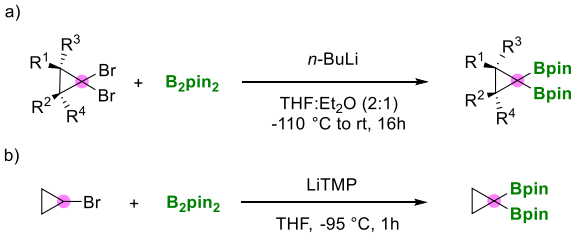
Wu and co-workers studied a copper-catalysed stereodefined procedure for the selective synthesis of cyclopropyl vicinal bis(boronates) from terminal alkenes. The reaction proceeds in the presence of IPr·CuCl/Xantphos as catalytic system, NaOEt, B_2pin_2 in dimethylacetamide (DMAc) under 10 bars of CO

(Scheme 5.4).[2] This strategy involves, firstly, the formation of β-boroalkylcopper species that undergo the desired product through a carbonylative cyclopropanation at a later stage (Scheme 5.4).



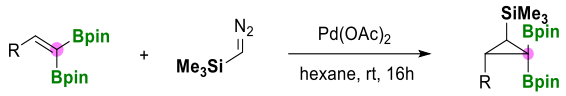
Scheme 5.4 Cyclopropanation of terminal alkenes with IPrCuCl/Xantphos catalytic system, NaOEt, B_2pin_2 and CO.

Hiyama and co-workers reported the synthesis of 1,1-diborylcyclopropanes from the corresponding 1,1-dibromocyclopropanes. The reaction of 1,1-dibromocyclopropanes with *n*-butyl lithium (*n*-BuLi) generates cyclopropylidene carbenoid species that subsequently reacts with B_2pin_2 to furnish the corresponding *gem*-diborylcyclopropanes (Scheme 5.5a).[10] Moreover, Harris et al. established the reactivity of bromocyclopropanes and B_2pin_2 in the presence of an excess of LiTMP. In this case, the reaction proceeds *via* the formation of cyclopropyl bromide lithiolate species followed by the concomitant reaction with B_2pin_2 (Scheme 5.5b).[11]



Scheme 5.5 Synthesis of 1,1-diborylcyclopropanes from a) 1,1-dibromocyclopropanes and b) bromocyclopropanes.

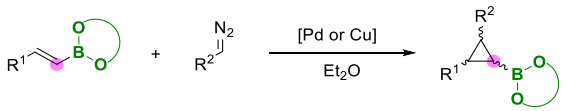
Within those precedents in mind, we planned a new strategic synthesis of 1,1-cyclopropyl bis(boronates) from the corresponding 1,1-diborylalkenes *via* Pd-catalysed carbene insertion of (trimethylsilyl)diazomethane (Scheme 5.6). The stereoselectivity of the reaction was the main challenge in this study.



Scheme 5.6 Stereoselective cyclopropanation of 1,1-diborylalkenes *via* Pd-catalysed (trimethylsilyl)diazomethane insertion.

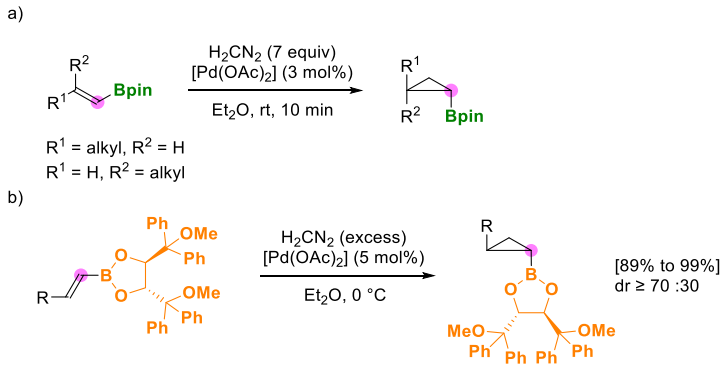
5.2. Context of the work

The use of alkenylboronates as substrates for the preparation of cyclopropanes has also been described through carbene insertion. The reaction proceeds *via* metal-catalysed carbene insertion from the substituted diazomethane and the corresponding alkenylboronates (Scheme 5.7).[12]



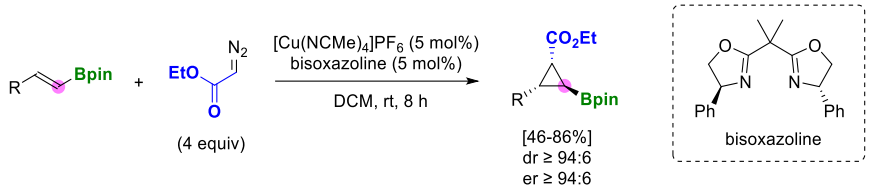
Scheme 5.7 Synthtesis of cyclopropylboronates *via* metal-catalysed carbene insertion into alkenylboronates.

The reactivity of alkenylboronates with diazomethane in the presence of $Pd(OAc)_2$ was firtsly studied by Carboni and co-workers. The cyclopropanation proceeds by addition of a carbene which is generated by diazomethane decomposition in the presence of palladium acetate (Scheme 5.8a).[13] Pietruszka and co-workers promoted the use of chiral diols in the alkenylboronates to furnish the diastereoselective cyclopropanation of the olefins with $[Pd(OAc)_2]$ and diazomethane (Scheme 5.8b).[14]



Scheme 5.8 Synthesis of cyclopropylboronates *via* Pd-catalysed carbene insertion to alkenylboronates with a) pinacol boryl and b) chiral boryl moieties. Isolated yields in brackets.

Alternatively, Pérez and co-workers studied the diastereo- and enantioselective cyclopropanation of alkenylboronates with ethyl diazoacetate, using copper(I)/bisoxazoline catalytic systems. The reaction of *E*-alkenylboronates with 4 equiv of ethyl diazoacetate is catalysed by the presence of $[Cu(NCMe)_4]PF_6$ (5 mol%) and a bisoxazoline ligand to afford 1-boryl-2,3-disubstituted cyclopropanes (Scheme 5.9).[1]



Scheme 5.9 Diastereo- and enantioselective Cu-catalysed cyclopropanation of 1-alkenylboronates.

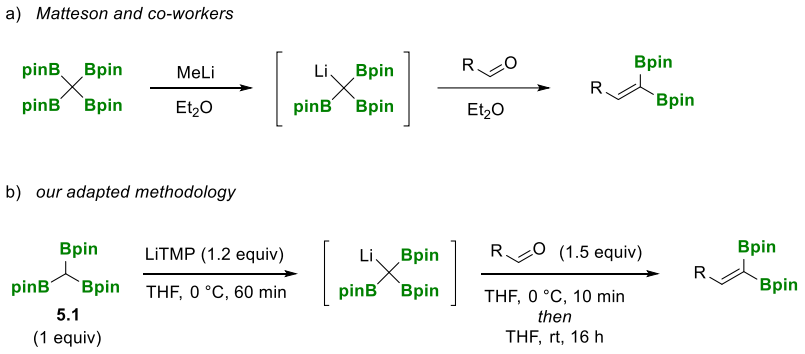
5.3. Specific objectives

The main objective of the chapter is to explore the cyclopropanation reaction of 1,1-diborylalkenes *via* palladium-catalysed (trimethylsilyl)diazomethane insertion. The specific objectives are:

1. Design new synthetic strategies for the synthesis of 1,1-diborylalkenes.
2. Determine the viability of (trimethylsilyl)diazomethane insertion on 1,1-diborylalkenes in the presence of Pd complex.
3. Study the stereoselectivity of the Pd-catalysed cyclopropanation.
4. Perform the orthogonal metal-free boron activation and the concomitant protodeboronation.
5. Synthesis of polyfunctional cyclopropyl alcohols.

5.4. Results and discussion

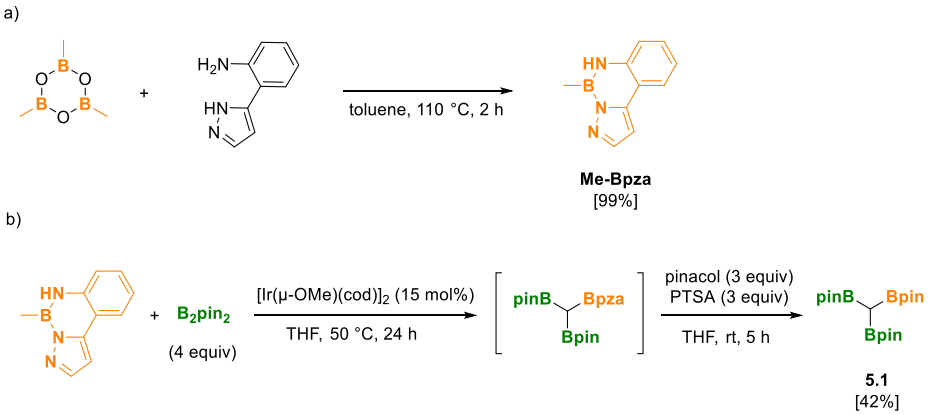
To carry out this study, it was necessary the synthesis of 2-substituted 1,1-diborylalkenes because they are not commercially available. Diverse synthetic methodologies were employed to afford the desired 2-substituted 1,1-diborylalkenes, depending on the nature of the substituents. Initially, it was designed a synthetic strategy based on the condensation of tris(pinacolboryl)methane (**5.1)** with aldehydes, in the presence of LiTMP followed by the B-O elimination (Scheme 5.10b). Matteson and co-workers originally described the reactivitiy of tris(boryl)methide carbanions, which were formed by treatment of tetra(boryl)methane with methyllithium (MeLi), in the presence of formaldehyde or benzaldehyde, affording the corresponding 2-substituted 1,1-diborylalkenes after the expected B-O elimination (Scheme 5.10a).[15]



Scheme 5.10 Strategic synthesis of 1,1-diborylalkenes *via* boron-Wittig reaction between a) tetra(pinacolboryl)methane and aldehydes, and b) tris(pinacolboryl)methane (**5.1**) and aldehydes.

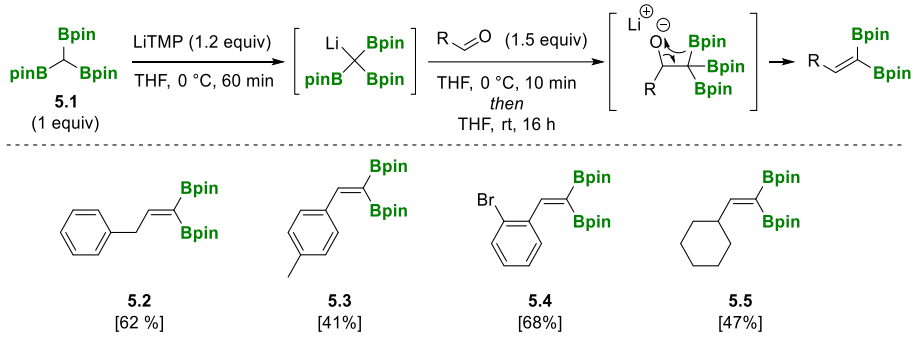
In order to perform the boron-Wittig reaction with tris(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)methane (**5.1**), we had to prepare this reagent since it is not commercially available. To afford the desired **5.1**, it was used an adapted synthetic methodology developed by Suginome and co-workers.[16] The first step consists on the reactivity of 1 equiv of trimethylboroxine with 1 equiv of

2-(1*H*-pyrazol-5-yl)aniline (pza), in toluene at 110 °C for 2 h. The generated 5-methyl-5,6-dihydrobenzo[e]pyrazolo[1,5-c][1,3,2]diazaborinine (**Me-Bpza**) was obtained in 99% isolated yield (Scheme 5.11a). The second step is an Ir-catalysed double C-H borylation sequence. The compound **Me-Bpza** reacts with 4 equiv of B_2pin_2 in the presence of 15 mol% of $[Ir(\mu\text{-OMe})(cod)]_2$ in THF and the reaction mixture was stirred at 50 °C for 24 h. After this period of time, 3 equiv of pinacol and 3 equiv of *p*-toluenesulfonic acid (PTSA) were added to the reaction, and the mixture was stirred for additional 5h at room temperature. After the purification, tris(pinacolboryl)methane **5.1** was obtained in 42% isolated yield (Scheme 5.11b).



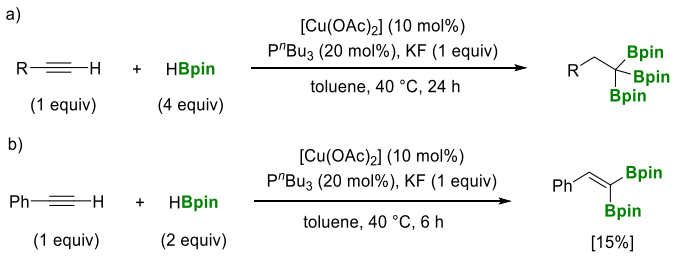
Scheme 5.11 Complete synthesis of tris(pinacolboryl)methane **5.1** in two steps, a) synthesis of **Me-Bpza** and b) Ir-catalysed double C-H activation/borylation of **Me-Bpza** and treatment with pinacol and PTSA. Isolated yields in brackets.

The isolation of **5.1** allowed us to start with the preparation of 1,1-bis(pinacolboryl)alkenes *via* boron-Witting reaction. The diborylated compounds **5.2**, **5.3**, **5.4** and **5.5** were synthesised through the condensation of tris(boryl)methane with the corresponding aldehydes followed by the subsequent B-O elimination (Scheme 5.12).



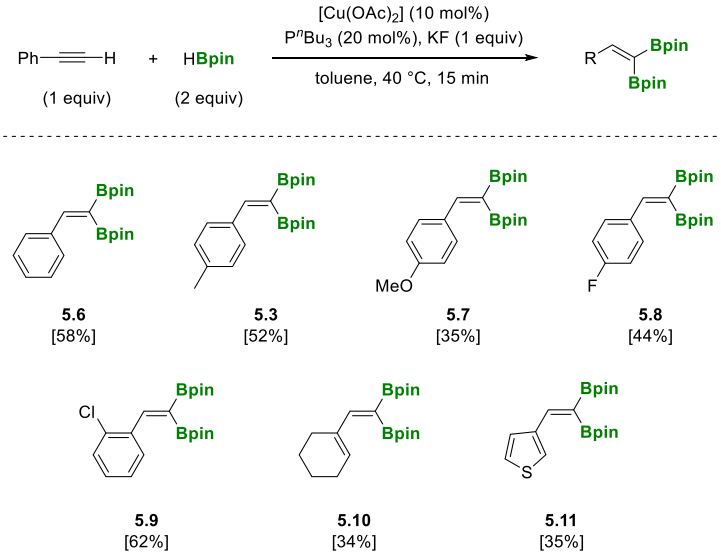
Scheme 5.12 Synthesis of 2-substituted 1,1-diborylalkenes **5.2**, **5.3**, **5.4** and **5.5**. Reaction conditions: 0.3 mmol (1 equiv) of **5.1** and 0.36 mmol (1.2 equiv) of LiTMP in 2 mL of THF were stirred at 0 °C for 30 min. Then 0.45 mmol (1.5 equiv) of the corresponding aldehyde were added and the mixture was stirred at 0 °C for 10 min followed by 16h at rt. Isolated yield in brackets.

We also developed an alternative methodology to prepare 2-substituted 1,1-diborylalkenes from easily available terminal alkynes *via* copper-catalysed dehydrogenative borylation/hydroboration with pinacolborane (HBpin). Marder and co-workers studied a related reactivity to afford triborylalkanes from terminal alkynes.[17] The reaction of terminal alkynes, with 4 equiv of HBpin, 1 equiv of KF and the presence of 10 mol% of $[Cu(OAc)_2]$ and 20 mol% of P^nBu_3, in toluene at 40 °C for 24 h, undergoes a dehydrogenative borylation followed by a double hydroboration to afford the desired tris(pinacolboryl)alkanes (Scheme 5.13a). They performed some mechanistic experiments, and they suggested the formation of 1,1-bis(boryl)alkene when using 2 equiv of HBpin and reducing the reaction time to 6 h (Scheme 5.13b).



Scheme 5.13 a) Cu-catalysed synthesis of 1,1,1-triborylalkanes and b) approach to 1,1-diborylalkenes. Isolated yields in brackets.

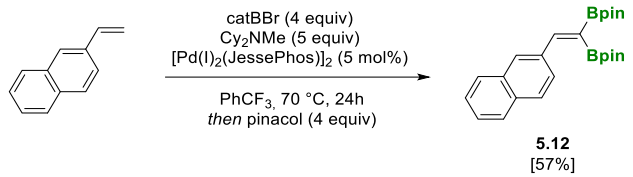
With this precedent in mind, we designed an alternative synthetic methodology to obtain the 2-substituted 1,1-diborylalkenes **5.6**, **5.7**, **5.8**, **5.9**, **5.10** and **5.11** (Scheme 5.14), as well as the preparation of **5.3** in order to compare the isolated yield with the one obtained in Scheme 5.12. The reaction proceeds using 1 equiv of the corresponding terminal alkyne, 2 equiv of HBpin and 1 equiv of KF in the presence of 10 mol% of [$Cu(OAc)_2$] and 20 mol% of P^nBu_3. The reaction was carried out with toluene as solvent and the mixture was stirred at 40 °C for 15 min. After the purification, the desired 1,1-bis(pinacolboryl)alkenes were obtained in moderate and good yields. The key point in the reactivity relies on the reaction time because at 15 minutes the formation of 2-substituted 1,1-diborylalkene starts to compete with its reactivity with HBpin towards the triborylated product formation. Therefore, after 15 min, we could isolate the desired 2-substituted 1,1-diborylalkenes in moderate yield, but ias it can be seen for **5.3**, the yields are slightly improved with respect to its synthesis in Scheme 5.12.



Scheme 5.14 Synthesis of 1,1-diborylalkenes. Reaction conditions: 2 mmol (1 equiv) of KF and 0.2 mmol (10 mol%) of $Cu(OAc)_2$ were mixed in 2.5 mL of toluene. Then 0.4 mmol (20 mol%)

of P^{n}Bu$_3$, 2 mmol (1 equiv) of the corresponding alkyne and 4 mmol (2 equiv) of HBpin were added in this order. The reaction mixture was stirred at 40 °C for 15 min. Isolated yields in brackets.

The 2-naphtyl substituted 1,1-diborylalkene **5.12** was prepared following a synthetic methodology reported by Watson and co-workers based on a boron-Heck reaction.[18] The substrate 2-vinylnaphthalene (1 equiv) reacts with 4 equiv of 2-bromo-1,3,2-benzodioxaborole (catBBr), 5 equiv of *N*,*N*-dicyclohexyl-methylamine (Cy_2NMe) and 5 mol% of $[Pd(I)_2(JessePhos)]_2$ in trifluorotoluene as solvent ($PhCF_3$), generating the corresponding 1,1-bis(catecholboryl)alkene. The subsequent treatment of the reaction with 4 equiv of pinacol was necessary to afford the desired 2-(2-naphthyl) 1,1-bis(pinacolboryl)alkene (Scheme 5.15).

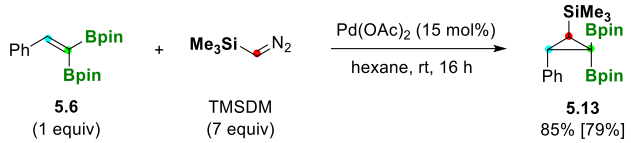


5.12
[57%]

Scheme 5.15 Synthesis of 1,1-diborylalkene **5.12** through a boron-Heck reaction. Reaction conditions: 0.025 mmol (5 mol%) of $[Pd(I)_2(JessePhos)]_2$ was stirred in 5 mL of $PhCF_3$ at rt for 10 min. Then 5 mmol (5 equiv) of Cy_2NMe, 4 mmol (4 equiv) of catBBr and 1 mmol (1 equiv) of 2-vinylnaphthalene were added sequentally and the reaction mixture was stirred at 70 °C for 24h. Then 4 mmol (4 equiv) of pinacol were added at rt and the mixture was stirred for additional 1 h at rt. Isolated yields in brackets.

With all the 2-substituted 1,1-bis(pinacolboryl)alkenes synthesised, we next studied the Pd-catalysed cyclopropanation using (trimethylsilyl)diazomethane (TMSDM) as carbene source to be added on the substrates affording polyfunctionalised 1,1-diboryl-2-silylcyclopropanes. The 1,1-diborylalkene **5.6** was selected as model substrate to perform the proof of concept. The reaction was conducted with 1 equiv of **5.6** and 7 equiv of TMSDM in the presence of 15 mol% of $Pd(OAc)_2$, in hexane at rt. The reaction was completed

within 16 hours, with total control of the stereoselectivity, resulting in the new product **5.13** where the trimethylsilyl and phenyl groups were placed in relative *anti* conformation (Scheme 5.16).



5.6 (1 equiv) | TMSDM (7 equiv) | **5.13** 85% [79%]

Scheme 5.16 Stereoselective cyclopropanation of **5.6** with (trimethylsilyl)diazomethane in the presence of $Pd(OAc)_2$. Reaction conditions: 0.2 mmol (1 equiv) of **5.6** and 0.03 mmol (15 mol%) of $Pd(OAc)_2$ in 1 mL of hexane were stirred at rt for 5 minutes. Then 1.4 mmol (7 equiv) of TMSDM (2M) in hexane were added and the reaction mixture was stirred at rt for 16 h. NMR yield calculated using naphthalene as internal standard. Isolated yield in brackets.

The stereoselectivity of the reaction was complete and in order to confirm the *anti* distribution of the trimethylsilyl and phenyl group, a 1D NOE experiment was conducted. The signals of the product **5.13** in the ^1H NMR spectrum are shown in Figure 5.1.

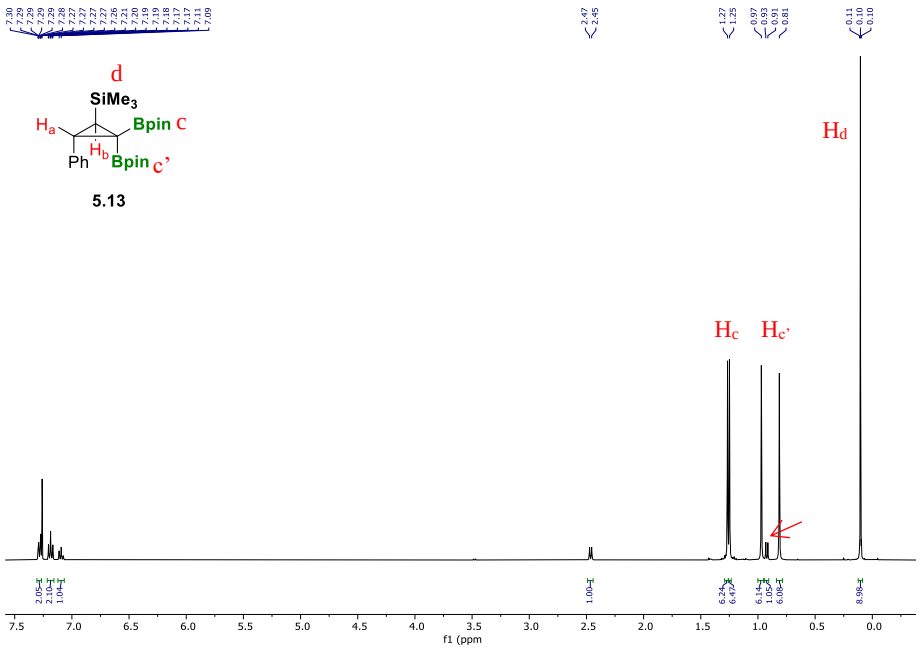


Figure 5.1 Signal assignment of ^{1}H NMR for product **5.13**.

To conduct the 1D NOE experiment of product **5.13**, the protons of trimethylsilylgroup were selected to be irradiated in order to justify the absolute stereoselectivity. The irradiated protons at 0.10 ppm disclose three signals on the 1D NOE spectrum corresponding to proton H_a at 2.45 ppm, proton H_b at 0.91 ppm and the pinacolboryl protons H_c at 1.24 ppm confirming not only the *anti* conformation of the trimethylsilyl and the phenyl group, but also confirming the correct assignment of the two boryl moieties on the ^{1}H NMR (Figure 5.2).

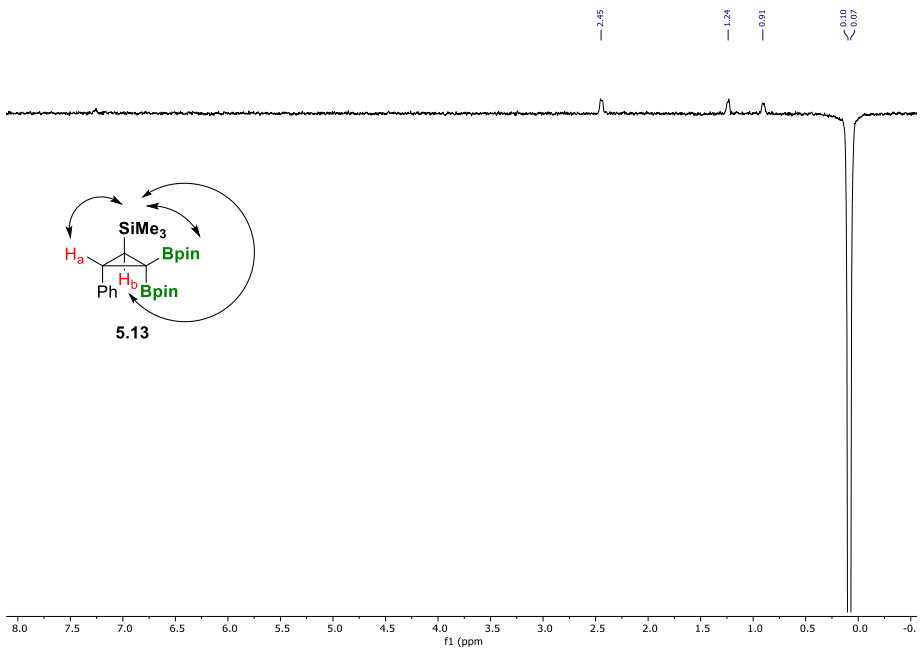
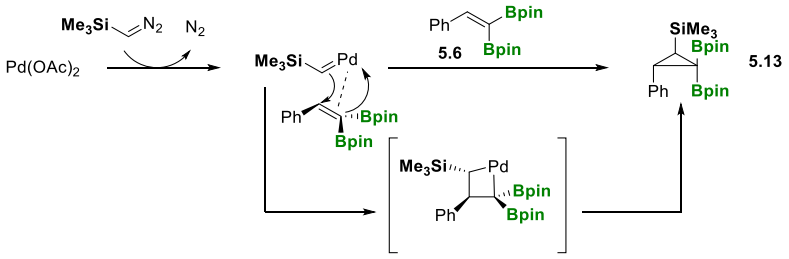


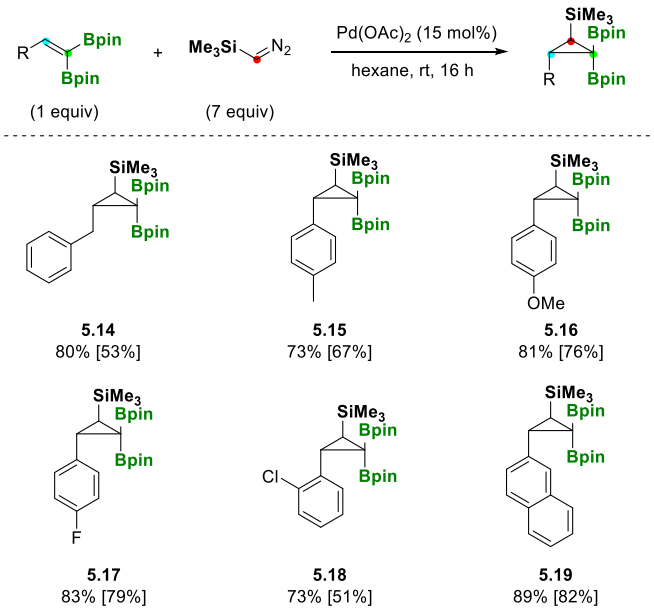
Figure 5.2 1D NOE experiment irradiating at 0.10 ppm (H_d) of product **5.13**.

The suggested model for the diastereoselectivity on the Pd-catalysed cyclopropanation of 1,1-bis(pinacolboryl)alkene **5.6** with TMSDM might involve the formation of the palladium carbene with the subsequent N_2 release followed by the migratory insertion of Pd=CH-TMS into the compound **5.6** (Scheme 5.17).



Scheme 5.17 Suggested mechanistic model of Pd-catalysed stereoselective cyclopropanation of **5.6**.

We next conducted the Pd-catalysed stereoselective cyclopropanation extending the reactivity to other 2-substituted 1,1-bis(pinacolboryl)alkenes. The *gem*-diborylalkene **5.2**, containing a benzyl group, undergoes cyclpropanation reaction to afford **5.14** in 53% isolated yield (Scheme 5.18).

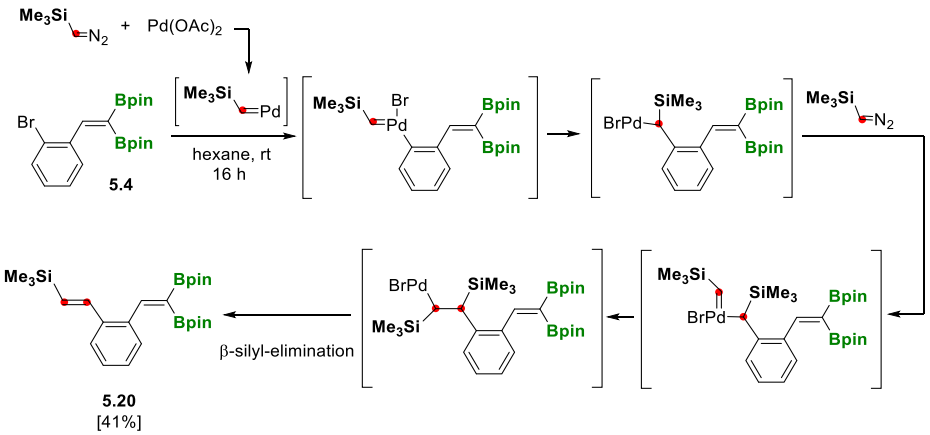


Scheme 5.18 Substrate scope of 2-substituted 1,1-bis(pinacolboryl)alkenes for Pd-catalysed stereoselective cyclopropanation with TMDSM in the presence of $Pd(OAc)_2$. Reaction conditions: 0.2 mmol (1 equiv) of the *gem*-diborylalkene and 0.03 mmol (15 mol%) of $Pd(OAc)_2$ in 1 mL of hexane were stirred at rt for 5 minutes. Then 1.4 mmol (7 equiv) of TMSDM (2M= in hexane were added and the reaction mixture was stirred at rt for 16 h. NMR yield calculated using naphthalene as internal standard. Isolated yield in brackets.

The 1,1-diborylalkenes **5.3**, **5.7** and **5.8**, bearing *para* substituents (Me-, MeO- and F-) on the aryl group, react with (trimethylsilyl)diazomethane, in the presence of $Pd(OAc)_2$ generating the corresponding 1,1-diborylcyclopropanes **5.15**, **5.16** and **5.17** in similar isolated yields (67%, 76% and 79%, respectively). It suggests that the cyclopropanation is slightly influenced by electron rich or electron poor aryl substituents decreasing the yield when the aryl contains an electron-donating group on the *para* position. However, the *gem*-diborylalkene **5.9**, which contains an *ortho* chloride group on the aryl, proceeded throughout the cyclopropanation reaction to furnish the product **5.18** in moderate 51%

isolated yield. Finally, 2-substituted 1,1-diborylalkene **5.12** (containing a naphthyl group) generates the desired product **5.19** in 82% isolated yield.

Surprisingly, when 2-bromophenyl 1,1-diborylalkene **5.4**, containing a Br group on *ortho* position of the aryl group, reacts with (trimethylsilyl)diazomethane in the presence of $Pd(OAc)_2$, the cyclopropanation does not occur and the *(E)*-vinyl silane product **5.20** was obtained instead, in 41% isolated yield (Scheme 5.19). The observed reactivity can be explained by the oxidative addition of the Ar-Br to the Pd, followed by a double-palladium carbene migratory insertion process.[19] Finally, β-silyl-elimination occurs affording the unexpected product **5.20** (Scheme 5.19).

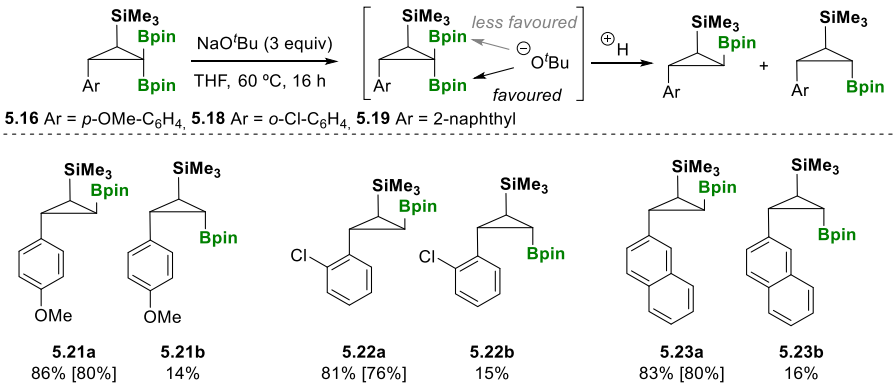


Scheme 5.19 Pd-catalysed olefination of *gem*-diborylalkene **5.4** with TMSDM.

Interestingly, all attempts to conduct the Pd-catalysed stereoselective cyclopropanation of *gem*-diborylalkenes **5.5**, **5.10** and **5.11**, which contain 2-cyclohexyl, 2-cyclohexenyl and 2-(3-thiophenyl) groups respectively, were not successful, suggesting an inhibited migratory insertion of the alkene into the Pd=CH-TMS intermediate as a consequence of the lower electrophilic character of the 2-substituted $C(sp^2)$.

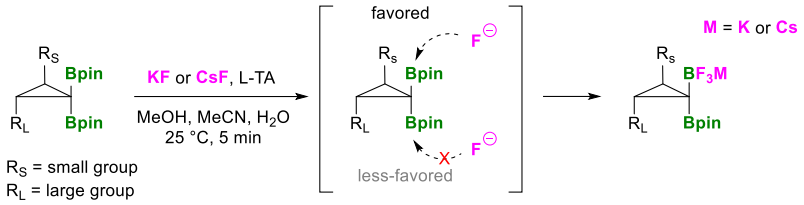
The orthogonal functionalisation of *gem*-bis(pinacolboryl)cyclopropanes was also studied. The addition of 3 equiv of NaO^tBu to the previously prepared 1,1-

diboryl-2-silylcyclopropane **5.16**, allowed the protodeboronation to occur, showing a preferred activation of the Bpin moiety placed in *syn* conformation to the aryl group, generating **5.21a** in 86% yield. The activation of the Bpin moiety in *syn* conformation to the trimethylsilyl group occurs in minor manner, affording the protodeboronated product **5.21b** only in 14% yield (Scheme 5.20). Similar trend was observed when the *gem*-bis(pinacolboryl)cyclopropanes **5.18** and **5.19** reacted under the protodeboronation conditions generating the products **5.22a**/**5.22b**, and **5.23a**/**5.23b** respectively (Scheme 5.20). The trimethylsilyl group, might act as a protecting group towards the oxidation of the *trans* vicinal Bpin group.



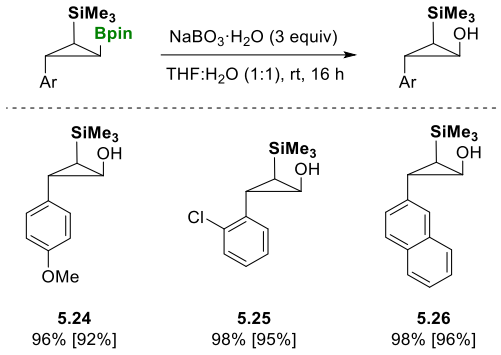
Scheme 5.20 Site-selective protodeboronation of *gem*-bis(pinacolboryl)cyclopropanes with NaO^{t}Bu. Reaction conditions: 0.2 mmol (1 equiv) of the corresponding *gem*-bis(pinacolboryl)cyclopropanes and 0.6 mmol (3 equiv) of NaO^{t}Bu in 2 mL of THF were stirred at 60 °C for 16 h. NMR yields calculated using naphthalene as internal standard. Isolated yields in brackets.

This hypothesis was in agreement with the diastereoselective desymmetrisation of *gem*-bis(pinacolboryl)cyclopropanes reported by Masarwa and co-workers.[20,21] The desymmetrisation reaction was performed with KF or CsF in the presence of a slight excess of L-tartaric acid (L-TA), in MeOH and acetonitrile (MeCN), towards the formation of trifluorinated boron salt on the less steric hindered Bpin moiety (Scheme 5.21).



Scheme 5.21 Diastereoselective desymmetrisation of *gem*-diborylcyclopropanes with KF or CsF.

Finally, the oxidation of the isolated products **5.21a**, **5.22a** and **5.23a** was performed with 3 equiv of $NaBO_3 \cdot H_2O$ in 2 mL of a mixture of THF:H_2O (1:1), and the reaction was stirred for 16 h at room temperature. The corresponding alcohols **5.24-5.26** were obtained in quantitative yields (Scheme 5.22).



Scheme 5.22 Oxidation of protodeboronated cyclopropanes **5.21a**, **5.22a** and **5.23a** with $NaBO_3 \cdot H_2O$. Reaction conditions: 0.1 mmol (1 equiv) of protodeboronated cyclopropane and 0.3 mmol (3 equiv) of $NaBO_3 \cdot H_2O$ in a mixture of THF:H_2O (1:1) were stirred at rt for 16 h. NMR yields calculated using naphthalene as internal starndard. Isolated yields in brackets.

5.5. Conclusions

Summarising this chapter, two new strategic synthesis of 1,1-diborylalkenes were designed. The first one consists in a boron-Wittig reaction between aldehydes and triborylmethide lithium salt. The second one is a Cu-catalysed dehydrogenative borylation/hydroboration of terminal alkynes with pinacolborane (HBpin). It was conducted a Pd-catalysed stereoselective cyclopropanation of 2-substituted 1,1-diborylalkenes with (trimethylsilyl)diazomethane affording substituted *gem*-bis(pinacolboryl)cyclopropanes, placing the TMS and the aryl groups in *anti* conformation.

Further orthogonal activation of boryl moieties were perfomed *via* protodeboronation pathway, controlling the activation with the steric hindrance of TMS group. Substituted stereodefined cyclopropanols were generated with the subsequent oxidation of the protodeboronated products.

5.6. References

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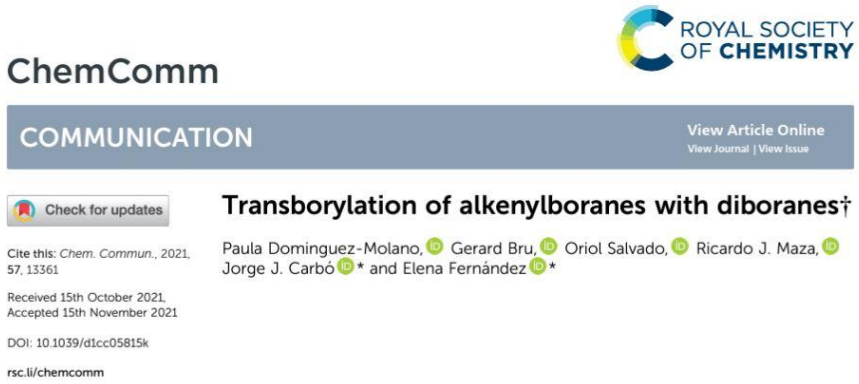
CHAPTER 6

Scientific collaborations

This chapter includes contributions to other publications in which I have participated in parallel to the main line of research of this doctoral thesis. These collaborations have been carried out in conjunction with other members of the research group.

6.1. Transborylation of alkenylboranes with diboranes

(*Chem. Commun.* **2021**, *57*, 13361-13364)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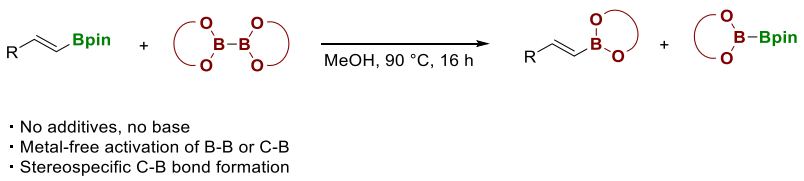
Transborylation of alkenylboranes with diboranes†

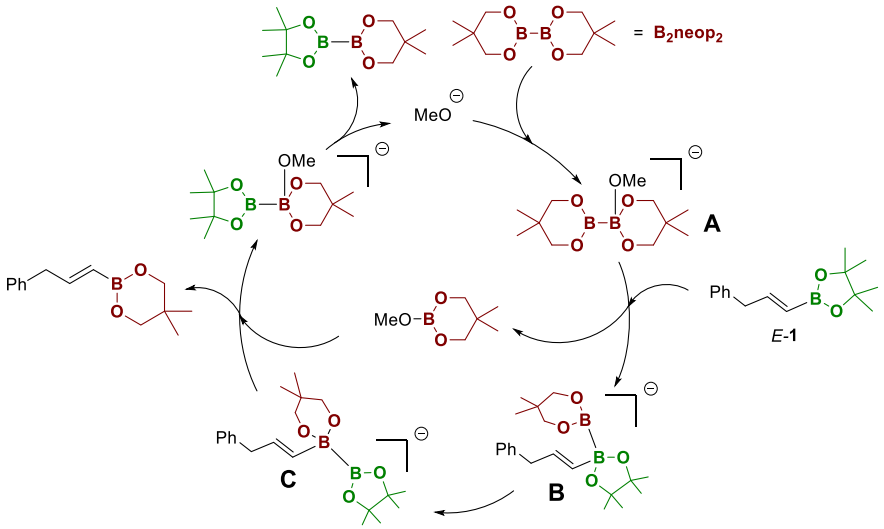
Paula Dominguez-Molano, Gerard Bru, Oriol Salvado, Ricardo J. Maza, Jorge J. Carbó * and Elena Fernández *

This article was published on Chemical Communications journal, and it describes a new stereocontrolled exchange of boryl moieties between alkenylboronates and diboron reagents (Scheme 6.1). The reactivity has been demonstrated as an efficient strategy for *(E)*-1,2-, *(Z)*-1,2-, 1,1- and 1,1,2-substituted vinylboranes, as well as for diverse type of diboron reagents.



Scheme 6.1 Stereoretentive metal-free transborylation of alkenylboronates with diboron reagents.

The role of the alcohol solvent or alkoxy base in transborylation is regarded to the diboron reagent activation, acting as Lewis base. In the case of methanol, the methoxide can be generated *via* autoprotolysis and the mechanism proposed by DFT calculations can be divided in four main steps. The first one is the diboron activation by the alkoxide, followed by the nucleophilic attack of the activated boron to the electrophilic C(sp^2)-B. The third step is the shift of the alkenyl fragment from the initial C-B to the formation of the new C-B bond. Finally, the transborylated product and the mixed diboron reagent are formed preserving the *E* stereochemistry of the original alkene (Scheme 6.2).

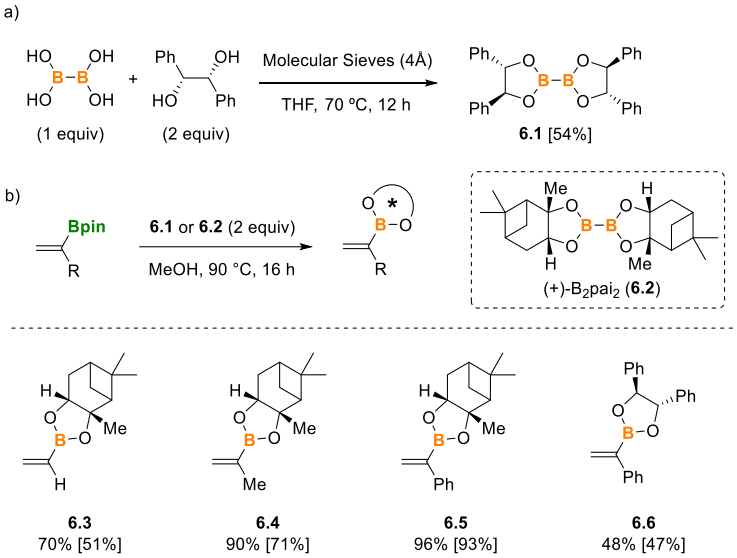


Scheme 6.2 Suggested mechanism for the transborylation of *E*-1 with B_2neop_2 in the presence of MeOH.

My personal contribution to this project was mainly monitoring the experimental part of the full study which were performed by a member of the research group (Paula Dominguez-Molano) as part of her master thesis. During all the process I was contributing with different ideas for the development of the project as well as giving support to the master student.

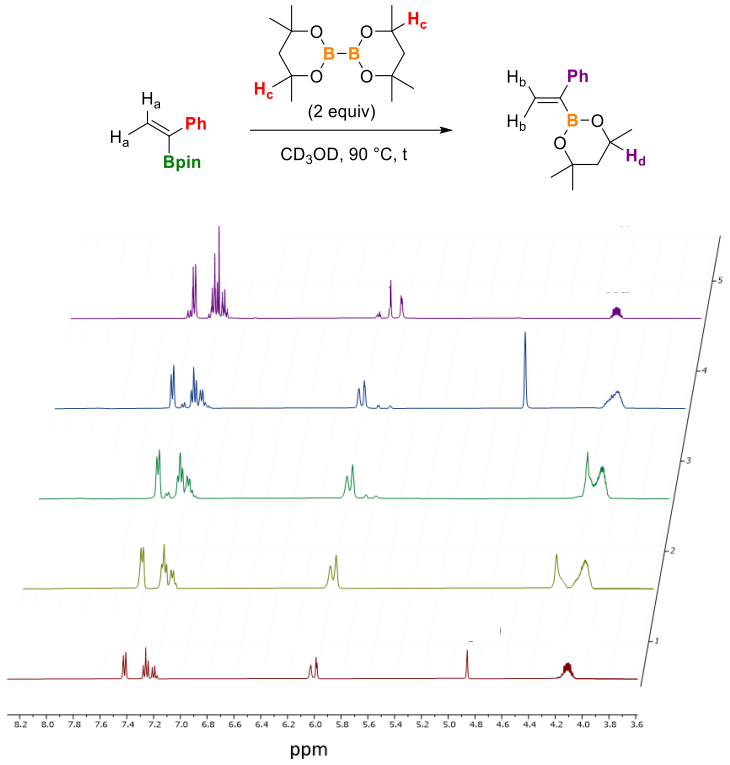
Experimentally, I also synthesised the chiral diboron reagent, (*S*,*S*)-B_2(O-CHPh-CHPh-O)$_2$ (**6.1**) (Scheme 6.3a) from an adapted methodology reported

by Tang and co-workers. (D. Chen, G. Xu, Q. Zhou, L. W. Chung, W. Tang, *J. Am. Chem. Soc.* **2017**, *139*, 9767–9770). I went through the study of the transborylation between 1-substituted-1-borylethenes and the chiral diborons **6.1** and (+)-B_2pai$_2$ (**6.2**) (Scheme 6.3b).



Scheme 6.3 a) Synthesis of chiral diboron reagent **6.2**. Reaction conditions: 1 mmol (1 equiv) of tetrahydorxy diboron and 2 mmol (2 equiv) of (*S*,*S*)-(-)-hydrobenzoin in 2 mL of THF were stirred at 70 °C for 16 h. b) Transborylation reactions between alkenyl pinacolboronates and chiral diboron reagents **6.1** and **6.2**. Reaction conditions: 0.3 mmol (1 equiv) of alkenylboronate and 0.6 mmol (2 equiv) of diboron reagent in 2 mL of MeOH were stirred at 90 °C for 16 h. NMR yields calculated using naphthalene as internal standard. Isolated yields in brackets.

Finally, I conducted an *in situ* ^{1}H NMR experiment (in collaboration with Paula Domínguez-Molano, the first author of the article) to study the evolution of the reactivity between 1-phenyl-1-(pinacolboryl)ethene and B_2hex$_2$ in deuterated methanol (CD_3OD). A ^{1}H NMR experiment was registered at t = 0 min rt to observe the mixture of the initial reagents. After 7 min at 90 °C no reaction products were observed, but after 3 h at 90 °C the protons H_b, corresponding to the transborylated product started to appear. After 16 h at 90 °C, the ^{1}H NMR experiment was conducted at room temperature observing the new proton signals H_b, H_d and signals due to the aromatic group, demonstrating the formation of desired transborylated product (Figure 6.1).


Ha
Ph
Ha
Bpin
Hc
Hc
(2 equiv)
CD3OD, 90 °C, t
Hb
Ph
Hb
Hd
ppm

6.2. 1,2-Dialkylation of 1,1-arylboryl alkenes *via* borata-alkene intermediate

(*Adv. Synth. Catal*. **2022**, *364*, 1701-1707)

COMMUNICATIONS doi.org/10.1002/adsc.202200154 Advanced Synthesis & Catalysis

Very Important Publication

1,2-Dialkylation of 1,1-Arylboryl Alkenes Via Borata-Alkene Intermediate

Sara González,[a] Oriol Salvado,[a] and Elena Fernández[a,*]

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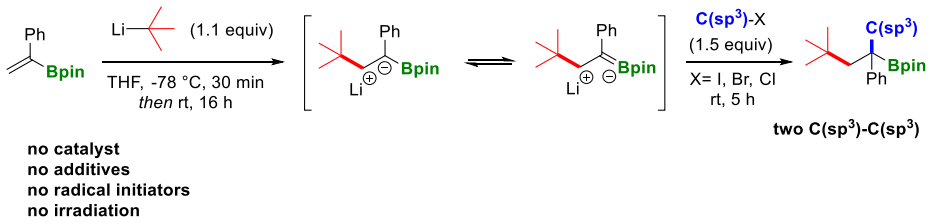
Manuscript received: February 10, 2022; Revised manuscript received: March 30, 2022;

This article was published on Advances in Synthesis and Catalysis journal and was assigned as VIP article (Very Important Publication). It describes the conjugated addition of *tert*-butyllithium to vinylboronic esters generating a borata-alkene intermediate, which undergoes a sequential S_N2 reaction with alkyl halides at room temperature (Scheme 6.4).

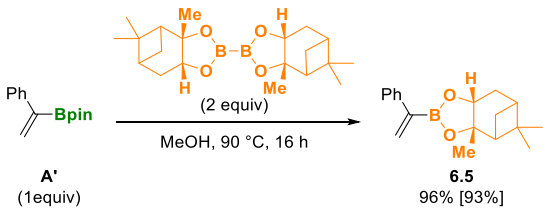


Scheme 6.4 1,2-Dicarbofunctionalisation of 1,1-arylborylethylene with the subsequent formation of two C(sp^3)-C(sp^3) bonds.

This new reactivity avoids the use of metal catalysts, additives, radical initiators, or specific irradiation generating two C(sp^3)-C(sp^3) bonds through 1,2-dicarbofunctionalisation of 1,1-arylborylalkenes.

My personal contribution to this project was mainly supervising the experimental work which was part of the doctoral thesis of a first year PhD student, Sara González. During all the process I contributed overseeing the correct development of the project with different suggestions, as well as supporting the PhD student in the daily work.

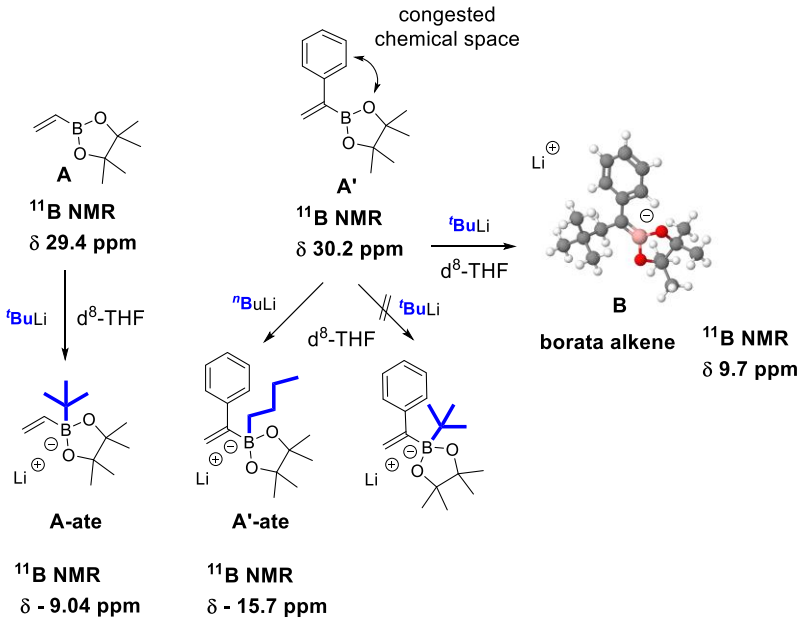
In the experimental part, I performed the transborylation between 1,1-phenyl(pinacolboryl)ethylene and (+)-B_2pai_2 generating the transborylated product **6.5** (93% isolated yield), which could be used for the subsequent study of the dicarbofunctionalisation in a chiral approach (Scheme 6.5).



Scheme 6.5 Transborylation between 1,1-phenyl(pinacolboryl)ethylene and (+)-B_2pai_2 to isolate the chiral substrate **6.5**. Reaction conditions: 0.3 mmol (1 equiv) of 1,1-phenyl(pinacolboryl)ethylene and 0.6 mmol (2 equiv) of (+)-B_2pai_2 in 2 mL of MeOH were stirred at 90 °C for 16 h. NMR yields calculated using naphthalene as internal standard. Isolated yield in brackets.

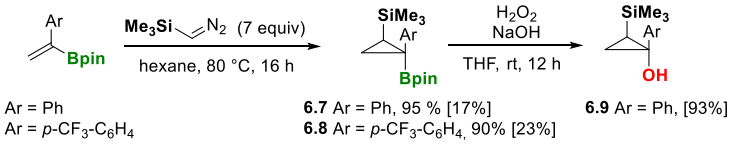
Also, I conducted several ^{11}B NMR experiments (in collaboration with Sara González, the first author of the article) to justify the formation of the borata-alkene intermediate (Scheme 6.6). The work hypothesis to justify the unexpected reactivity between alkenylboronate **A'** and ^{t}BuLi was based on the nucleophilic addition of ^{t}Bu moiety to the terminal carbon of the olefin. The presence of the Ph group in *geminal* position to the Bpin group was fundamental due to the supression of the boron "ate" complex formation, favouring the borata-alkene intermediate formation. The expected interaction of ^{t}Bu moiety with the empty p orbital of the boron seems to be inexistent due to the congested chemical environment in the 1,1-disubstituted alkene. To confirm the hyphothesis, a ^{11}B NMR of the unhindered vinylborane **A** and ^{t}BuLi was

conducted and the boron signal at -9.04 ppm confirms the formation of the quaternised boron "ate" specie in the media (Scheme 6.6, left). The next NMR experiment was carried out mixing the alkenylboronate **A'** and ^{n}BuLi in order to check if the boron "ate" intermediate is formed. To our delight, the ^{11}B signal at -15.7 ppm confirms the presences of boron "ate" species in the media (Scheme 6.6, centre). The addition of ^{t}BuLi to the alkenylboronate **A'** was also checked and no ^{11}B signals in the negative chemical shift of the spectra were observed, suggesting that the boron "ate" intermediate was not formed (Scheme 6.6, centre). Instead, a signal at 9.7 ppm was observed, confirming the formation of the borata-alkene intermediate **B** (Scheme 6.5, right).



Scheme 6.6 ^{11}B NMR experiments to study the formation of the borata-alkene intermediate when reacting alkenylboronat **A'** and ^{t}BuLi. All the NMR experiments were conducted in d^{8}-THF.

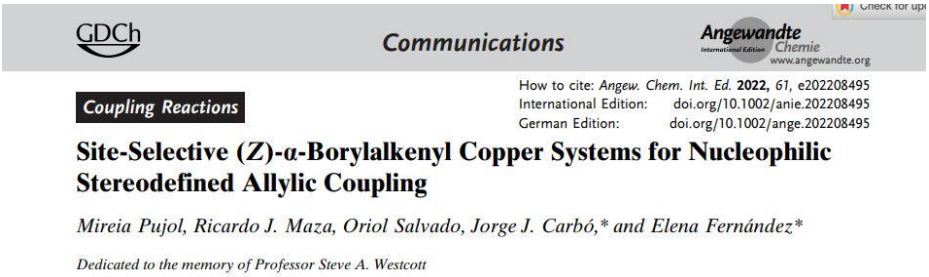
I was also responsible of the experiment based on the trimethylsilyldiazomethane (TMSDM) insertion on the 1,1-arylborylethylene to afford the corresponding trisubstituted cyclopropanes **6.7** and **6.8**, although they only could be isolated in low yields. The realative stereoselectivity shows the exclusive formation of the cyclopropyl compounds with the trimehtylsilyl group and Bpin moiety in *anti* conformation. The subsequent oxidation of the boryl moiety was conducted generating the substituted cyclopropanol **6.9** in 93% isolated yield (Scheme 6.7).



Scheme 6.7 Cyclopropanation reaction of 1,1-arylborylethylene compounds with TMSDM and the subsequent oxidation. Reaction conditions for the cyclopropanation: 0.3 mmol (1 equiv) of alkenylboronates and 2.1 mmol (7 equiv) of TMSDM solution in hexane were stirred at 80 °C for 16 h. Reaction conditions for the oxidation: 0.2 mmol (1 equiv) of cyclopropane was mixed with 1 mL of 3M NaOH solution and 2 mL of H_2O_2 (33% v/v). NMR yields were calculated using naphthalene as internal standard. Isolated yields in brackets.

6.3. Site-selective (*Z*)-α-borylalkenyl copper systems for nucleophilic stereodefined allylic coupling

(*Angew. Chem. Int. Ed.* **2022**, *61*, e202208495)



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Coupling Reactions

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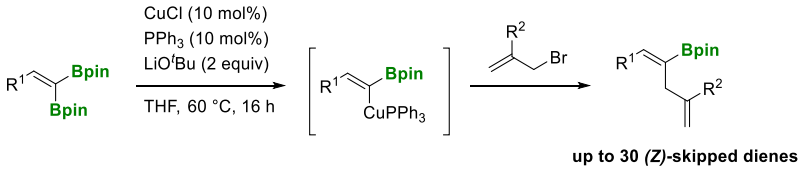
Site-Selective (Z)-α-Borylalkenyl Copper Systems for Nucleophilic Stereodefined Allylic Coupling

Mireia Pujol, Ricardo J. Maza, Oriol Salvado, Jorge J. Carbó, and Elena Fernández**

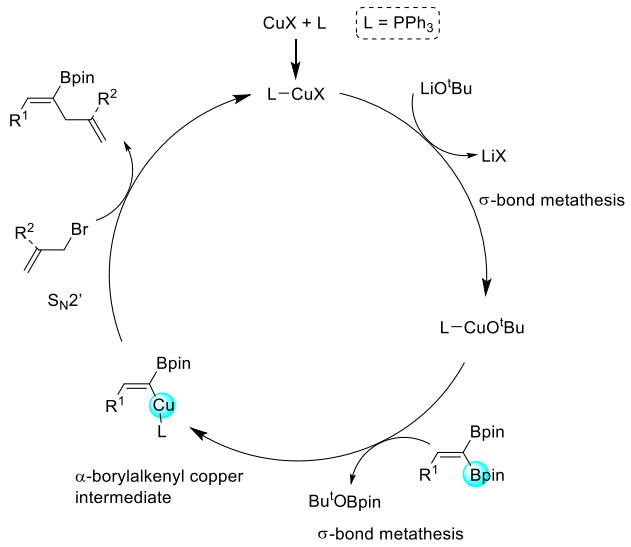
Dedicated to the memory of Professor Steve A. Westcott

This article was published on Angewandte Chemie International Edition journal, and it describes a stereoselective Cu-catalysed allylic coupling between 1,1-diborylalkenes and allyl bromides. The reaction proceeds towards the formation of *(Z)*-α-borylalkenyl copper (I) species and the subsequent nucleophilic attack to the allyl bromides *via* S_N2' pathway (Scheme 6.8). The reactivity allows the formation of up to 30 different *(Z)*-skipped dienes in a stereoselective manner.



Scheme 6.8 Cu-catalysed nucleophilic stereodefined allylic coupling between *gem*-diborylalkenes and allyl bromides.

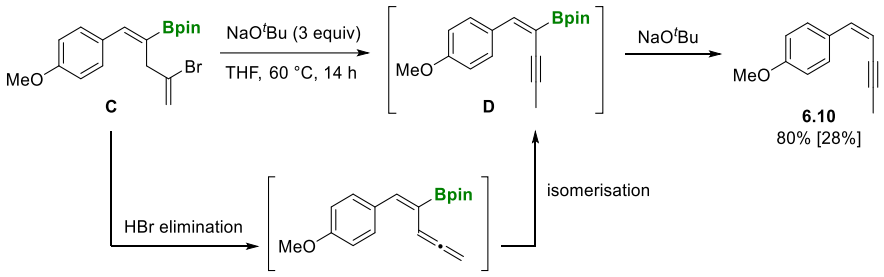
The observed reactivity was opposite to the previously reported activation/functionalisation of 1,1-diborylalkenes. All precedents showed that the activation of 1,1-diborylalkene takes place along the less hindered boryl moiety in *trans* position to the R^1 substituent. However, in our project, the *cis* boryl moiety was exclusively activated under our optimised reaction conditions. Computational studies were conducted in collaboration with Ricardo J. Maza and J. Carbó in order to justify that the observed reactivity involved the energetically favoured activation of the Bpin moiety placed in *cis* position to the R^1 group. With the experimental and computational results, the followed catalytic cycle was suggested (Scheme 6.9).



Scheme 6.9 Suggested mechanism for Cu-catalysed synthesis of (*Z*)-skipped dienes from 1,1-diborylalkenes.

My personal contribution to this project was mainly the supervision of the experimental work which was conducted by a member of the group (Mireia Pujol) as part her master thesis. During all the process I was monitoring the master student as well as giving suggestions for the study.

In the experimental part I conducted the first base-assisted transformation of the skipped dienes affording the enyne product **6.10** (Scheme 6.10). The *(Z)*-skipped diene **C** reacts with 3 equiv of NaO^{t}Bu generating the boryl enyne intermediate **D** that undergoes a protodeboronation with the excess of base. The formation of the intermediate **D** was suggested *via* HBr elimination/isomerisation.



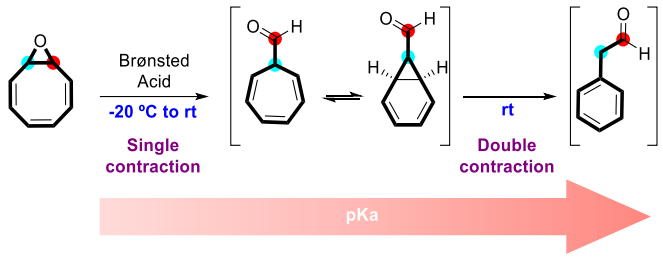
Scheme 6.10 Base-assisted transformations of the skipped diene **C** towards the formation of the enyne product **6.10**.

6.4. Switchable Brønsted acid-catalysed ring contraction of cyclooctatetraene oxide towards the enantioselective synthesis of cycloheptatrienyl-substituted homoallylic alcohols and oxaborinanes

(Article submitted)

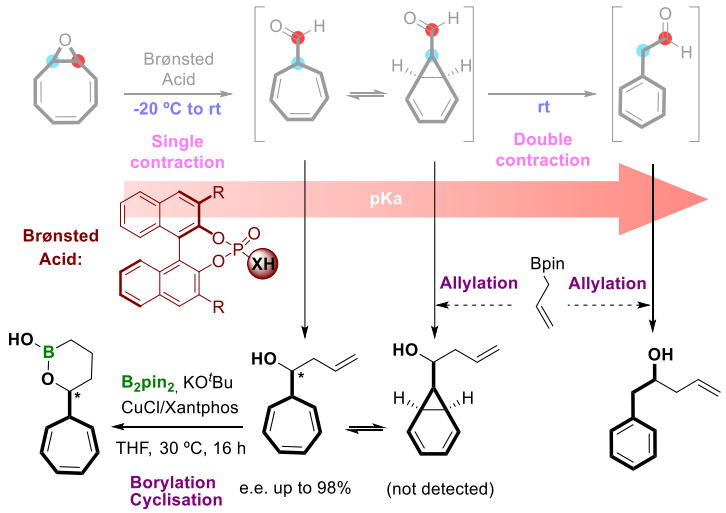
This article has been submitted for publication. This project was made in collaboration with the Department of Organic and Inorganic Chemistry of University of the Basque Country (UPV/EHU), the Instituto de Biocomputación y Física de Sistemas Complejos (BIFI) of the Universidad de Zaragoza and the Instituto de Síntesis Química y Catálisis Homogénea (ISQCH) of the Universidad de Zaragoza.

In this project it has been studied the reactivity of cyclooctatetraene, which undergoes two sequential ring-contraction reactions, under mild conditions in the presence of catalytic amounts of Brønsted acids, with allylboronates to generate homoallylic alcohols. The reaction can be controlled by the acidity of the Brønsted acid, as well as by the temperature parameter, obtaining selectively the cycloheptatriene carbaldehyde product, from a single ring-contraction pathways, or the phenylacetaldehyde product, formed after a second ring-contraction (Scheme 6.11).



Scheme 6.11 Switchable Bronsted acid-catalysed single and double ring-contraction approach.

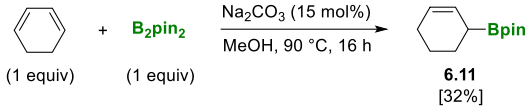
Additionally, the acid-catalysed ring-contraction was followed by an *in situ* enantioselective allylation reaction with allylboronates, in the presence of a chiral phosphoric acid catalyst, affording enantioenriched cycloheptatrienyl-substituted homoallylic alcohols. Finally, the generated cycloheptatrienyl homoallylic alcohols were also converted into enantioenriched oxaborinanes *via* copper-catalysed nucleophilic borylatation/cyclisation (Scheme 6.12)



Scheme 6.12 Switchable acid-catalysed cyclooctatetraene oxide single or double ring-contraction/allylation towards enantioselective homoallylic alcohol and subsequent borylation/cyclisation.

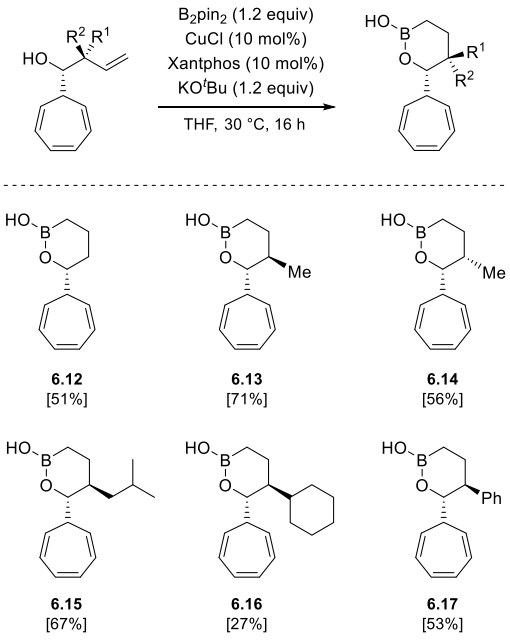
My personal contribution to this project was in two parts. Firstly, I synthesised one of the allylboronates (**6.11**) which was prepared following a methodology

previously reported by our group (Scheme 6.13). (R. J. Maza, E. Davenport, N. Miralles, J. J. Carbó, E. Fernández, *Org. Lett*. **2019**, *21*, 2251–2255.)



Scheme 6.13 Synthesis of **6.11** via metal-free 1,4-hydroboration of cyclohexa-1,3-diene.

But my main contribution to the project was the entire study of the borylation/cyclisation reaction of the enantioenriched homoallylic alcohols previously synthesised by Jana Sendra, the first author of the article. The reaction proceeds towards the formation of oxaborinanes using B_2pin_2, KO^{t}Bu and CuCl/Xantphos as catalytic system, in THF (Scheme 6.14).



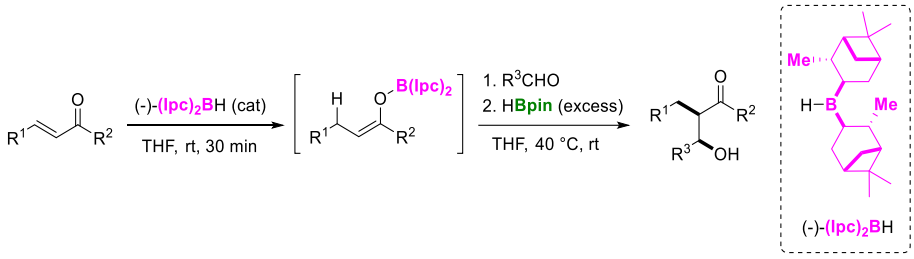
Scheme 6.14 Stereoselective synthesis of oxaborinanes from enantionenriched homoallylic alcohols. Reaction conditions: 0.15 mmol (1 equiv) of homoallylic alcohol, 0.015 mmol (10 mol%) of CuCl, 0.015 mmol (10 mol%) of Xantphos, 0.18 mmol (1.2 equiv) of B_2pin_2 and 0.18 mmol (1.2 equiv) of KO^{t}Bu in 0.3 mL of THF were stirred at 30 °C for 16 h. Isolated yields in brackets.

Chapter 6

6.5. Enantionselective reductive aldol condensation of α,β-unsaturated ketones with aldehydes.

This project was conducted during an international stage of 3 months (from 1st March of 2022 to 31st May of 2022) at University of Edinburgh under the supervision of Prof. Stephen P. Thomas.

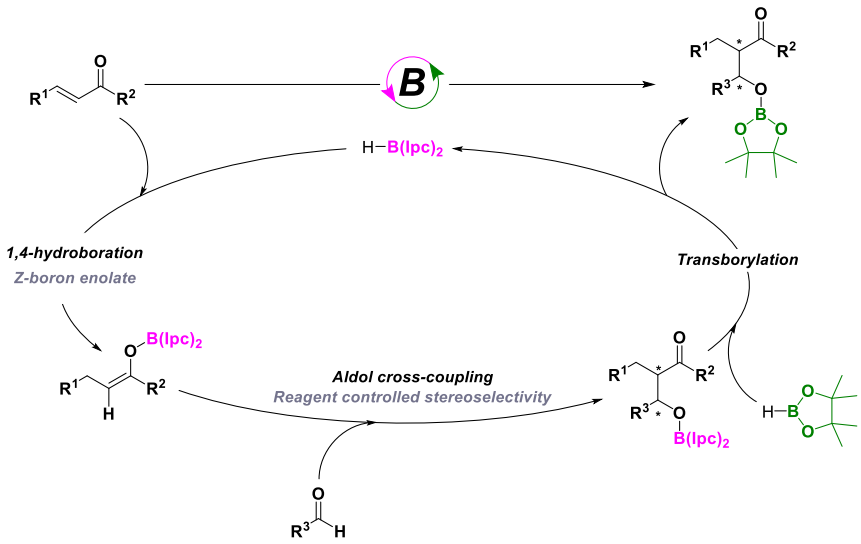
The aim of the project was to render enantioenriched reagents through B-O/B-H catalytic transborylation reaction, applied in the borane-catalysed reductive aldol reaction between α,β-unsaturated ketones and aldehydes, based on previous work conducted in their group. The focus was to use pinacolborane (HBpin) to facilitate the turnover of the enantioenriched dialkylborane with the aim to generate aldol coupled products with the retention of the diastereoselectivity and enantioselectivity. For the general study of the reactivity, bis((1*R*,2*S*,3*R*,5*R*)-2,6,6-trimethylbicyclo[3.1.1]heptan-3-yl)borane ((-)-(Ipc)$_2$BH) was used as catalytic chiral borane and HBpin as turnover borane (Scheme 6.15).



Scheme 6.15 General conditions for the study of the borane-catalysed reductive aldol reaction between α,β-unsaturated ketones and aldehydes using (-)-(Ipc)$_2$BH as catalytic chiral borane and HBpin as turnover borane.

The proposal mechanistic approach for the studied reaction was explained through a first step which consists in a 1,4-hydroboration of the enone followed

by the aldol cross-coupling reaction with the corresponding aldehyde. At this point the B-O/B-H transborylation is suggested to occur recovering the chiral borane and forming the desired aldol product (Scheme 6.16).



Scheme 6.16 Proposed catalytic cycle for the reductive aldol condensation through transborylation pathway.

CHAPTER 7

Concluding remarks

The present doctoral thesis has established new synthetic and reactivity trends of *gem*-diborylalkanes and *gem*-diborylalkenes towards the formation of unprecedented organoboron compounds. The selective acivation modes of the polyborylated compounds and their stereocontrolled reactivity have been deeply studied.

In Chapter 3, the boron-Wittig olefination reaction between aromatic or aliphatic aldehydes and *gem*-diborylsilylmethide lithium salts has been successfully conducted. The challenging stereocontrol on the generated trisubstituted 1,1-silylborylalkenes has been reached depending on the nature of the aldehydes. Heterocyclic aldehydes, containing nitrogen, oxygen or sulphur atoms, lead the favoured formation of *E*-stereoisomers, due to a plausible interaction of the heteroatoms and the Bpin moiety during the stereodetermining step. Substituents at *ortho* position of arylaldehydes also contribute to the stereoselectivity of the reaction favouring the formation of *E*-stereodefined trisubstituted olefines when the arylaldehydes are bearing *ortho*-methoxy groups. In contrast, with other *ortho* substituents such as bulky halides or phosphine groups the obtention of trisubstituted *Z*-1,1-silylborylalkenes is favoured. Finally, the use of α,β-unsaturated aldehydes allows the access to 1,1-silylboryl conjugated dienes and enynes. The afforded (*E*)-stereoisomeric trisubstituted 1,1-silylborylalkenes have been prepared for the first time in this thesis, complementing the alternative existing methodologies to synthesise the analogous trisubstituted *Z*-1,1-silylborylalkenes.

In Chapter 4, regioselective ring-opening of vinyl aziridines with diborylalkyl lithium salts has been established. The preference of the nucleophilic attack on the vinyl group undergoes S_N2' diborylalkylation on the 2-methyl-1-tosyl-2-vinylaziridine. Alternatively, the reactivity of the α,α-diborylcarbanions with 1-tosyl-2-vinylaziridine proceeds through S_N2 pathway on the less sterically hindered position. The S_N2 ring-opeing/C-C bond formation of bicyclic aziridine 7-tosyl-7-azabicyclo[4.1.0]hep-2-ene occurs at the allylic position, generating exclusively homoallyldiboronate species with relative *trans*

disposition of the amine and the diborylmethyl moiety. The afforded products maintained the two boryl moieties except for reactions involving aryl-substituted *gem*-diborylalkanes which are prone to develop protodeboronation. All the products synthesised in this Chapter have been prepared for the first time in the present work.

In Chapter 5, two new synthetic strategies have been efficiently developed to prepare 1,1-diborylalkenes. Condensation of aldehydes with triborylmethide lithium salt, allows the formation of *gem*-diborylalkenes. Alternatively, a copper-catalysed dehydrogenative borylation/hydroboration of terminal alkynes has been reported as an adapted methodology to afford mainly *gem*-diborylalkenes. Stereoselective cyclopropanation of 2-aryl-1,1-diborylalkenes with (trimethylsilyl)diazomethane has been studied in the presence of catalytic [$Pd(OAc)_2$], obtaining the exclusive formation of *gem*-bis(pinacolboryl)cyclopropanes, with the silyl group and the aryl groups in *trans* disposition. The transition-metal-free activation of the polyfunctionalised *gem*-diborylcyclopropanes with NaO^tBu, promotes the favoured protodeboronation on the Bpin moiety *cis* to the aryl group. Subsequent oxidation allows the synthesis of stereoselective substituted cyclopropanols.

CHAPTER 8

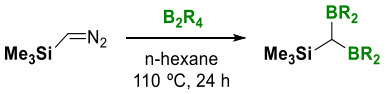
Experimental section

8.1. General considerations

Solvents and reagents were obtained from commercial suppliers, such as Sigma-Aldrich Inc., Apollo Scientific, Fluorochem, Abcr GmbH, Alfa Aesar, Acros Organics or TCI Chemicals; and were dried and/or purified (if needed) by standard procedures.[1] Bis(pinacolado)diboron (B_2pin_2) and bis(hexylene glycolato)diboron (B_2hex_2) were obtained as a generous donation from Dalian Allychem Co., and were used without further purification. All air-sensitive reactions and procedures were conducted in oven and flame-dried glassware under an inert atmosphere of argon and using Schlenk-type techniques. Flash chromatography purification procedures were performed on standard silica gel (Merck Kiesegel 60 Å, 230-400 mesh particle size). Thin Layer Chromatography analyses (TLC) were performed on Merck Kiesegel 60 F_{254} and were developed using standard visualising agents as UV fluorescence (254 and 366 nm) or potassium permanganate and. NMR spectra were recorded at a Varian 400 spectrometer. ^{1}H NMR and ^{13}C NMR chemical shifts (δ) are reported in ppm with the solvent residual signals as reference internal standard ($CDCl_3$ = 7.26 ppm ^{1}H and 77.16 ppm ^{13}C). ^{11}B NMR chemical shifts (δ) are reported in ppm relative to $BF_3 \cdot Et_2O$. Data are reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet and br = broad), coupling constants (Hz), integration). High Resolution Mass Spectra (HRMS) were recorded using a 6210 Time of Flight (TOF) mass spectrometer from Agilent Technologies with an ESI interface that is located at the Servei de Recursos Científics i Tècnics of the Universitat Rovira i Virgili, Tarragona or using a BIOTOF II TOF mass spectrometer from Bruker with APCI or EI interface that is located at the Unidade de Espectrometría de Masas e Proteómica of the Universidade de Santiago de Compostela. GC-MS analyses were performed on a 8860 GC System with a 5977B GC/MSD from Agilent Technologies equipped with a capillary column HP-5MS Ultra Inert (30 m, 0.25 mm i.d., 0.25 μm thickness) and using He as the carrier gas. Melting points were conducted in a Digital Melting Point IA 9100.

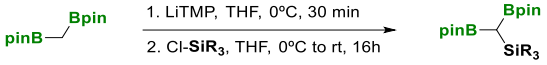
8.2. Experimental section for Chapter 3

8.2.1. General procedure A for the preparation of *gem*-diborylsilanes



An oven-dried Teflon screw-cap Schlenk flask, equipped with a magnetic stir bar, was charged with 4 mmol (1 equiv) of diboron reagent, in the glove-box. Then, 8 mmol (2 equiv) of a 2.0 M solution in hexane of (trimethylsilyl)diazomethane was added dropwise. After stirring the mixture in the glovebox for 5 min the Schlenk flask was sealed and heated at 110 °C for 24 h under constant stirring. The reaction was cooled at room temperature, the solvent was gently concentrated on a rotary evaporator and the resulting crude purified by silica gel flash chromatography to afford the product.

8.2.2. General procedure B for the preparation of *gem*-diborylsilanes

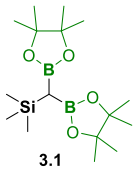


For this synthesis we followed the previous reported procedure by Cho et al.[2] with some modifications. An oven-dried Teflon screw-cap Schlenk flask, equipped with a magnetic stir bar, was charged with LiTMP (2 mmol, 1 equiv) and bis(pinacolboryl)methane (2 mmol, 1 equiv) in dry THF (3mL). The mixture was stirred for 30 minutes at 0 ºC. Then, the corresponding chlorosilane (2.4 mmol, 1.2 equiv) in dry THF (1 mL) was added and the reaction was stirred at 0 ºC for 10 minutes, followed by 16h at room temperature. The solvents were

removed under vacuum and reaction crude was purified by silica gel chromatography to afford the desired product.

8.2.3. Characterisation of *gem*-diborylsilanes

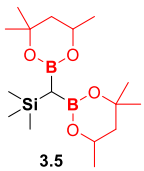
(Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)methyl)trimethylsilane (3.1)



3.1

Synthesised by General procedure A using B_2pin_2 as diboron reagent and purified by flash column chromatography (hexane:ethyl acetate = 15:1) yielded **3.1** (83%, 1.63 g) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 1.21 (s, 12H), 1.20 (s, 12H), 0.28 (s, 1H), 0.09 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 82.7, 25.1, 24.6, 0.6. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.9. **HRMS** (ESI) for **$C_{16}H_{34}B_2O_4SiNa$ [M+Na$^+$]$^+$:** calculated: 363.2310; found: 363.2309.

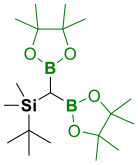
(Bis(4,4,6-trimethyl-1,3,2-dioxaborinan-2-yl)methyl)trimethylsilane (3.5)



3.5

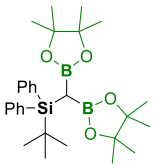
Synthesised by General procedure A using B_2hex_2 as diboron reagent and purified by flash column chromatography (hexane:ethyl acetate = 15:1) yielded **3.5** (56%, 789 mg) as a colourless oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 4.11 (m, J = 11.6, 6.2, 3.0 Hz, 2H), 1.68 (d, 13.9 Hz, 2H), 1.40 dd, 13.9, 2.9 Hz, 2H), 1.28 (s, 12H), 1.23 (d, 5 Hz, 6H), 0.01 (s, 9H), -0.13 (m, 1H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 70.0, 64.3, 46.2, 31.5, 28.1, 23.5, 0.6. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 30.0. **HRMS** (ESI) for **$C_{16}H_{34}B_2O_4SiNa$ [M+Na$^+$]$^+$:** calculated: 363.2310; found: 363.2314.

(Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)methyl)(tert-butyl)dimethylsilane (3.35)


3.35

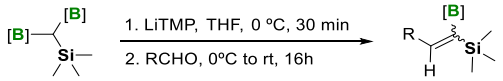
Synthesised by General procedure B using *tert*-butylchlorodimethylsilane and and purified by flash column chromatography (hexane:ethyl acetate = 15:1) yielded **3.35** (46%, 355 mg) as a white solid. Spectral data are in agreement with the reported.[2] **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 1.22 (s, 9H), 1.21 (s, 12H), 0.87 (s, 12H), 0.39 (s, 1H), 0.07 (s, 6H).

(Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)methyl)(tert-butyl)diphenylsilane (3.36)


3.36

Synthesised by General procedure B using *tert*-butylchlorodiphenylsilane and and purified by flash column chromatography (hexane:ethyl acetate = 15:1) yielded **3.36** (27%, 276 mg) as a pale yellowish solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.77 – 7.68 (m, 4H), 7.36 – 7.23 (m, 6H), 1.06 (s, 9H), 1.02 (s, 12H), 1.00 (s, 12H), 0.92 (s, 1H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 136.6, 128.5, 126.9, 82.8, 28.5, 24.8, 24.6, 19.1. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.4. **HRMS** (ESI) for **$C_{29}H_{48}NB_2O_4Si$ [M+HH_4^+]$^+$:** calculated: 524.3539; found: 524.3551

8.2.4. General procedure for *gem*-silylborylation of aldehydes

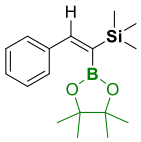


A Schlenk-tube, equipped with a magnetic stir bar, was charged with the *gem*-diborylsilane (0.3 mmol, 1 equiv) and LiTMP (0.36 mmol, 1.2 equiv) in dry THF (2 mL). The mixture was stirred for 30 minutes at 0ºC. Then the corresponding aldehyde (0.24 mmol, 0.8 equiv) was added and the reaction was

stirred at 0 ºC for 10 minutes, followed by 16 h at room temperature. The solvents were removed under vacuum, the reaction crude was analysed by NMR, using naphthalene as internal standard, and the crude residue was purified by silica gel chromatography to afford the desired product.

8.2.5. Characterisation of *gem*-silylborylalkenes

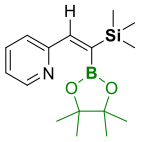
(*E*)-Trimethyl(2-phenyl-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)vinyl)silane (3.2-*E*)



3.2-*E*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 200:1) yielded **3.2-*E*** (51%, 77 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.44 – 7.38 (m, 2H), 7.32 – 7.20 (m, 4H), 1.29 (s, 12H), 0.20 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 150.1, 140.6, 128.1, 127.9, 127.86, 83.6, 25.2, -0.7. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.3. **HRMS** (ESI) for **$C_{17}H_{31}BNO_2Si$ [M+NH_4^+]$^+$:** calculated: 320.2217; found: 320.2212.

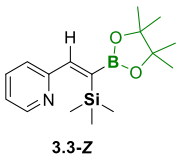
(*E*)-2-(2-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolan-2-yl)-2-(trimethylsilyl)vinyl)pyridine (3.3-*E*)



3.3-*E*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 10:1) (basifying the silica gel column with 1% of NEt_3) and yielded **3.3-*E*** (71%, 108 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 8.49 (d, J = 5.0 Hz, 1H), 7.66 (dd, J = 7.6, 1.7 Hz, 1H), 7.17 – 7.09 (m, 2H), 7.02 (s, 1H), 1.38 (s, 12H), 0.22 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 155.3, 146.6, 143.6, 138.3, 122.2, 122.1, 82.5, 76.8, 26.2, -0.8. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 27.6. **HRMS** (ESI) for **$C_{16}H_{27}BNO_2Si$ [M+H^+]$^+$:** calculated 304.1904; found: 304.1909.

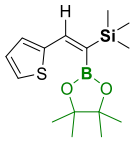
(*Z*)-2-(2-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolan-2-yl)-2-(trimethylsilyl)vinyl)pyridine (3.3-*Z*)



3.3-*Z*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 200:1) yielded **3.3-*Z*** (21%, 32 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 8.54 (d, J = 4.8 Hz, 1H), 7.73 (s, 1H), 7.62 (td, J = 7.7, 1.8 Hz, 1H), 7.26 – 7.22 (m, 1H), 7.12 (ddd, J = 7.6, 4.7, 1.1 Hz, 1H), 1.31 (s, 12H), 0.14 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 156.7, 152.6, 148.4, 136.1, 124.3, 122.3, 83.5, 24.9, 1.6. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.5. **HRMS** (ESI) for **$C_{16}H_{27}BNO_2Si$ [M+H^+]$^+$:** calculated 304.1904; found: 304.1913.

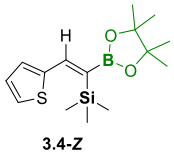
(E)-Trimethyl(1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-2-(thiophen-2-yl)vinyl)silane (3.4-*E*)



3.4-*E*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 100:1) yielded **3.4-*E*** (71%, 176 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.24 (s, 1H), 7.22 (ddd, J = 5.0, 1.2, 0.6 Hz, 1H), 7.12 (ddd, J = 3.6, 1.2, 0.7 Hz, 1H), 6.95 (dd, J = 5.1, 3.6 Hz, 1H), 1.36 (s, 12H), 0.18 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 145.3, 140.9, 128.0, 127.1, 126.0, 83.7, 25.4, -0.7. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.0. **HRMS** (ESI) for **$C_{15}H_{29}BNO_2SSi$ [M+NH_4^+]$^+$:** calculated 326.1781; found: 326.1784.

(*Z*)-Trimethyl(1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-2-(thiophen-2-yl)vinyl)silane (3.4-*Z*)

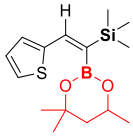


3.4-*Z*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 100:1) yielded **3.4-*Z*** (16%, 39 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.88 (s, 1H), 7.28 (dd, J = 5.0, 1.2 Hz, 1H), 7.04 – 7.00

(m, 1H), 6.97 (dd, J = 5.0, 3.5 Hz, 1H), 1.29 (s, 12H), 0.14 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 147.7, 143.8, 128.0, 127.0, 16.5, 83.4, 24.9, 0.8. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.9. **HRMS** (ESI) for **$C_{15}H_{29}BNO_2SSi$ [M+NH_4^+]$^+$:** calculated 326.1781; found: 326.1731.

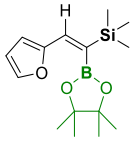
(*E*)-Trimethyl(2-(thiophen-2-yl)-1-(4,4,6-trimethyl-1,3,2-dioxaborinan-2-yl)vinyl)silane (3.6-*E*)



3.6-*E*

Synthesised using **3.5** and purified by flash column chromatography (pentane:ethyl ether = 100:1) yielded **3.6-*E*** (65%, 158 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.19 – 7.15 (m, 1H), 7.13 (s, 1H), 7.01 (ddd, J = 3.7, 1.3, 0.6 Hz, 1H), 6.94 (dd, J = 5.1, 3.6 Hz, 1H), 4.33 (m, J = 15.3, 6.2, 3.1 Hz, 1H), 1.86 (dd, J = 13.9, 2.9 Hz, 1H), 1.68 (ddd, J = 14.0, 11.6, 0.8 Hz, 1H), 1.41 (s, 3H), 1.34 (s, 3H), 1.30 (d, J = 6.2 Hz, 3H), 0.15 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 145.9, 137.8, 127.5, 127.0, 125.2, 71.6, 65.4, 46.1, 31.3, 28.0, 23.2, -0.9. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 28.9. **HRMS** (ESI) for **$C_{15}H_{29}BNO_2SSi$ [M+NH_4^+]$^+$:** calculated 326.1781; found: 326.1787.

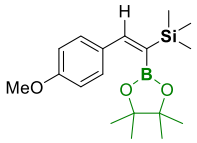
(*E*)-(2-(Furan-2-yl)-1-(4,4,6-trimethyl-1,3,2-dioxaborinan-2-yl)vinyl)trimethylsilane (3.7-*E*)



3.7-*E*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 100:1) yielded **3.7-*E*** (71%, 167 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.31 (dd, J = 1.6, 0.8 Hz, 1H), 6.86 (s, 1H), 6.36 (dd, J = 3.3, 1.8 Hz, 1H), 6.29 (dd, J = 3.4, 0.8 Hz, 1H), 1.36 (s, 12H), 0.17 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 155.0, 142.0, 134.6, 111.7, 109.9, 83.7, 25.2, -0.8. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.7. **HRMS** (ESI) for **$C_{15}H_{29}BNO_2SSi$ [M+NH_4^+]$^+$:** calculated 310.2010; found: 310.2001.

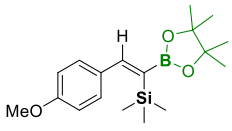
(*E*)-(2-(4-Methoxyphenyl)-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)vinyl)trimethylsilane (3.8-*E*)



3.8-*E*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 200:1) yielded **3.8-*E*** (63%, 105 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.41 – 7.32 (m, 2H), 7.20 (s, 1H), 6.84 – 6.79 (m, 2H), 3.80 (s, 3H), 1.30 (s, 12H), 0.18 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 159.5, 149.8, 133.5, 129.3, 113.4, 83.5, 55.4, 25.2, -0.6. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.8. **HRMS** (ESI) for **$C_{18}H_{29}BO_3Si$ [M+H$^+$]$^+$:** calculated: 333.2063; found: 333.2057.

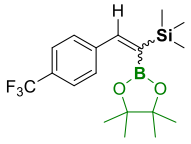
(*Z*)-(2-(4-Methoxyphenyl)-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)vinyl)trimethylsilane (3.8-*Z*)



3.8-*Z*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 200:1) yielded **3.8-Z** (23%, 49 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.95 (s, 1H), 7.24 – 7.19 (m, 2H), 6.86 – 6.81 (m, 2H), 3.81 (s, 3H), 1.29 (s, 12H), 0.04 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 159.3, 156.9, 133.9, 129.9, 113.2, 83.2, 55.3, 24.9, 1.1. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.5. **HRMS** (ESI) for **$C_{18}H_{29}BO_3Si$ [M+H$^+$]$^+$:** calculated: 333.2063; found: 333.2050.

(*E*)- and (Z)-Trimethyl(1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-2-(4-(trifluoromethyl)phenyl)vinyl)silane (3.9-*E*) and (3.9-*Z*)

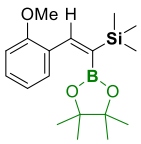


3.9 *E:Z = 2:1*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 200:1) yielded **3.9-*E*** and **3.9-Z** as mixture 2:1 (89%, 79 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 8.62 (d, J = 4.7 Hz, 1H), 7.97 (s, 1H), 7.58 – 7.47 (m, 10H), 7.34 (ddt, J = 8.3, 1.7, 0.9 Hz, 2H), 7.32 –

7.25 (m, 1H), 1.31 (s, 12H), 1.28 (s, 24H), 0.21 (s, 18H), -0.01 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 155.0, 150.0, 148.3, 145.1, 144.0, 136.0, 129.7, 129.4, 128.5, 128.1, 125.1 (q, J = 3.8 Hz), 124.8 (q, J = 3.8 Hz), 123.8, 123.0, 83.8, 83.6, 25.2, 24.9, 0.9, -0.8. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.0. **HRMS** (ESI) for **$C_{18}H_{30}BNF_3O_2Si$ [M+NH_4^+]$^+$:** calculated: 388.2091; found: 388.2087.

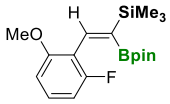
(*E*)-(2-(2-Methoxyphenyl)-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)vinyl)trimethylsilane (3.10-*E*)



3.10-*E*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 200:1) yielded **3.10-*E*** (67%, 89 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.53 (s, 1H), 7.42 (dd, J = 7.5, 1.7 Hz, 1H), 7.25 – 7.17 (m, 1H), 6.84 (tt, J = 7.5, 0.8 Hz, 1H), 6.80 (dd, J = 8.2, 1.0 Hz, 1H), 3.80 (S. 3H), 1.24 (s, 12H), 0.19 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 157.1, 146.2, 130.1, 129.2, 128.8, 119.9, 110.3, 83.4, 55.4, 25.1, -0.6. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.7. **HRMS** (ESI) for **$C_{18}H_{33}BNO_3Si$ [M+NH_4^+]$^+$:** calculated: 350.2323; found: 350.2317.

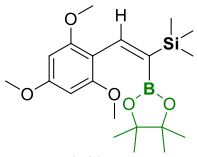
(*E*)-(2-(2-Fluoro-6-methoxyphenyl)-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)vinyl)trimethylsilane (3.11-*E*)



3.11-*E*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 200:1) yielded **3.11-*E*** (92%, 129 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.18 (s, 1H), 7.13 (td, J = 8.3, 6.4 Hz, 1H), 6.66 – 6.59 (m, 2H), 3.80 (s, 3H), 1.19 (s, 12H), 0.20 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 161.5, 159.1, 158.4 (d, J = 7.7 Hz), 140.2, 128.5 (d, J = 10.9 Hz), 118.1 (d, J = 16.1 Hz), 108.0 (d, J = 23.6 Hz), 106.3, 83.0, 56.1, 25.1, -0.6. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.2. **HRMS** (ESI) for **$C_{18}H_{33}BNO_3Si$ [M+NH_4^+]$^+$:** calculated: 350.2323; found: 350.2325.

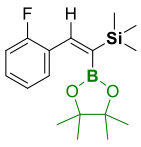
(*E*)-2-(2-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolan-2-yl)-2-(trimethylsilyl)vinyl)pyridine (3.12-*E*)



3.12-*E*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 200:1) yielded **3.12-*E*** (67%, 132 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.16 (s, 1H), 6.09 (s, 2H), 3.80 (s, 3H), 3.73 (s, 6H), 1.18 (s, 12H), 0.18 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 160.4, 158.8, 141.8, 112.9, 91.7, 82.4, 56.1, 55.4, 25.4, -0.4. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.0. **HRMS** (ESI) for **$C_{20}H_{34}BO_5Si$ $[M+H^+]^+$:** calculated: 393.2269; found: 393.2279.

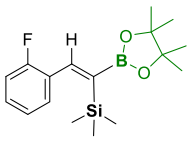
(*E*)-(2-(2-Fluorophenyl)-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)vinyl)trimethylsilane (3.13-*E*)



3.13-*E*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 200:1) yielded **3.13-*E*** (49%, 63 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.49 (td, J = 7.8, 1.8 Hz, 1H), 7.38 (s, 1H), 7.26 – 7.16 (m, 1H), 7.03 (td, J = 7.6, 1.3 Hz, 1H), 6.98 (ddd, J = 10.5, 8.2, 1.2 Hz, 1H), 1.26 (s, 12H), 0.20 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 161.6, 159.1, 142.4, 129.5, 129.3, 128.5 (d, J = 12.9 Hz), 123.52, 115.4 (d, J = 22.1 Hz), 83.6, 25.2, -0.7. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.2. **HRMS** (ESI) for **$C_{17}H_{30}BNFO_2Si$ $[M+NH_4^+]^+$:** calculated: 338.2123; found: 338.2134.

(*Z*)-(2-(2-Fluorophenyl)-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)vinyl)trimethylsilane (3.13-*Z*)

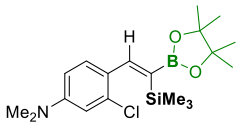


3.13-*Z*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 200:1) yielded **3.13-*Z*** (36%, 47 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.90 (s, 1H), 7.26 – 7.16 (m, 2H), 7.06 (td, J =

7.5, 1.1 Hz, 1H), 7.00 (ddd, J = 9.6, 8.2, 1.2 Hz, 1H), 1.30 (s, 12H), -0.02 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 161.1, 158.7, 149.7, 130.7, 129.4, 129.2 (d, *J* = 16.1 Hz), 115.2 (d, J = 21.8 Hz), 83.4, 24.9, 0.5. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.5. **HRMS** (ESI) for **$C_{17}H_{30}BNFO_2Si$ [M+NH_4^+]$^+$:** calculated: 338.2123; found: 338.2131.

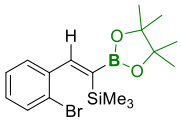
(*Z*)-3-Chloro-*N*,*N*-dimethyl-4-(2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-2-(trimethylsilyl)vinyl)aniline (3.14-*Z*)



3.14-*Z*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 100:1) yielded **3.14-*Z*** (45%, 69 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.94 (s, 1H), 7.11 (d, J = 8.6 Hz, 1H), 6.66 (d, J = 2.6 Hz, 1H), 6.52 (dd, J = 8.6, 2.6 Hz, 1H), 2.95 (s, 6H), 1.29 (s, 12H), 0.02 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 154.8, 151.0, 134.3, 131.2, 127.4, 112.2, 109.7, 83.1, 40.4, 24.9, 1.0. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.1. **HRMS** (ESI) for **$C_{19}H_{32}BNO_2SiCl$ [M+H^+]$^+$:** calculated: 380.1995; found: 380.1984.

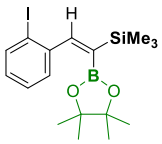
(*Z*)-(2-(2-Bromophenyl)-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)vinyl)trimethylsilane (3.15-*Z*)



3.15-*Z*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 200:1) yielded **3.15-*Z*** (73%, 88 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.84 (s, 1H), 7.52 (dd, J = 7.9, 1.2 Hz, 1H), 7.26 – 7.18 (m, 2H), 7.12 (m, 1H), 1.30 (s, 12H), -0.07 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 156.1, 142.1, 132.1, 130.4, 129.0, 126.7, 122.8, 83.3, 24.9, 0.7. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 30.8. **HRMS** (ESI) for **$C_{17}H_{30}BNBrO_2Si$ [M+NH_4^+]$^+$:** calculated: 398.1322; found: 398.1329.

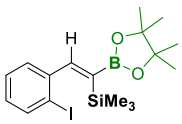
(*E*)-(2-(2-Iodophenyl)-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)vinyl)trimethylsilane (3.16-E)



3.16-*E*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 200:1) yielded **3.16-E** (7%, 15 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.80 (dd, J = 7.9, 1.2 Hz, 1H), 7.49 (dd, J = 7.7, 1.7 Hz, 1H), 7.25 – 7.19 (m, 2H), 6.91 (td, J = 7.6, 1.7 Hz, 1H), 1.22 (s, 12H), 0.22 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 153.8, 143.3, 139.0, 129.2, 128.6, 127.8, 99.7, 83.6, 25.0, -0.7. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.5. **HRMS** (ESI) for **$C_{17}H_{30}BNIO_2Si$ [M+NH_4^+]$^+$:** calculated: 446.1184; found: 446.1174.

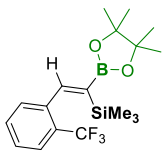
(*Z*)-(2-(2-Iodophenyl)-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)vinyl)trimethylsilane (3.16-*Z*)



3.16-*Z*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 200:1) yielded **3.16-*Z*** (45%, 97 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.80 (dd, J = 7.9, 1.2 Hz, 1H), 7.72 (s, 1H), 7.32 – 7.26 (m, 1H), 7.19 (dd, J = 7.7, 1.8 Hz, 1H), 6.95 (td, J = 7.4, 1.0 Hz, 1H), 1.30 (s, 12H), -0.08 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 159.8, 145.8, 138.3, 129.5, 128.9, 127.5, 98.2, 83.3, 24.9, 0.7. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 30.8. **HRMS** (ESI) for **$C_{17}H_{30}BNIO_2Si$ [M+NH_4^+]$^+$:** calculated: 446.1184; found: 446.1186.

(*Z*)-Trimethyl(1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-2-(2-(trifluoromethyl)phenyl)vinyl)silane (3.17-*Z*)

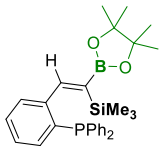


3.17-Z

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 300:1) yielded **3.17-*Z*** (78%, 116 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 8.10 (s, 1H), 7.60 (d, J = 7.4 Hz, 1H), 7.45 (t, J = 7.9

Hz, 1H), 7.36 (t, J = 7.6 Hz, 1H), 7.24 (d, J = 7.2 Hz, 1H), 1.29 (s, 12H), -0.13 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 153.8, 141.0, 131.1, 130.7, 128.0, 127.7, 127.4, 125.6, 125.4 (q, J = 5.3 Hz), 83.3, 24.9, 0.4. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 30.8. **HRMS** (ESI) for $C_{18}H_{30}BF_3NO_2Si$ **[M+NH_4^+]$^+$:** calculated: 388.2101; found: 388.2091.

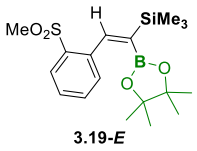
(*Z*)-Diphenyl(2-(2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-2-(trimethylsilyl)vinyl)phenyl)phosphane (3.18-*Z*)



3.18-*Z*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 300:1) yielded **3.18-*Z*** (28%, 36 mg) as a pale yellowish scum. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 8.18 (s, 1H), 7.38 – 7.28 (m, 10H), 7.24 (dd, J = 7.0, 1.5 Hz, 1H), 7.20 – 7.13 (m, 2H), 6.96 – 6.88 (m, 1H), 1.23 (s, 12H), -0.20 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 157.0, 156.91, 136., 136.3, 136.2, 134.6, 134.4, 131.9, 129.3, 129.2, 128.7, 128.5, 128.4, 127.9, 127.7, 83.0, 24.9, 0.8. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 30.6. **HRMS** (ESI) for **$C_{29}H_{40}BNO_2PSi$ [M+NH_4^+]$^+$:** calculated: 504.2659; found: 504.2654.

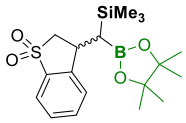
(*E*)-Trimethyl(2-(2-(methylsulfonyl)phenyl)-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)vinyl)silane (3.19-*E*)



3.19-*E*

Synthesised using **3.1** and purified by flash column chromatography pentane:ethyl ether = 10:1) yielded **3.19-*E*** (17%, 26 mg) as a colourless oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 8.02 – 7.97 (m, 1H), 7.92 (s, 1H), 7.57 – 7.49 (m, 1H), 7.45 – 7.39 (m, 2H), 3.03 (s, 3H), 1.06 (s, 12H), 0.21 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 148.6, 142.2, 137.7, 133.3, 130.9, 128.2, 127.8, 83.5, 43.9, 24.9, -1.0. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.6. **HRMS** (ESI) for **$C_{18}H_{33}BNO_4SSi$ [M+NH_4^+]$^+$:** calculated: 398.1993; found: 398.2012.

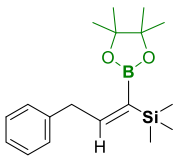
3-((4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)(trimethylsilyl)methyl)-2,3-dihydrobenzo[b]thiophene 1,1-dioxide (3.20)



3.20

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 10:1) yielded **3.20** (21%, 32 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.73 – 7.66 (m, 1H), 7.60 – 7.52 (m, 1H), 7.47 – 7.39 (m, 2H), 3.96 (dd, J = 12.5, 9.5 Hz, 1H), 3.82 – 3.71 (m, 1H), 3.48 (dd, J = 12.5, 7.3 Hz, 1H), 1.44 (d, J = 4.0 Hz, 1H), 1.04 (s, 6H), 0.82 (s, 6H), 0.17 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 144.3, 138.9, 133.3, 128.3, 125.2, 121.0, 83.2, 56.0, 35.5, 30.4, 25.0, 24.0, -0.4.**^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 33.0. **HRMS** (ESI) for **$C_{18}H_{33}BNO_4SSi$ [M+NH_4^+]$^+$:** calculated: 398.1993; found: 398.2008.

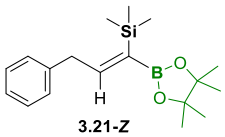
(*E*)-Trimethyl(3-phenyl-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)prop-1-en-1-yl)silane (3.21-*E*)



3.21-*E*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 100:1) yielded **3.21-*E*** (63%, 59 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.32 – 7.25 (m, 2H), 7.24 – 7.16 (m, 3H), 6.53 (t, J = 6.9 Hz, 1H), 3.63 (d, J = 7.0 Hz, 2H), 1.31 (s, 12H), 0.08 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 155.3, 141.3, 129.6, 129.3, 126.7, 83.9, 43.0, 25.8, -0.0. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.4. **HRMS** (ESI) for **$C_{18}H_{33}BNO_2Si$ [M+NH_4^+]$^+$:** calculated: 334.2374; found: 334.2351.

(*Z*)-Trimethyl(3-phenyl-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)prop-1-en-1-yl)silane (3.21-*Z*)

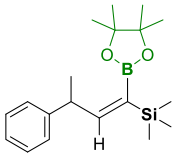


3.21-*Z*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 100:1) yielded **3.21-*Z*** (21%, 19 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.32 – 7.27 (m, 2H), 7.22 – 7.17 (m, 3H), 7.02 (t, J = 7.0

Hz, 1H), 3.58 (d, J = 7.0 Hz, 2H), 1.23 (s, 12H), 0.23 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 158.6, 140.1, 128.8, 128.6, 126.2, 83.1, 41.3, 24.9, 1.2. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 30.9. **HRMS** (ESI) for **$_{18}H_{33}BNO_2Si$ [M+NH_4^+]$^+$:** calculated: 334.2374; found: 334.2362.

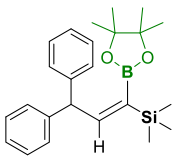
(*E*)-Trimethyl(3-phenyl-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)but-1-en-1-yl)silane (3.22-*E*)



3.22-*E*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 100:1) yielded **3.22-*E*** (60%, 60 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.36 – 7.26 (m, 4H), 7.24 – 7.11 (m, 1H), 6.41 (d, J = 9.2 Hz, 1H), 3.91 (dq, J = 9.3, 6.9 Hz, 1H), 1.36 (d, J = 6.9 Hz, 3H), 1.30 (s, 6H), 1.30 (s, 6H), 0.07 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 161.2, 146.5, 129.1, 127.9, 126.6, 83.8, 45.7, 25.8, 25.7, 22.0, 0.0. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.3. **HRMS** (ESI) for **$C_{19}H_{35}BNO_2Si$ [M+NH_4^+]$^+$:** calculated: 348.2530; found: 348.2519.

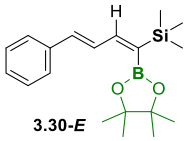
(*E*)-(3,3-Diphenyl-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)prop-1-en-1-yl)trimethylsilane (3.23-*E*)



3.23-*E*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 100:1) yielded **3.23-*E*** (98%, 115 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.34 – 7.24 (m, 6H), 7.25 – 7.13 (m, 4H), 6.84 (d, J = 9.5 Hz, 1H), 5.28 (d, J = 10.0 Hz, 1H), 1.27 (s, 12H), 0.11 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 158.0, 145.0, 129.2, 129.2, 126.8, 83.8, 56.2, 25.7, 0.0. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.7. **HRMS** (ESI) for **$C_{24}H_{37}BNO_2Si$ [M+NH_4^+]$^+$:** calculated: 410.2713; found: 410.2687.

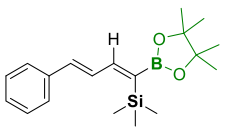
Trimethyl((1*E*,3*E*)-4-phenyl-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)buta-1,3-dien-1-yl)silane (3.30-*E*)



3.30-*E*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 100:1) yielded **3.30-*E*** (55%, 146 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.57 (d, J = 11.1 Hz, 1H), 7.44 – 7.38 (m, 2H), 7.37 – 7.30 (m, 2H), 7.28 – 7.23 (m, 1H), 7.18 (ddd, J = 15.3, 11.2, 0.7 Hz, 1H), 6.72 (d, J = 15.3 Hz, 1H), 1.28 (s, 12H), 0.27 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 156.1, 137.8, 137.2, 129.6, 128.8, 128.3, 127.0, 83.1, 24.9, 1.4. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.6. **HRMS** (ESI) for **$C_{19}H_{33}BNO_2Si$ [M+NH_4^+]$^+$:** calculated: 346.2374; found: 346.2387.

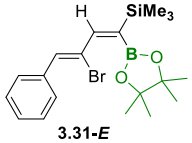
Trimethyl((1*Z*,3*E*)-4-phenyl-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)buta-1,3-dien-1-yl)silane (3.30-*Z*)



3.30-*Z*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 100:1) yielded **3.30-*Z*** (23%, 61 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.44 – 7.35 (m, 3H), 7.35 – 7.29 (m, 2H), 7.27 – 7.21 (m, 1H), 7.12 (d, J = 10.6 Hz, 1H), 6.66 (dd, J = 15.5, 0.7 Hz, 1H), 1.34 (s, 12H), 0.15 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 153.6, 137.5, 136.0, 130.9, 128.7, 127.9, 126.9, 83.2, 25.1, -0.7. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.5. **HRMS** (ESI) for **$C_{19}H_{33}BNO_2Si$ [M+NH_4^+]$^+$:** calculated: 346.2374; found: 346.2367.

((1*E*,3*E*)-3-Bromo-4-phenyl-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)buta-1,3-dien-1-yl)trimethylsilane (3.31-*E*)

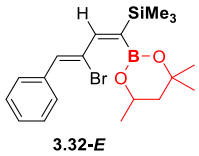


3.31-*E*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 300:1) yielded **3.31-*E*** (74%, 121 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$,

400 MHz) δ 7.67 – 7.62 (m, 2H), 7.38 – 7.33 (m, 2H), 7.32 – 7.27 (m, 1H), 7.08 (s, 1H), 6.83 (s, 1H), 1.30 (s, 12H), 0.20 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 148.0, 135.8, 132.3, 129.5, 128.3, 128.2, 126.1, 83.8, 25.5, -0.6. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 30.9. **HRMS** (ESI) for **$C_{19}H_{32}BNBrO_2Si$ [M+NH_4^+]$^+$:** calculated: 424.1479; found: 424.1467.

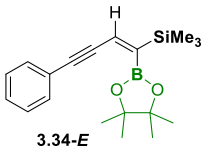
((1*E*,3*E*)-3-Bromo-4-phenyl-1-(4,4,6-trimethyl-1,3,2-dioxaborinan-2-yl)buta-1,3-dien-1-yl)trimethylsilane (3.32-*E*)



3.32-*E*

Synthesised using **3.5** and purified by flash column chromatography (pentane:ethyl ether = 300:1) yielded **3.32-*E*** (73%, 119 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.66 – 7.61 (m, 2H), 7.38 – 7.32 (m, 2H), 7.31 – 7.27 (m, 1H), 7.05 (s, 1H), 6.73 (s, 1H), 4.27 (m, 1H), 1.80 (dd, J = 13.9, 2.9 Hz, 1H), 1.64 – 1.56 (m, 1H), 1.35 (s, 3H), 1.32 (s, 3H), 1.29 (d, J = 6.1 Hz, 3H), 0.17 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 144.5, 136.2, 132.8, 129.5, 128.2, 128.1, 127.3, 71.5, 65.1, 45.9, 31.5, 27.7, 23.3, -0.7. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 28.6. **HRMS** (ESI) for **$C_{19}H_{32}BNBrO_2Si$ [M+NH_4^+]$^+$:** calculated: 424.1479; found: 424.1471.

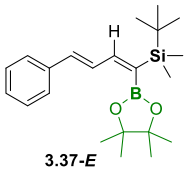
(*E*)-Trimethyl(4-phenyl-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)but-1-en-3-yn-1-yl)silane (3.34-*E*)



3.34-*E*

Synthesised using **3.1** and purified by flash column chromatography (pentane:ethyl ether = 200:1) yielded **3.34-*E*** (71%, 93 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.45 – 7.39 (m, 2H), 7.32 – 7.27 (m, 3H), 6.53 (s, 1H), 1.32 (s, 12H), 0.14 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 131.6, 129.7, 128.3, 128.3, 123.7, 92.3, 90.1, 83.6, 25.1, -1.1. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.7. **HRMS** (ESI) for **$C_{19}H_{31}BNO_2Si$ [M+NH_4^+]$^+$:** calculated: 344.2215; found: 344.2217.

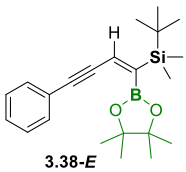
tert-Butyldimethyl((1_E_,3_E_)-4-phenyl-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)buta-1,3-dien-1-yl)silane (3.37-_E_)



3.37-*E*

Synthesised using **3.35** and purified by flash column chromatography (pentane:ethyl ether = 200:1) yielded **3.37-*E*** (81%, 91 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.42 – 7.37 (m, 2H), 7.36 – 7.19 (m, 4H), 7.09 (d, J = 10.8 Hz, 1H), 6.65 (d, J = 15.4 Hz, 1H), 1.35 (s, 12H), 0.90 (s, 9H), 0.14 (s, 6H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 154.6, 137.5, 135.9, 130.7, 128.7, 127.9, 126.8, 83.3, 27.0, 25.2, 17.7, -5.2. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.9. **HRMS** (ESI) for **$C_{22}H_{36}BO_2Si$ [M+H^+]$^+$:** calculated: 371.2578; found: 371.2586.

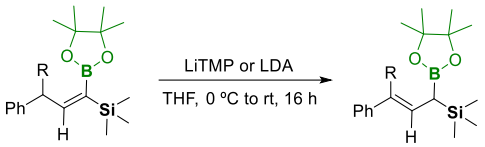
(_E_)-_tert_-Butyldimethyl(4-phenyl-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)but-1-en-3-yn-1-yl)silane (3.38-_E_)



3.38-*E*

Synthesised using **3.35** and purified by flash column chromatography (pentane:ethyl ether = 200:1) yielded **3.38-*E*** (85%, 94 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.45 – 7.39 (m, 2H), 7.33 – 7.25 (m, 3H), 6.53 (s, 1H), 1.31 (s, 12H), 0.91 (s, 9H), 0.12 (s, 6H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 131.6, 130.8, 128.3, 128.3, 123.6, 92.1, 90.0, 83.7, 26.8, 25.1, -5.6. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.7. **HRMS** (ESI) for **$C_{22}H_{37}BNO_2Si$ [M+NH_4^+]$^+$:** calculated: 386.2687; found: 386.2690.

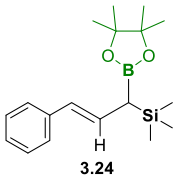
8.2.6. General procedure for the isomerization of *gem*-silylborylated alkenes



A Schlenk-tube equipped with a magnetic stir bar was charged with the LiTMP or LDA (0.36 mmol, 1.2 equiv) and was cooled down to 0 ºC. Then the gem-silylborylted alkene (0.3 mmol, 1 equiv) and dry THF (2 mL) were added. The mixture was stirred for 30 minutes at 0 ºC and left at room temperature 16 h. The reaction crude was analysed by NMR using naphthalene as internal standard and the crude residue was purified by silica gel chromatography to afford the desired product.

8.2.7. Characterisation of allylic *gem*-silylborylated compounds

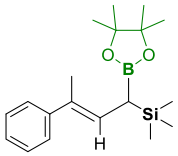
(*E*)-Trimethyl(3-phenyl-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)allyl)silane (3.24)



3.24

Purified by flash column chromatography (pentane:ethyl ether = 100:1) yielded **3.24** (65%, 61 mg) as a white solid. **^{1}H NMR** (CDCl, 400 MHz) δ 7.34 – 7.30 (m, 2H), 7.28 – 7.23 (m, 2H), 7.15 – 7.09 (m, 1H), 6.35 (dd, J = 15.7, 10.8 Hz, 1H), 6.15 (d, J = 15.4 Hz, 1H), 1.68 (d, J = 10.8 Hz, 1H), 1.25 (s, 6H), 1.24 (s, 6H), 0.09 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 140.3, 130.6, 129.9, 128.5, 127.4, 127.0, 84.5, 26.5, 0.0. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 33.4. **HRMS** (ESI) for **$C_{18}H_{33}BNO2Si$ $[M+NH_4^+]^+$:** calculated: 334.2374; found: 334.2344.

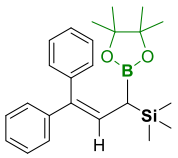
(*E*)-Trimethyl(3-phenyl-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)but-2-en-1-yl)silane (3.25)



3.25

Purified by flash column chromatography (pentane:ethyl ether = 100:1) yielded **3.25** (15%, 25 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.40 – 7.36 (m, 2H), 7.29 (dd, J = 8.5, 6.9 Hz, 2H), 7.21 – 7.13 (m, 1H), 6.01 (dq, J = 11.9, 1.4 Hz, 1H), 1.95 (d, J = 1.4 Hz, 3H), 1.91 (d, J = 11.9 Hz, 1H), 1.26 (s, 6H), 1.25 (s, 6H), 0.10 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 144.7, 130.3, 128.1, 126.4, 125.9, 125.6, 83.1, 25.1, 25.1, 15.9, -1.1. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.5. **HRMS** (ESI) for **$C_{19}H_{35}NBO_2Si$ [M+NH_4^+]$^+$:** calculated: 348.2530; found: 348.2546.

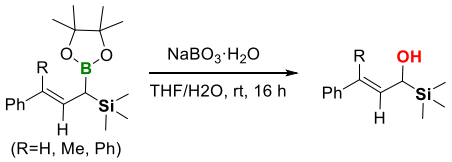
(3,3-Diphenyl-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)allyl)trimethylsilane (3.26)



3.26

Purified by flash column chromatography (pentane:ethyl ether = 100:1) yielded **3.26** (33%, 39 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.40 – 7.30 (m, 2H), 7.29 – 7.11 (m, 8H), 6.27 (d, J = 12.5 Hz, 1H), 1.90 (d, J = 12.5 Hz, 1H), 1.25 (s, 6H), 1.24 (s, 6H), 0.03 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 145.0, 141.9, 139.2, 131.7, 129.5, 129.2, 129.1, 128.3, 127.7, 127.3, 84.2, 26.2, 26.1, 0.0. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.6. **HRMS** (ESI) for **$C_{24}H_{37}BNO_2Si$ [M+NH_4^+]$^+$:** calculated: 410.2713; found: 410.2694.

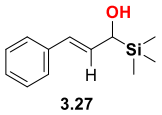
8.2.8. General procedure for the oxidation of the allylic *gem*-silylborylated compounds



An oven dried Schlenk-tube flask was charged with the allylic *gem*-silylborylated compound (0.2 mmol, 1 equiv), $NaBO_3 \cdot H_2O$ (0.4 mmol, 2 equiv), 1 mL of THF and 1 mL of H_2O and the mixture was stirred for 16 h. The reaction was quenched with $Na_2S_2O_3$, extracted 3 times with 15 mL of Et_2O and the organic layer was dried with $MgSO_4$ anhydride, filtered and the solvent evaporated. The reaction crude was analysed by NMR using naphthalene as internal standard and the crude residue was purified by silica gel chromatography to afford the desired product.

8.2.9. Characterisation of allylic alcohols

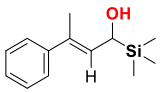
(*E*)-3-Phenyl-1-(trimethylsilyl)prop-2-en-1-ol (3.27)



3.27

Purified by flash column chromatography (pentane:ethyl ether = 10:2) yielded **3.27** (92%, 37 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.40 – 7.34 (m, 2H), 7.33 – 7.27 (m, 2H), 7.23 – 7.17 (m, 1H), 6.51 – 6.37 (m, 2H), 4.20 (dd, J = 4.9, 0.8 Hz, 1H), 1.26 (s, 1H), 0.10 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 137.5, 131.9, 128.5, 126.8, 126.0, 125.5, 68.93, -4.0. **HRMS** (ESI) for **$C_{12}H_{16}Si$ [M-H_2O^+]$^+$:** calculated: 188.1021; found: 188.1027.

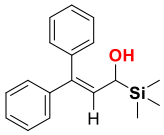
(*E*)-3-Phenyl-1-(trimethylsilyl)but-2-en-1-ol (3.28)



3.28

Purified by flash column chromatography (pentane:ethyl ether = 10:2) yielded **3.28** (93%, 32 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.42 – 7.38 (m, 2H), 7.37 – 7.28 (m, 2H), 7.26 – 7.22 (m, 1H), 5.91 (dq, J = 10.1, 1.3 Hz, 1H), 4.42 (d, J = 10.1 Hz, 1H), 2.03 (d, J = 1.3 Hz, 3H), 1.37 (s, 1H), 0.10 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 143.6, 133.6, 129.7, 128.4, 127.0, 125.8, 65.8, 16.7, -3.7. **HRMS** (ESI) for **$C_{13}H_{19}Si$ [M-H_2O^+]$^+$:** calculated: 202.1178; found: 202.1186.

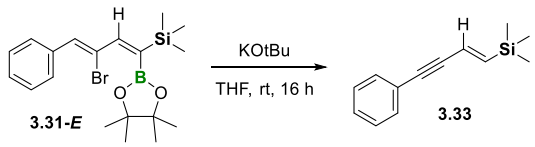
3,3-Diphenyl-1-(trimethylsilyl)prop-2-en-1-ol (3.29)



3.29

Purified by flash column chromatography (pentane:ethyl ether = 10:2) yielded **3.29** (95%, 54 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.33 – 7.09 (m, 10H), 6.14 (d, J = 11.0 Hz, 1H), 4.06 (d, J = 11.0 Hz, 1H), 1.34 (s, 1H), 0.00 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 142.4, 141.7, 139.7, 129.8, 129.7, 128.3, 128.1, 127.3, 127.3, 127.2, 66.0, -3.7. **HRMS** (ESI) for **$C_{18}H_{20}Si$ [M-H_2O^+]$^+$:** calculated: 264.1334; found: 264.1344.

8.2.10. General procedure for the synthesis of compound 3.33

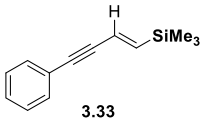


3.31-*E* 3.33

An oven dried Schlenk flask was charged with KO^{t}Bu (1.6 mmol, 4 equiv). Then, the gem-borylsilane **3.31** (0.4 mmol, 1 equiv) was added with 2 mL of THF. The reaction was stirred for 16 h at room temperature. The solvent was removed on the rotatory evaporator and the resulting crude was purified by silica gel chromatography column to afford the desired product **3.33**.

8.2.11. Characterisation of product 3.33

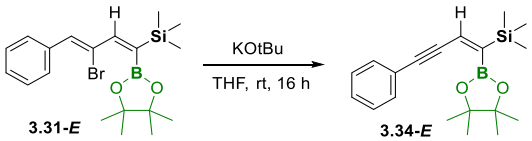
(*E*)-Trimethyl(4-phenylbut-1-en-3-yn-1-yl)silane (3.33)



3.33

Purified by flash column chromatography (pentane) yielded **3.33** (20%, 20 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.48 – 7.41 (m, 2H), 7.36 – 7.29 (m, 3H), 6.55 (d, J = 19.3 Hz, 1H), 6.18 (d, J = 19.2 Hz, 1H), 0.13 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 145.9, 131.7, 128.4, 128.3, 123.4, 89.9, 89.7, -1.4. **HRMS** (ESI) for **$C_{13}H_{17}Si$ [M+H$^+$]$^+$:** calculated: 201.1100; found: 201.1099.

8.2.12. General procedure for the synthesis of compound 3.34-*E* from 3.31-*E*

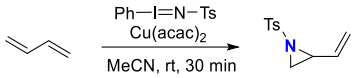


3.31-*E* 3.34-*E*

An oven-dried Schlenk flas was charged with KOtBu (0.6 mmol, 1.5eq). Then, the gem-borylsilane **3.31-*E*** (0.4 mmol, 1 equiv) was added with 2 mL of THF. The reaction was stirred for 16 h at room temperature. The solvent was removed on the rotatory evaporator and the resulting crude was purified by silica gel chromatography column to afford the desired product **3.34-*E***.

8.3. Experimental section for Chapter 4

8.3.1. General procedure for the preparation of vinyl aziridines

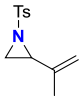


Vinyl aziridines were synthesised with an adapted methodology from M.P. Muldowney et al.[3] PhI=NTs (0.6 mmol) was added to a solution of 1,3-cyclohexadiene (0.6 mmol) and copper catalyst [$Cu(acac)_2$] (0.06 mmol) in acetonitrile (1 mL) under argon, and the reaction followed by TLC. When the solution turned homogenous it was poured into 1M NaOH (30 mL) and extracted with diethyl ether (1 x 30 mL). The organic layer was dried ($MgSO_4$) and the solvent removed under reduced pressure to leave either an oil or solid containing the aziridine, iodobenzene and diene starting material. This impure mixture could be dissolved in acetonitrile (30 mL) and washed with petroleum ether (5 x 10 mL). Removal of the acetonitrile under reduced pressure produced the corresponding vinyl aziridines. If it is needed silica gel chromatography column techniques were used to afford the desired vinyl aziridines.

8.3.2. Characterisation of vinyl aziridines

2-Methyl-1-tosyl-2-vinylaziridine (4.8)

4.8

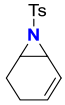


4.8a

Synthesised using General procedure for the preparation of vinyl aziridines. Purified by flash column chromatography (hexane:ethyl acetate = 20:1) provided a mixture of **4.8**:**4.8a** (2:1) in a (79%). **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.75 (m, $2H_{4.8}$, $2H_{4.8a}$), 7.28 – 7.16 (m, $2H_{4.8}$, $2H_{4.8a}$), 5.89 (dd, J = 17.2, 10.7 Hz, $1H_{4.8}$), 5.33 (dd, J = 17.3, 0.8 Hz, $1H_{4.8}$), 5.24 (dd, J = 10.6, 0.8 Hz, $1H_{4.8}$), 4.98 (m, $1H_{4.8a}$), 4.87 (m, $1H_{4.8a}$), 3.18 (dd, J = 7.1, 4.6 Hz, $1H_{4.8a}$), 2.64 (d, J = 7.1 Hz, $1H_{4.8a}$), 2.55 (d, J = 5.9 Hz, $2H_{4.8}$), 2.36 (s, $3H_{4.8a}$), 2.35 (s, $3H_{4.8}$), 2.22 (d, J =

4.6 Hz, 1H$_{4.8a}$), 1.57 (s, 3H$_{4.8}$), 1.50 (m, 3H$_{4.8a}$). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 144.5(4.8a), 143.9(4.8), 138.8(4.8a), 137.6(4.8), 137.0(4.8), 135.1(4.8a), 129.7(4.8a), 129.5(4.8), 127.8(4.8a), 127.4(4.8), 118.2(4.8), 115.6(4.8a), 49.8(4.8), 43.3(4.8a), 42.0(4.8), 32.4(4.8a), 21.6(4.8a), 21.5(4.8), 18.5(4.8), 17.7(4.8a). **HRMS** (ESI) for**$C_{12}H_{16}NO_2S^+[M+H^+]^+$:** calculated: 237.083, found: 237.0825.

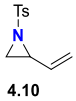
7-Tosyl-7-azabicyclo[4.1.0]hept-2-ene (4.9)



4.9

Purified by flash column chromatography (hexane:ethyl acetate = 20:1) yielded **4.9** (70%) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.74 (d, J = 6.7 Hz, 1H), 7.25 (d, J = 7.9 Hz, 2H), 5.81 (m, 2H), 3.29 – 3.18 (m, 1H), 3.16 – 3.04 (m, 1H), 2.36 (s, 3H), 1.96 (m, 3H), 1.49 – 1.41 (m, 1H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 144.1, 135.6, 133.5, 129.6, 127.6, 120.4, 41.6, 36.5, 21.6, 20.4, 18.6. **HRMS** (ESI) for**$C_{13}H_{15}NNaO_2S^+[M+Na^+]^+$:** calculated: 272.0721, found: 272,0721.

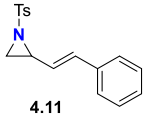
1-Tosyl-2-vinylaziridine (4.10)



4.10

Synthesised using General procedure for the preparation of vinyl aziridines. Purified by flash column chromatography (hexane:ethyl acetate = 20:1) yielded **4.10** (81%) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.89 – 7.63 (m, 2H), 7.26 (d, J = 7.3 Hz, 2H), 5.51 – 5.38 (m, 1H), 5.35 (dt, J = 17.2, 1.7 Hz, 1H), 5.16 (dt, J = 9.8, 1.7 Hz, 1H), 3.28 –3.11 (m, 1H), 2.74 – 2.64 (m, 1H), 2.37 (s, 3H), 2.14 (dd, J = 4.6, 1.3 Hz, 1H). **^{13}C NMR** (CDCl3, 100 MHz) δ 144.5, 135.1, 132.9, 129.7, 127.8, 120.3, 40.9, 34.1, 21.6. **HRMS** (ESI) for **$C_{11}H_{13}NNaO_2S^+[M+Na^+]^+$:** calculated: 246.0564, found: 246.0563.

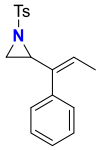
(*E*)-2-Styryl-1-tosylaziridine (4.11)



4.11

Synthesised using General procedure for the preparation of vinyl aziridines. Purified by flash column chromatography (hexane:ethyl acetate = 20:1) yielded **4.11** (63%) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.77 (d, J = 8.3 Hz, 2H), 7.34 – 7.07 (m, 7H), 6.65 (d, J = 15.9 Hz, 1H), 5.76 (dd, J = 15.9, 7.9 Hz, 1H), 3.45 – 3.29 (m, 1H), 2.79 (d, J = 7.1 Hz, 1H), 2.36 (s, 3H), 2.24 (d, J = 4.5 Hz, 1H). **^{13}C NMR** (CDCl3, 100 MHz) δ 144.6, 135.7, 135.1, 135.1, 129.7, 128.6, 128.2, 127.8, 126.4, 124.0, 41.2, 34.6, 21.6. **HRMS** (ESI) for **$C_{17}H_{18}NO_2S^+[M+H^+]^+$:** calculated: 300.1058, found: 300.1054.

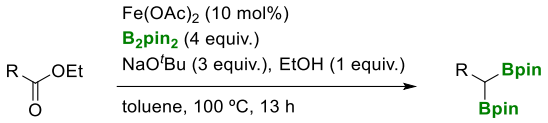
(*E*)-2-(1-Phenylprop-1-en-1-yl)-1-tosylaziridine (4.12)



4.12

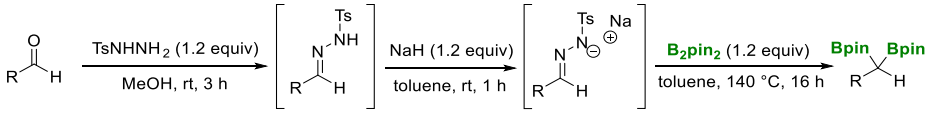
Synthesised using General procedure for the preparation of vinyl aziridines. Purified by flash column chromatography (hexane:ethyl acetate = 20:1) yielded **4.12** (65%) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.71 (d, J = 8.3 Hz, 2H), 7.29 – 7.10 (m, 5H), 7.03 – 6.90 (m, 2H), 5.81 (q, J = 6.9, 1H), 3.44 – 3.32 (m, 1H), 2.63 (d, J = 7.0 Hz, 1H), 2.36 (s, 3H), 2.07 (d, J = 4.6 Hz, 1H), 1.47 (dd, J = 6.9 Hz, 4H). **^{13}C NMR** ($CDCl_3$, 100 MHz) ^{13}C NMR (101 MHz, $CDCl_3$) δ 144.3, 136.3, 135.3, 135.1, 129.6, 129.0, 128.1, 127.9, 127.5, 127.2, 43.8, 33.0, 21.6, 14.6. **HRMS** (ESI) for **$C_{18}H_{19}NNaO_2^+[M+Na^+]^+$:** calculated: 336.1034, found: 336.1033.

8.3.3. General procedure A for the preparation of *gem*-diborylalkanes



In the glove box, in an oven-dried Schlenk tube equipped with a magnetic bar B_2pin_2 (4 mmol, 4 equiv.), NaO^tBU (3 mmol, 3 equiv.), $Fe(OAc)_2$ (0.1 mmol, 10 mol%) and dry toluene (7 mL) were added. The Schlenk flask was sealed and taken out of the glove box and the mixture was stirred at 100 ºC for 1 h. Then, the corresponding ester (1 mmol, 1 equiv.) and dry EtOH (1 mmol, 1 equiv.) were added sequentially, and the resulting mixture was stirred at 100 ºC for 12 h. The reaction was quenched by ethyl acetate and water. The layers are separated and the aqueous layer was extracted with ethyl acetate (3x45mL). The organic layer was dried over anhydrous $MgSO_4$, filtered and the solvent was removed by using rotatory evaporator. The crude was purified by silica gel flash chromatography to afford the *gem*-diborylalkanes.

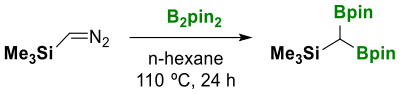
8.3.4. General procedure B for the preparation of *gem*-diborylalkanes



Tosylhydrazide (14.4 mmol) were dissolved in methanol (30mL) in a Schlenk flask. Then a solution of the corresponding aldehyde (12 mmol) in MeOH was added to the solution of tosylhydrazide. The mixed solution was stirred for 3 h. TLC analysis was performed until the spot of aldehyde disappeared. At this point methanol was removed and the obtained N-tosylhydrazones was next reacted with 60% NaH in 80 mL of dry toluene. The mixture was stirred at

room temperature for 1 h. Then B_2pin_2 (14.4 mmol) was added along with additional 5 mL of dry toluene. Then the Schlenk flask was stirred during 16 h at 110 ºC. After the reaction was cooled down to room temperature, the obtained suspension was filtered with Celite® and solvent was concentrated on a rotary evaporator. The crude residue was purified by silica gel flash chromatography to afford the *gem*-diborylalkanes.

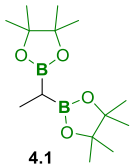
8.3.5. General procedure for the preparation of compound 4.7



An oven-dried Teflon screw-cap Schlenk flask, equipped with a magnetic stir bar, was charged with 4 mmol (1 equiv) of diboron reagent, in the glove-box. Then, 8 mmol (2 equiv) of a 2.0 M solution in hexane of (trimethylsilyl)diazomethane was added dropwise. After stirring the mixture in the glovebox for 5 min the Schlenk flask was sealed and heated at 110 °C for 24 h under constant stirring. The reaction was cooled at room temperature, the solvent was gently concentrated on a rotary evaporator and the resulting crude purified by silica gel flash chromatography to afford the product.

8.3.6. Characterisation of *gem*-diborylalkanes

2,2'-(Ethane-1,1-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (4.1)

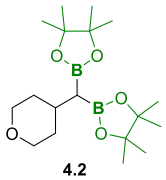


4.1

Synthesised using General procedure A. Purified by flash column chromatography (hexane:ethyl acetate = 20:1) yielded **4.1** (59%) as a colourless oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 1.22 – 1.09 (m, 24H), 1.01 – 0.92 (m, 3H), 0.65 (q, J = 5.2, 3.1 Hz, 1H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 82.8, 24.8, 24.5, 9.0. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ

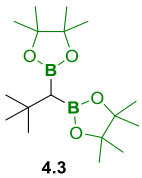
33.9. **HRMS** (ESI) for**$C_{14}H_{29}B_2O_4^+$[M+H$^+$]$^+$:** calculated: 283.2252, found: 283.2254.

2,2'-((Tetrahydro-2*H*-pyran-4-yl)methylene)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (4.2)


4.2

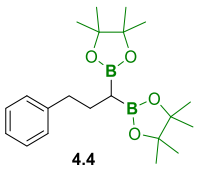
Synthesised using General procedure A. Purified by flash column chromatography (hexane:ethyl acetate = 20:1) yielded **4.2** (38%) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 3.82 (dd, J = 11.3, 3.8 Hz, 2H), 3.33 (td, J = 11.9, 2.0 Hz, 2H), 1.83 (m, 1H), 1.62 (dd, J = 12.9, 4.0 Hz, 2H), 1.32 – 1.09 (m, 26H), 0.62 (d, J = 10.2 Hz, 1H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 83.0, 68.4, 35.4, 33.0, 24.9, 24.5. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 34.0. **HRMS** (ESI) for **$C_{18}H_{35}B_2O_5^+$[M+H$^+$]$^+$:** calculated: 353.2671, found: 353.2676.

2,2'-(2,2-Dimethylpropane-1,1-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (4.3)


4.3

Synthesised using General procedure B. Purified by flash column chromatography (hexane:ethyl acetate = 20:1) yielded **4.3** (75%, 2.92 g) as a white-yellowish solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 1.15 (m, 24H), 0.99 (s, 9H), 0.70 (s, 1H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 82.6, 31.8, 31.3, 24.9, 24.5. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 33.2. **HRMS** (ESI) for **$C_{17}H_{38}B_2NO_4$[M+NH$_4^+$]$^+$:** calculated: 342.2987, found: 342.2985.

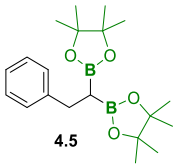
2,2'-(3-Phenylpropane-1,1-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (4.4)


4.4

Synthesised using General procedure B. Purified by flash column chromatography (hexane:ethyl acetate = 20:1) yielded **10** (43%, 1.95 g) as an oil. **^{1}H NMR** ($CDCl_3$, 400

MHz) δ 7.21 – 7.01 (m, 5H), 2.51 (dd, J = 9.2, 6.8 Hz, 2H), 1.84 – 1.72 (m, 2H), 1.58 (s, 1H), 1.17 (s, 24H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 142.9, 128.5, 128.0, 125.4, 82.9, 38.7, 27.9, 24.9, 24.4. **^{11}B NMR** (128.3 MHz, $CDCl_3$) δ 34.0.

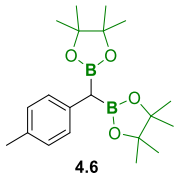
2,2'-(2-Phenylethane-1,1-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (4.5)



4.5

Synthesised using General procedure B. Purified by flash column chromatography (hexane:ethyl acetate = 20:1) yielded **4.5** (47%, 2.05 g) as a yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.13 (m, 5H), 2.81 (d, J = 8.4 Hz, 2H), 1.56 (s, 1H), 1.09 (s, 24H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 144.4, 128.3, 127.9, 125.3, 83.0, 31.3, 25.0, 24.7, 24.5. **^{11}B NMR** (128.3 MHz, $CDCl_3$) δ 33.7. **HRMS** (ESI) for **$C_{20}H_{36}B_2NO_4$ $[M+NH_4^+]^+$:** calculated: 376.283, found: 376.2832.

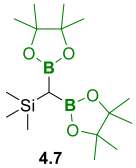
2,2'-(*p*-Tolylmethylene)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (4.6)



4.6

Synthesised using General procedure B. Purified by flash column chromatography (hexane:ethyl acetate = 20:1) yielded **4.6** (42%, 1.80 g) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.07 (d, J = 8.0 Hz, 2H), 6.94 (d, J = 7.9 Hz, 2H), 2.20 (s, 3H), 1.53 (s, 1H), 1.15 (s, 12H), 1.12 (s, 12H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 136.2, 128.9, 128.7, 83.3, 30.9, 24.6, 24.6, 20.9. **^{11}B NMR** (128.3 MHz, $CDCl_3$) δ 33.2. **HRMS** (ESI) for **$C_{20}H_{36}B_2NO_4$ $[M+NH_4^+]^+$:** calculated: 376.283, found: 376.283.

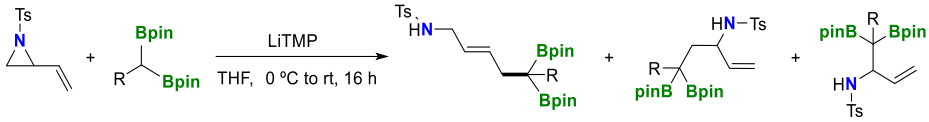
(Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)methyl)trimethylsilane (4.7)



4.7

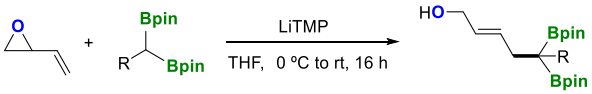
Purified by flash column chromatography (hexane:ethyl acetate = 15:1) yielded **4.7** (83%, 1.63 g) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 1.21 (s, 12H), 1.20 (s, 12H), 0.28 (s, 1H), 0.09 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 82.7, 25.1, 24.6, 0.6. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.9. **HRMS** (ESI) for **$C_{16}H_{34}B_2O_4SiNa$ [M+Na$^+$]$^+$:** calculated: 363.2310; found: 363.2309.

8.3.7. General procedure for the diborylalkylation/ring-opening of vinyl aziridines with diborylalkyl lithium salts.



A Schlenk-tube equipped with a magnetic stir bar was charged with geminal-diborylalkanes (0.5 mmol, 1 equiv) and LiTMP (0.6 mmol, 1.2 equiv) in dry THF as solvent (2 mL). The mixture was stirred during 30 min at 0 ºC. Then, a solution of the vinyl aziridine (0.4 mmol, 0.8 equiv) in 1 mL of THF was added. The reaction was stirred during 10 min at 0 ºC, followed by 16 h at room temperature. The crude residue was purified by silica gel flash chromatography to afford the desired product.

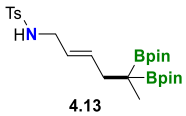
8.3.8. General procedure for the diborylalkylation/ring-opening of vinyl epoxides with diborylalkyl lithium salts.



A Schlenk-tube equipped with a magnetic stir bar was charged with geminal-diborylalkanes (0.5 mmol, 1 equiv) and LiTMP (0.6 mmol, 1.2 equiv) in dry THF as solvent (2 mL). The mixture was stirred during 30 min at 0 ºC. Then, a solution of the vinyl epoxide (0.4 mmol, 0.8 equiv) in 1 mL of THF was added. The reaction was stirred during 10 min at 0 ºC, followed by 16 h at room temperature. The crude residue was purified by silica gel flash chromatography to afford the desired product.

8.3.9. Characterisation of ring-opening products

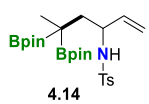
(*E*)-4-Methyl-N-(2-methyl-5,5-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)hex-2-en-1-yl)benzenesulfonamide (4.13)



4.13

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **3** (35%, 71 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.66 (d, J = 8.3 Hz, 2H), 7.22 (d, J = 8.4 Hz, 2H), 5.23 (td, J = 7.4, 1.3 Hz, 1H), 4.23 (m, 1H), 3.35 (d, 2H), 2.35 (s, 3H), 2.10 (d, J = 7.1 Hz, 2H), 1.49 (s, 3H), 1.13 (s, 24H), 0.88 (s, 3H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 143.2, 137.1, 130.5, 129.6, 128.6, 127.1, 83.0, 51.5, 31.7, 24.6, 24.6, 21.5, 16.0, 14.5. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 34.3. **HRMS** (ESI) for **$C_{52}H_{86}B_4N_2O_{12}S_2Na$ [2M+Na$^+$]$^+$:** calculated: 1061.5892, found: 1061.5908.

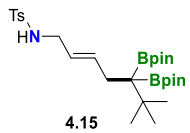
_N_-(5,5-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)hex-1-en-3-yl)-4-methylbenzenesulfonamide (4.14)



4.14

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.14** (64%, 129 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.61 (d, J = 8.3 Hz, 2H), 7.16 (d, J = 7.8 Hz, 1H), 5.35 (ddd, J = 16.8, 10.0, 7.7 Hz, 2H), 4.87 (dt, J = 17.1, 1.1 Hz, 1H), 4.71 (dt, J = 10.2, 1.0 Hz, 1H), 3.87 – 3.73 (m, 1H), 2.32 (s, 3H), 1.80 (dd, J = 14.5, 10.4 Hz, 1H), 1.46 (m, 1H), 1.25 – 1.07 (m, 24H), 0.97 (s, 3H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 142.7, 139.2, 138.7, 129.1, 127.4, 115.5, 83.7, 83.2, 54.9, 38.6, 25.2, 24.6, 24.6, 24.5, 21.4, 14.8. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 34.2. **HRMS** (ESI) for **$C_{25}H_{42}B_2NO_6S$ [M+H$^+$]$^+$:** calculated: 506.2919, found: 506.2913.

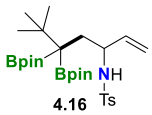
(_E_)-_N_-(6,6-Dimethyl-5,5-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)hept-2-en-1-yl)-4-methylbenzenesulfonamide (4.15)



4.15

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.15** (38%, 83 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.67 (d, J = 8.3 Hz, 2H), 7.23 (d, J = 8.0 Hz, 2H), 5.79 – 5.62 (m, 1H), 5.33 – 5.12 (m, 1H), 4.22 (t, J = 5.9 Hz, 1H), 3.49 – 3.32 (m, 2H), 2.35 (s, 3H), 2.20 (dd, J = 7.0, 1.5 Hz, 2H), 1.18 – 1.05 (m, 24H), 0.92 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 143.2, 138.0, 137.1, 129.6, 127.1, 123.4, 82.5, 45.5, 34.0, 32.8, 29.6, 24.9, 24.7, 21.5. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 33.2. **HRMS** (ESI) for **$C_{28}H_{48}B_2NO_6S$ [M+H$^+$]$^+$:** calculated: 548.3388, found: 548.3391.

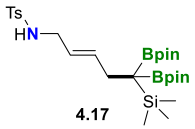
_N_-(6,6-Dimethyl-5,5-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)hept-1-en-3-yl)-4-methylbenzenesulfonamide (4.16)



4.16

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.16** (53%, 116 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.58 (d, J = 8.3 Hz, 2H), 7.13 (d, J = 8.0 Hz, 2H), 6.54 (d, J = 4.8 Hz, 1H), 5.24 (ddd, J = 17.0, 10.0, 8.3 Hz, 1H), 4.92 (dd, J = 17.0, 1.6 Hz, 1H), 4.68 (dd, J = 10.1, 1.6 Hz, 1H), 4.13 – 4.02 (m, 1H), 2.31 (s, 3H), 1.65 (d, J = 4.2 Hz, 2H), 1.20 (s, 18H), 1.18 (s, 6H), 0.97 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 142.1, 140.0, 139.9, 128.9, 127.3, 115.2, 83.3, 83.2, 57.0, 35.7, 34.4, 29.5, 25.2, 25.2, 25.0, 24.3, 21.4. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 33.4. **HRMS** (ESI) for **$C_{28}H_{48}B_2NO_6S$ [M+H$^+$]$^+$:** calculated: 548.3388, found: 548.3398.

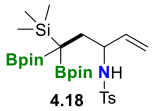
(_E_)-N-(5,5-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-5-(trimethylsilyl)pent-2-en-1-yl)-4-methylbenzenesulfonamide (4.17)



4.17

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.17** (25%, 56 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.69 (d, J = 8.3 Hz, 2H), 7.26 (d, J = 7.6 Hz, 2H), 5.78 – 5.61 (m, 1H), 5.34 – 5.16 (m, 1H), 4.19 (t, J = 5.9 Hz, 1H), 3.43 (td, J = 6.2, 1.2 Hz, 2H), 2.38 (s, 3H), 2.21 (dd, J = 7.0, 1.4 Hz, 2H), 1.13 (s, 24H), 0.01 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 144.0, 138.6, 137.9, 130.4, 127.9, 124.1, 83.3, 46.3, 31.3, 25.7, 25.5, 22.2, 0.0. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 33.1. **HRMS** (ESI) for **$C_{27}H_{48}B_2NO_6SSi$ [M+H$^+$]$^+$:** calculated: 564.3158, found: 564.3147.

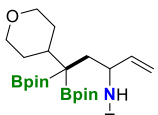
_N_-(5,5-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-5-(trimethylsilyl)pent-1-en-3-yl)-4-methylbenzenesulfonamide (4.18)



4.18

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.18** (56%, 126 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.60 (d, J = 8.3 Hz, 2H), 7.13 (d, J = 8.7 Hz, 2H), 6.33 (d, J = 5.6 Hz, 1H), 5.34 (ddd, J = 17.1, 10.1, 7.9 Hz, 1H), 4.96 – 4.84 (m, 1H), 4.75 – 4.64 (m, 1H), 4.22 – 4.12 (m, 1H), 2.30 (s, 3H), 1.73 – 1.54 (m, 2H), 1.27 (s, 6H), 1.25 (s, 6H), 1.10 (s, 6H), 1.07 (s, 6H), 0.01 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 143.5, 141.3, 140.9, 130.3, 128.6, 116.4, 84.7, 84.1, 59.1, 35.0, 26.9, 26.6, 26.1, 25.4, 22.7, 0.0. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32,9. **HRMS** (ESI) for **$C_{27}H_{48}B_2NO_6SSi$ [M+H$^+$]$^+$:** calculated: 564.3158, found: 564.3132.

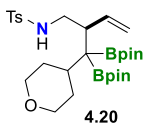
4-Methyl-_N_-(5-(tetrahydro-2_H_-pyran-4-yl)-5,5-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)pent-1-en-3-yl)benzenesulfonamide (4.19)



4.19

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.19** (63%, 145 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.62 (d, J = 8.3 Hz, 2H), 7.17 (d, J = 8.0 Hz, 2H), 6.05 (d, J = 5.4 Hz, 1H), 5.39 (m, 1H), 4.93 (d, J = 17.1 Hz, 1H), 4.76 (d, J = 10.1 Hz, 1H), 3.82 (m, 2H), 3.19 (qd, J = 11.4, 2.8 Hz, 2H), 2.34 (s, 3H), 1.87 –1.33 (m, 7H), 1.21 (s, 6H), 1.19 (s, 6H), 1.17 (s, 6H), 1.15 (s, 6H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 142.6, 139.9, 138.9, 129.1, 127.5, 115.2, 83.6, 83.5, 68.6, 68.6, 55.6, 37.6, 35.0, 31.1, 30.8, 25.1, 24.8, 24.8, 24.6, 21.4. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 33.8. **HRMS** (ESI) for **$C_{29}H_{47}B_2NO_7SNa$ [M+Na$^+$]$^+$:** calculated: 598.3157, found: 598.3162.

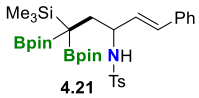
4-Methyl-*N*-(2-((tetrahydro-2*H*-pyran-4-yl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)methyl)but-3-en-1-yl)benzenesulfonamide (4.20)



4.20

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.20** (36%, 83 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.69 (d, J = 8.3 Hz, 2H), 7.21 (d, J = 8.0 Hz, 2H), 5.50 (dt, J = 17.1, 10.1 Hz, 1H), 5.00 (dd, J = 10.1, 1.9 Hz, 1H), 4.82 (dd, J = 17.1, 1.9 Hz, 1H), 4.57 – 4.50 (m, 1H), 3.86 – 3.72 (m, 2H), 3.34 – 3.28 (m, , 2H), 3.27 – 3.10 (m, 2H), 2.75 – 2.64 (m, 1H), 2.38 – 2.26 (m, 4H), 1.75 – 1.33 (m, 4H), 1.14 (s, 6H), 1.13 (s, 6H), 1.08 (s, 12H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 142.9, 139.3, 137.5, 129.4, 127.3, 118.0, 83.2, 83.1, 68.8, 68.7, 45.6, 44.8, 37.1, 31.4, 30.5, 24.9, 24.8, 24.8, 24.8, 24.7, 21.4. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 34,6. **HRMS** (ESI) for **$C_{29}H_{47}B_2NO_7SNa$ [M+Na$^+$]$^+$:** calculated: 598.3157, found: 598.3165.

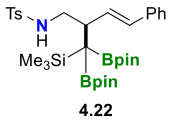
(*E*)-4-Methyl-N-(1-phenyl-5,5-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-5-(trimethylsilyl)pent-1-en-3-yl)benzenesulfonamide (4.21)



4.21

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.21** (12%, 31 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.50 (d, J = 8.3 Hz, 2H), 7.15 – 7.01 (m, 3H), 6.97 – 6.85 (m, 4H), 6.35 (d, J = 6.2 Hz, 1H), 6.15 (d, J = 15.8 Hz, 1H), 5.40 (dd, J = 15.8, 8.6 Hz, 1H), 4.43 – 4.32 (m, 1H), 2.13 (s, 3H), 1.73 – 1.60 (m, 2H), 1.25 (s, 6H), 1.20 (s, 6H), 1.19 (s, 6H), 1.16 (s, 6H), 0.01 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 143.3, 141.1, 138.0, 132.7, 131.7, 130.3, 129.4, 128.5, 128.4, 127.5, 84.8, 84.2, 58.5, 34.8, 27.0, 26.6, 26.1, 25.3, 22.5, 0.0. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 33.4. **HRMS** (ESI) for **$C_{33}H_{52}B_2NO_6SSi$ [M+H$^+$]$^+$:** calculated: 640.3471, found: 640.3475.

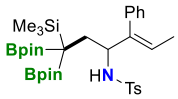
(*E*)-*N*-(2-(Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)(trimethylsilyl) methyl)-4-phenylbut-3-en-1-yl)-4-methylbenzenesulfonamide (4.22)



4.22

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.22** (23%, 59 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.79 – 7.71 (m, 2H), 7.33 – 7.12 (m, 7H), 6.06 (dd, J = 16.0, 9.8 Hz, 1H), 5.96 (d, J = 16.0 Hz, 1H), 4.69 (dd, J = 8.3, 3.6 Hz, 1H), 3.39 – 3.22 (m, 2H), 2.59 – 2.49 (m, 1H), 2.38 (s, 3H), 1.25 (s, 6H), 1.21 (s, 6H), 1.18 (s, 12H), 0.01 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 142.6, 137.9, 136.8, 132.5, 131.5, 129.2, 128.3, 127.2, 127.0, 125.9, 82.7, 82.4, 47.2, 43.3, 25.2, 25.0, 24.5, 24.2, 21.2, 0.0. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 34.2. **HRMS** (ESI) for **$C_{33}H_{52}B_2NO_6SSi$ [M+H$^+$]$^+$:** calculated: 640.3471, found: 640.3473.

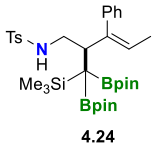
(*E*)-4-Methyl-N-(4-phenyl-1,1-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1-(trimethylsilyl)hex-4-en-3-yl)benzenesulfonamide (4.23)



4.23

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.23** (9%, 24 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.73 – 7.65 (m, 2H), 7.29 – 7.13 (m, 5H), 7.09 – 7.00 (m, 2H), 6.60 (d, J = 4.9 Hz, 1H), 5.34 – 5.24 (m, 1H), 4.74 – 4.65 (m, 1H), 2.37 (s, 3H), 1.75 (dd, J = 14.5, 2.8 Hz, 1H), 1.54 (dd, J = 14.5, 11.0 Hz, 1H), 1.34 (s, 6H), 1.27 (s, 6H), 1.24 (s, 6H), 1.19 (s, 6H), 0.01 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) 143.3, 141.1, 138.0, 132.7, 131.7, 130.3, 129.4, 128.5, 128.4, 127.5, 84.8, 84.2, 78.6, 78.3, 78.0, 58.5, 34.8, 27.0, 26.6, 26.1, 25.3, 22.5, -0.0. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32,9. **HRMS** (ESI) for **$C_{34}H_{54}B_2NO_6SSi$ [M+H$^+$]$^+$:** calculated: 654.3627, found: 654.3631.

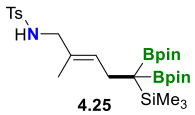
(*Z*)-*N*-(2-(Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)(trimethylsilyl) methyl)-3-phenylpent-3-en-1-yl)-4-methylbenzenesulfonamide (4.24)



4.24

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.24** (12%, 31 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.60 (d, J = 8.3 Hz, 2H), 7.30 – 7.08 (m, 5H), 7.08 – 6.97 (m, 2H), 6.57 (dd, J = 8.0, 2.4 Hz, 1H), 5.55 (qd, J = 6.7, 1.3 Hz, 1H), 3.10 – 2.98 (m, 2H), 2.97 – 2.80 (m, 2H), 2.36 (s, 3H), 1.39 (dd, J = 6.7, 1.2 Hz, 3H), 1.22 (br, 24H), 0.01 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 142.0, 141.9, 140.9, 137.0, 128.8, 128.4, 127.3, 126.7, 125.8, 122.7, 82.7, 82.3, 45.7, 44.9, 24.9, 24.7, 24.6, 24.2, 20.9, 14.0, 0.0. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 34.6. **HRMS** (ESI) for **$C_{34}H_{54}B_2NO_6SSi$ [M+H$^+$]$^+$:** calculated: 654.3627, found: 654.3620.

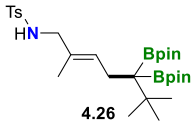
(*E*)-4-Methyl-*N*-(2-methyl-5,5-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-5-(trimethylsilyl)pent-2-en-1-yl)benzenesulfonamide (4.25)



4.25

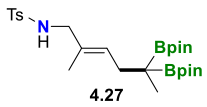
Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.25** (93%, 215 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.73 (d, J = 8.3 Hz, 2H), 7.29 (d, J = 7.7 Hz, 2H), 5.45 – 5.35 (m, 1H), 4.17 (t, J = 6.0 Hz, 1H), 3.34 (d, J = 6.0 Hz, 2H), 2.42 (s, 3H), 2.22 (d, J = 7.0 Hz, 2H), 1.55 (s, 3H), 1.16 (s, 24H), 0.05 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 144.0, 137.9, 133.3, 130.4, 128.8, 128.0, 83.3, 52.7, 26.9, 25.7, 25.5, 22.4, 15.4, 0.0. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.8. **HRMS** (ESI) for **$C_{28}H_{49}B_2NO_6SSiNa$ [M+Na$^+$]$^+$:** calculated: 600.3133, found: 600.3134.

(*E*)-4-Methyl-*N*-(2,6,6-trimethyl-5,5-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)hept-2-en-1-yl)benzenesulfonamide (4.26)



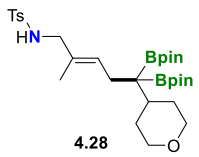
Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.26** (96%, 216 mg) as a white-yellowish solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.67 (d, J = 8.3 Hz, 2H), 7.22 (d, J = 8.0 Hz, 2H), 5.41 (tq, J = 6.9, 1.3 Hz, 1H), 4.24 (t, J = 5.9 Hz, 1H), 3.33 (d, J = 5.3 Hz, 2H), 2.34 (s, 3H), 2.16 (d, J = 6.5 Hz, 2H), 1.47 (d, J = 1.4 Hz, 3H), 1.11 (s, 24H), 0.93 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 143.1, 137.2, 132.0, 129.5, 127.7, 127.2, 82.5, 51.8, 33.9, 29.6, 28.1, 24.8, 24.7, 21.5, 14.5. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 33.3. **HRMS** (ESI) for **$C_{29}H_{49}B_2NO_6SNa$ [M+Na^+]$^+$:** calculated: 584.3364, found: 584.3375.

(*E*)-4-Methyl-N-(2-methyl-5,5-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)hex-2-en-1-yl)benzenesulfonamide (4.27)



Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **23** (98%, 204 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.66 (d, J = 8.3 Hz, 2H), 7.22 (d, J = 8.4 Hz, 2H), 5.23 (td, J = 7.4, 1.3 Hz, 1H), 4.23 (m, 1H), 3.35 (d, J = 6.1, 2H), 2.35 (s, 3H), 2.10 (d, J = 7.1 Hz, 2H), 1.49 (s, 3H), 1.13 (s, 24H), 0.88 (s, 3H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 143.2, 137.1, 130.5, 129.6, 128.6, 127.1, 83.0, 51.5, 31.7, 24.6, 24.6, 21.5, 16.0, 14.5. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 34.3. **HRMS** (ESI) for **$C_{26}H_{43}B_2NO_6SNa$ [M+Na^+]$^+$:** calculated: 542.2894, found: 542.2906.

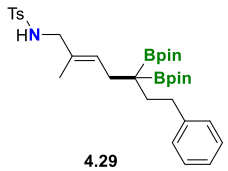
(*E*)-4-Methyl-*N*-(2-methyl-5-(tetrahydro-2H-pyran-4-yl)-5,5-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)pent-2-en-1-yl)benzenesulfonamide (4.28)



4.28

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.28** (99%, 233 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.67 (d, J = 8.4 Hz, 2H), 7.23 (d, J = 7.8 Hz, 2H), 5.32 (td, J = 7.0, 1.3 Hz, 1H), 4.22 (t, J = 6.3 Hz, 1H), 3.84 (dd, J = 10.7, 3.3 Hz, 2H), 3.35 (d, J = 6.1 Hz, 2H), 3.29 (td, J = 11.4, 2.7 Hz, 2H), 2.36 (s, 3H), 2.20 (d, J = 7.1 Hz, 2H), 1.79 (m, 1H), 1.55 – 1.39 (m, 4H), 1.35 (s, 3H), 1.13 (s, 24H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 143.2, 137.1, 129.7, 129.6, 129.2, 127.2, 83.0, 68.9, 51.5, 37.6, 31.3, 27.2, 24.8, 24.7, 21.5, 14.6. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 33.4. **HRMS** (ESI) for **$C_{30}H_{49}B_2NO_7SNa$ [M+Na$^+$]$^+$:** calculated: 612.3313, found: 612.3314.

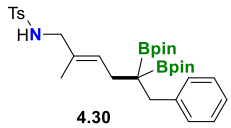
(*E*)-4-Methyl-*N*-(2-methyl-7-phenyl-5,5-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)hept-2-en-1-yl)benzenesulfonamide (4.29)



4.29

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.29** (50%, 122 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.65 (d, J = 8.4 Hz, 2H), 7.23 – 7.13 (m, 4H), 7.11 – 7.00 (m, 3H), 5.22 (tq, J = 7.4, 1.4 Hz, 1H), 4.20 (t, J = 6.3 Hz, 1H), 3.36 (d, J = 6.3 Hz, 2H), 2.48 – 2.36 (m, 2H), 2.35 (s, 3H) 2.33 – 2.22 (m, 2H), 1.79 – 1.64 (m, 2H), 1.58 (s, J = 1.4 Hz, 3H), 1.14 (s, 24H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 143.4, 143.2, 137.1, 130.5, 129.6, 128.5, 128.4, 128.2, 127.1, 125.5, 83.2, 51.6, 33.9, 32.4, 27.6, 24.8, 24.7, 21.5, 14.7. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 34.0. **HRMS** (ESI) for **$C_{33}H_{49}B_2NO_6SNa$ [M+Na$^+$]$^+$:** calculated: 632.3364, found: 632.3381.

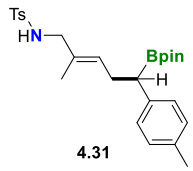
(*E*)-4-Methyl-*N*-(2-methyl-6-phenyl-5,5-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)hex-2-en-1-yl)benzenesulfonamide (4.30)



4.30

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.30** (75%, 179 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.67 (d, J = 8.3 Hz, 2H), 7.23 (d, J = 8.3 Hz, 2H), 7.13 – 7.03 (m, 5H), 5.24 (tq, J = 6.8, 1.2 Hz, 1H), 4.13 (t, J = 6.2 Hz, 1H), 3.35 (d, J = 6.2 Hz 2H), 2.81 (s, 2H), 2.34 (s, 3H), 2.10 (d, J = 6.7 Hz, 2H), 1.38 (d, J = 1.3 Hz, 3H), 1.14 (s, 12H), 1.13 (s, 12H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 143.2, 141.5, 137.1, 130.4, 129.7, 129.6, 128.8, 127.7, 127.1, 125.5, 83.3, 51.5, 35.3, 27.4, 24.9, 24.7, 21.5, 14.7. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.9. **HRMS** (ESI) for **$C_{32}H_{47}B_2NO_6SNa$ [M+Na$^+$]$^+$:** calculated: 618.3207, found: 618.3213.

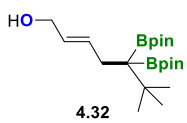
(*E*)-4-Methyl-*N*-(2-methyl-5-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-5-(p-tolyl)pent-2-en-1-yl)benzenesulfonamide (4.31)



4.31

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.31** (65%, 122 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.63 (d, J = 8.4 Hz, 2H), 7.22 (d, J = 7.9 Hz, 2H), 6.97 (s, 4H), 5.21 – 5.14 (m, 1H), 4.04 (t, J = 6.5 Hz, 1H), 3.31 (d, J = 6.3 Hz, 2H), 2.34 (s, 3H), 2.33 – 2.31 (m, 1H), 2.21 (s, 3H), 2.20 – 2.11 (m, 2H), 1.42 (s, 3H), 1.11 (s, 6H), 1.09 (s, 6H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 143.2, 139.3, 137.1, 134.7, 130.7, 129.6, 129.0, 128.5, 128.2, 127.1, 83.4, 51.3, 30.9, 24.6, 24.6, 21.5, 20.9, 14.3. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.2. **HRMS** (ESI) for **$C_{26}H_{37}BNO_4S$ [M+H$^+$]$^+$:** calculated: 470.2536, found: 470.2548.

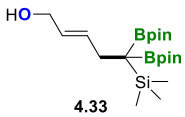
(*E*)-6,6-Dimethyl-5,5-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)hept-2-en-1-ol (4.32)



4.32

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.32** (90%, 142 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 5.93 – 5.77 (m, 1H), 5.68 – 5.51 (m, 1H), 3.97 (d, J = 6.2 Hz, 2H), 2.31 (dd, J = 7.1, 1.4 Hz, 2H), 1.16 (s, 12H), 1.12 (s, 12H), 0.97 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 136.2, 128.4, 82.5, 64.2, 34.0, 32.9, 29.6, 24., 24.7. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 33.8. **HRMS** (ESI) for **$C_{21}H_{44}NB_2O_5$ [M+NH_4^+]$^+$:** calculated: 412.3405, found: 412.3409.

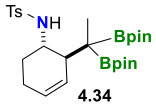
(*E*)-5,5-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-5-(trimethylsilyl)pent-2-en-1-ol (4.33)



4.33

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.33** (53%, 87 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 5.85 – 5.66 (m, 1H), 5.66 – 5.46 (m, 1H), 3.95 (d, J = 6.2 Hz, 2H), 2.28 (dd, J = 6.9, 1.3 Hz, 2H), 1.15 (s, 12H), 1.07 (s, 12H), 0.01 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 136.7, 129.0, 83.2, 64.8, 31.4, 25.6, 25.4, 0.0. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 33.3. **HRMS** (ESI) for **$C_{20}H_{44}B_2NO_5Si$ [M+NH_4^+]$^+$:** calculated: 428.31758, found: 428.3168.

***N*-(2-(1,1-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)ethyl)cyclohex-3-en-1-yl)-4-methylbenzenesulfonamide (4.34)**

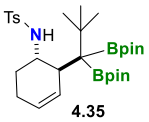


4.34

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.34** (98%, 208 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.69 (d, J = 8.3 Hz, 2H), 7.31 – 7.11 (m, 2H), 5.54 (dq, J = 10.0, 3.3 Hz, 1H), 5.36 (d, J = 7.3 Hz, 1H), 5.22 (dq, J = 10.1, 2.1 Hz, 1H), 3.28 (m, 1H), 2.74 – 2.56 (m, 1H), 2.33 (s, 3H), 1.90 – 1.77 (m,

2H), 1.72 – 1.59 (m, 1H), 1.35 – 1.33 (m, 1H), 1.32 (s, 6H), 1.31 (s, 6H), 1.15 (s, 6H), 1.14 (s, 6H), 0.83 (s, 3H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 142.8, 139.5, 130.9, 129.4, 128.3, 127.0, 83.9, 83.4, 52.4, 44.0, 29.3, 25.6, 25.1, 24.5, 24.5, 24.4, 21.4, 10.7. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 33.3. **HRMS** (ESI) for **$C_{27}H_{43}B_2NNaO_6S$ [M+Na$^+$]$^+$:** calculated: 554.2894, found: 554.2904.

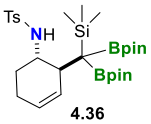
***N*-(2-(2,2-Dimethyl-1,1-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)propyl)cyclohex-3-en-1-yl)-4-methylbenzenesulfonamide (4.35)**



4.35

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.35** (98%, 225 mg) as a white-yellowish solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.71 (d, J = 8.3 Hz, 2H), 7.30 – 7.03 (m, 2H), 5.50 (d, 2H), 5.29 (d, J = 8.0 Hz, 1H), 4.29 (m, 1H), 2.32 (s, 3H), 2.28 – 2.18 (m, 1H), 1.91 (m, 3H), 1.44 – 1.25 (m, 1H), 1.13 (s, 24H), 0.88 (s. 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 142.4, 139.6, 130.6, 129.3, 127.5, 127.0, 82.7, 82.6, 51.5, 42.6, 35.3, 30.1, 25.3, 25.0, 24.9, 24.8, 24.5, 21.6, 21.4. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 34.2. **HRMS** (ESI) for **$C_{30}H_{50}B_2NO_6S$ [M+H$^+$]$^+$:** calculated: 574.3545, found: 574.3543.

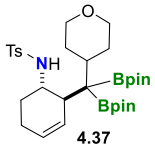
***N*-(2-(Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)(trimethylsilyl) methyl)cyclohex-3-en-1-yl)-4-methylbenzenesulfonamide (4.36)**



4.36

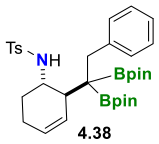
Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.36** (99%, 233 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.75 – 7.67 (m, 2H), 7.26 – 7.14 (m, 2H), 5.51 (br, 2H), 5.28 – 5.15 (m, 1H), 3.93 (m, 1H), 2.42 (d, J = 4.1 Hz, 1H), 2.34 (s, 3H), 1.99 – 1.77 (m, 3H), 1.36 (m, 1H), 1.14 (m, 18H), 1.12 (s, 6H), 0.00 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 141.8, 139.0, 129.3, 128.6, 126.1, 126.1, 82.1, 81.8, 52.2, 40.3, 24.3, 24.2, 24.13, 24.0, 23.4, 20.7, 20.7, 0.0. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 33.8. **HRMS** (ESI) for **$C_{29}H_{50}B_2NO_6SSi$ [M+H$^+$]$^+$:** calculated: 590.3314, found: 590.3321.

4-Methyl-*N*-(2-((tetrahydro-2*H*-pyran-4-yl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)methyl)cyclohex-3-en-1-yl)benzenesulfonamide (4.37)



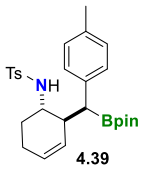
Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.37** (96%, 231 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.68 (d, J = 8.3 Hz, 2H), 7.20 (d, J = 6.9 Hz, 2H), 5.62 5.54 (m, 1H), 5.53 – 5.42 (m, 1H), 5.36 (d, J = 7.6 Hz, 1H), 3.85 – 3.73 (m, 1H), 3.73 – 3.61 (m, 1H), 3.61 – 3.49 (m, 1H), 3.18 (td, J = 11.3, 2.3 Hz, 1H), 3.04 (td, J = 11.2, 3.0 Hz, 1H), 2.56 (m, 1H), 2.35 (s, 3H), 1.98 – 1.79 (m, 3H), 1.75 – 1.57 (m, 2H), 1.56 – 1.41 (m, 2H), 1.39 – 1.25 (m, 2H), 1.20 (s, 12H), 1.09 (s, 12H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 142.8, 139.2, 131.4, 129.5, 126.9, 125.9, 83.5, 83.0, 68.8, 68.7, 50.5, 42.2, 36.2, 31.9, 31.0, 26.3, 25.1, 25.0, 24.7, 24.6, 22.2, 21.4. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.2. **HRMS** (ESI) for **$C_{31}H_{50}B_2NO_7S$ [M+H$^+$]$^+$:** calculated: 602.3494, found: 602.3508.

4-Methyl-*N*-(2-(2-phenyl-1,1-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)ethyl)cyclohex-3-en-1-yl)benzenesulfonamide (4.38)



Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.38** (51%, 124 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.79 – 7.71 (m, 2H), 7.33 – 7.21 (m, 4H), 7.14 – 7.04 (m, 3H), 5.28 (dq, J = 10.1, 2.1 Hz, 1H), 5.16 (br, 2H), 3.70 (m, 1H), 3.08 (d, J = 14.6 Hz, 1H), 2.93 (d, J = 14.6 Hz, 1H), 2.66 (m, 1H), 2.38 (s, 3H), 1.83 – 1.57 (m, 3H), 1.35 – 1.34 (m, 1H), 1.29 (s, 12H), 1.26 (s, 6H), 1.23 (s, 6H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 142.88, 142.41, 139.59, 131.34, 130.21, 129.5, 127.3, 127.0, 125.4, 125.2, 83.9, 83.5, 52.3, 43.6, 34.0, 28.4, 25.3, 25.2, 25.0, 24.6, 23.7, 21.5. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 35.2. **HRMS** (ESI) for **$C_{33}H_{47}B_2NO_6SNa$ [M+Na$^+$]$^+$:** calculated: 630.3207, found: 630.3219.

4-Methyl-*N*-(2-((4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)(p-tolyl)methyl)cyclohex-3-en-1-yl)benzenesulfonamide (4.39)

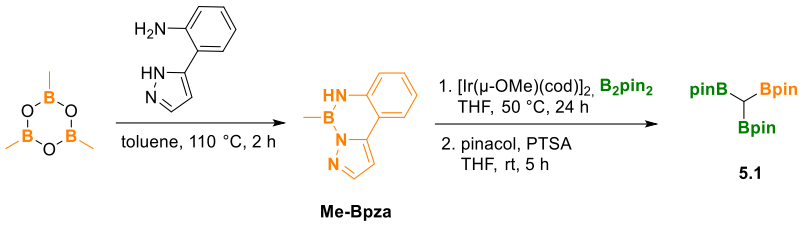


4.39

Purified by flash column chromatography (hexane:ethyl acetate = 9:1) yielded **4.39** (66%, 127 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.37 (d, J = 8.3 Hz, 2H), 7.07 (d, J = 7.9 Hz, 2H), 6.87 (d, J = 7.7 Hz, 2H), 6.77 (d, J = 8.1 Hz, 2H), 5.66 (br, 2H), 4.58 (d, J = 8.2 Hz, 1H), 3.11 – 3.03 (m, 1H), 2.35 (s, 3H), 2.34 – 2.27 (m, 1H), 2.24 (s, 3H), 2.12 – 1.86 (m, 3H), 1.70 – 1.58 (m, 1H), 1.57 – 1.43 (m, 1H), 1.13 – 0.97 (m, 12H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 142.6, 137.9, 136.3, 134.9, 129.3, 129.2, 128.5, 128.4, 127.5, 126.9, 83.5, 48.7, 43.1, 24.5, 22.2, 21.5, 21.0, 20.5. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.1. **HRMS** (ESI) for **$C_{27}H_{36}BNO_4SNa$ [M+Na^+]$^+$:** calculated: 504.2355, found: 504.2358.

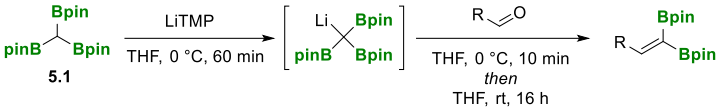
8.4. Experimental section for Chapter 5

8.4.1. General procedure for the synthesis of tris(pinacolboryl)methane (5.1)



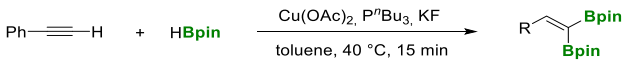
Trimethylboroxine (0.42 mmol, 1 equiv) and 2-(1H-pyrazol-5-yl)aniline (1.26 mmol, 3 equiv) were mixed with toluene (30 mL) in a rounded-bottom Schlenk flask and heated (oil bath) under reflux in a Dean-Stark apparatus for 2 h. The solvent was evaporated and the resulting mixture was 5-methyl-5,6-dihydrobenzo[e]pyrazolo[1,5-c][1,3,2]diazaborinine (**Me-Bpza**, 99%, 230 mg) as a pale brownish-white solid. In case the mixture was not pure enough, it was subjected to a bulb-tobulb distillation. Then, a Schlenk-tube equipped with a magnetic stir bar was charged with 5methyl-5,6-dihydrobenzo[e]pyrazolo[1,5-c][1,3,2] (1,26 mmol, 1 equiv), the iridium catalyst (0.19 mmol, 0.15 equiv) and B_2pin_2 (5.04 mmol, 4 equiv) in dry THF (2 mL) and the mixture was stirred and heated at 50 °C for 24 h. Then pinacol (3.78 mmol, 3 equiv) and p-toluenesulfonic acid monohydrated (3.78 mmol, 3 equiv) were added and the mixture was stirred for 5 h at room temperature. The crude was filtered through a pad of celite and washed with Et_2O and purified by silica gel chromatography to afford **5.1** (42%, 209 mg). The characterisation data are in agreement with the reported product in the literature.[4]

8.4.2. General procedure for the synthesis of 1,1-diborylalkenes (Method A)



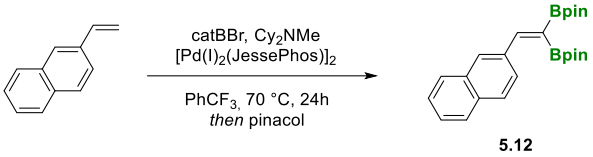
A Schlenk-tube equipped with a magnetic stir bar was charged with triborylmethane **5.1** (0.3 mmol, 1 equiv) and LiTMP (0.36 mmol, 1.2 equiv) in dry THF (2 mL). The mixture was stirred for 30 minutes at 0 °C. Then the corresponding aldehyde (0.45 mmol, 1.5 equiv) was added and the reaction was stirred at 0 °C for 10 minutes, followed by 16 h at room temperature. The crude residue was purified by silica gel chromatography to afford the desired products.

8.4.3. General procedure for the synthesis of 1,1-diborylalkenes (Method B)



A Schlenk-tube equipped with a magnetic stir bar was charged with $Cu(OAc)_2$ (10 mol%, 36 mg, 0.2 mmol), KF (1 equiv, 116 mg, 2 mmol) in dry toluene as solvent (2.5 mL). Then, P^{n}Bu*3* (mg, 99 μL, 0.4 mmol), the corresponding alkyne (204 mg, 0.22 mL, 2 mmol), and HBpin (512 mg, 0.58 mL, 4 mmol) were added in this order. The mixture was stirred for 15 min at 40 °C (oil bath). The reaction mixture was then diluted with Et_2O and filtered through a plug of celite in the air with copious washing (Et_2O). The solvent was gently evaporated d at the rotary evaporator and the crude residue was purified by silica gel flash chromatography to afford the desired products.

8.4.4. General procedure for the synthesis of 1,1-diborylalkene 5.12

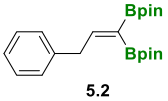


5.12

The synthesis of **5.12** was conducted with an adapted methodology from Watson and co-workers.[5] A Schlenk tube equipped with a magnetic stir bar was charged with $[Pd(I)_2(JessePhos)]_2$ (41 mg, 2.5 mol%) in dry trifluorotoluene (5 mL) and the solution was stirred at rt for 10 minutes. *N*,*N*-dicyclohexylmethylamine (1.1 mL, 5 equiv), a solution of *B*-bromocatecholborane in toluene (5 mL, ~0.8 M, 4 equiv), and the alkene (1 mmol, 1 equiv) were added sequentially. The reaction was stirred in an oil bath at 70 °C for 24 h. Subsequently, the flask was cooled to room temperature, opened to air, and charged with pinacol (472 mg, 4 equiv), ammonium pyrrolidinedithiocarbamate (50 mg, palladium scavenger, 6 equiv to palladium), and diluted with Et_2O (10 mL). The reaction was stirred at rt for 1 h. Then, the reaction was filtered through a pad of Celite® and concentrated in vacuo at 40 °C to remove all solvents. The resultant crude oil was diluted with Et_2O (20 mL) and washed with 1 M aqueous HCl (3 x 20mL) to remove the excess of amine. The organic layer was dried with $MgSO_4$, filtered through Celite, and concentrated in vacuo. The solvent was gently concentrated at the rotary evaporator and the crude residue was purified by silica gel flash chromatography to afford the desired product.

8.4.5. Characterisation of 1,1-diborylalkenes

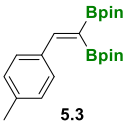
2,2'-(3-Phenylprop-1-ene-1,1-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (5.2)



5.2

Purified by flash column chromatography (pentane:ethyl ether = 100:3) yielded **5.2** (Method A: 62%, 55 mg) as a colourless oil. Spectral data are in agreement with the literature.[6]

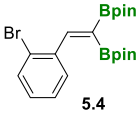
2,2'-(2-(*p*-Tolyl)ethene-1,1-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (5.3)



5.3

Purified by flash column chromatography (pentane:ethyl ether = 100:3) yielded **5.3** (Method A: 41%, 36 mg; Method B: 52%, 240 mg) as a pale yellowish viscous oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.60 (s, 1H), 7.31 (d, J = 8.1 Hz, 2H), 7.02 (d, J = 8.1 Hz, 2H), 2.25 (s, 3H), 1.25 (s, 12H), 1.20 (s, 12H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 155.1, 138.4, 136.8, 128.8, 128.2, 83.5, 83.1, 24.8, 24.6, 21.3. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 30.9. **HRMS** (ESI) for **$C_{21}H_{36}NB_2O_4^+$[M+NH_4^+]$^+$:** calculated: 388.2830, found: 388.2832.

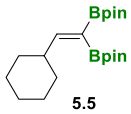
2,2'-(2-(2-Bromophenyl)ethene-1,1-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (5.4)



5.4

Purified by flash column chromatography (pentane:ethyl ether = 100:3) yielded **5.4** (Method A: 68%, 62 mg) as a pale yellowish viscous oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.77 (s, 1H), 7.48 (d, J = 7.8 Hz, 1H), 7.44 (d, J = 7.8 Hz, 1H), 7.13 (t, J = 7.7 Hz, 1H), 7.03 (t, J = 7.7 Hz, 1H), 1.20 (s, 12H), 1.16 (s, 12H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 153.9, 139.8, 132.6, 129.5, 129.3, 126.9, 123.9, 83.6, 83.3, 24.8, 24.5. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 30.2. **HRMS** (ESI) for **$C_{20}H_{35}B_2NBrO_4^+$ [M+NH_4^+]$^+$:** calculated: 454.1936, found: 454.1929.

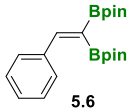
2,2'-(2-Cyclohexylethene-1,1-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (5.5)



5.5

Purified by flash column chromatography (pentane:ethyl ether = 100:3) yielded **5.5** (Method A: 47%, 41 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 6.73 (d, J = 8.8 Hz, 1H), 2.29 – 2.20 (m, 1H), 1.70 (dd, J = 8.8, 6.7 Hz, 4H), 1.64 – 1.57 (m, 2H), 1.28 (s, 12H), 1.21 (s, 12H), 1.18 – 1.03 (m, 4H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 166.0, 82.0, 81.7, 43.1, 31.6, 24.9, 24.8, 23.8, 23.6. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 30.7. **HRMS** (ESI) for **$C_{20}H_{40}NB_2O_4^+$[M+NH_4^+]$^+$:** calculated: 380.3143, found: 380.3149.

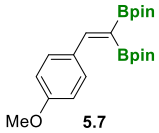
2,2'-(2-Phenylethene-1,1-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (5.6)



5.6

Purified by flash column chromatography (pentane:ethyl ether = 100:3) yielded **5.6** (Method B: 58%, 410 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.71 (s, 1H), 7.51 – 7.44 (m, 2H), 7.34 – 7.27 (m, 3H), 1.31 (s, 12H), 1.28 (s, 12H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 155.1, 139.6, 128.4, 128.2, 128.1, 83.6, 83.2, 24.8, 24.6. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 30.8. **HRMS** (ESI) for **$C_{20}H_{30}B_2O_4$ [M+H]$^+$:** calculated: 371.2568, found: 371.2567.

2,2'-(2-(4-Methoxyphenyl)ethene-1,1-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (5.7)

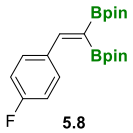


5.7

Purified by flash column chromatography (pentane:ethyl ether = 100:3) yielded **5.7** (Method B: 35%, 270 mg) as a pale yellowish viscous oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.65 (s, 1H), 7.48 – 7.40 (m, 2H), 6.86 – 6.78 (m, 2H), 3.80 (s, 3H), 1.32 (s, 12H), 1.27 (s, 12H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 159.9, 154.8, 132.4, 129.7, 113.5,

83.5, 83.0, 55.2, 24.8, 24.7. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.3. **HRMS** (ESI) for **$C_{21}H_{36}NB_2O_5$ [M+NH_4^+]$^+$:** calculated: 404.2779, found: 404.2782.

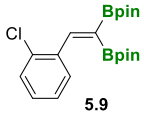
2,2'-(2-(4-Fluorophenyl)ethene-1,1-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (5.8)



5.8

Purified by flash column chromatography (pentane:ethyl ether = 100:3) yielded **5.8** (Method B: 44%, 210 mg) as a pale yellowish solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.66 (s, 1H), 7.49 – 7.43 (m, 2H), 6.98 (m, 2H), 1.31 (s, 12H), 1.27 (s, 12H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 153.8, 129.9, 129.8, 115.2, 114.9, 83.6, 83.2, 24.8, 24.6. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 30.8. **HRMS** (ESI) for **$C_{20}H_{29}B_2FO_4$ [M+H^+]$^+$:** calculated: 375.2210, found: 375.2215. **Melting point**: 78.4 °C.

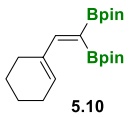
2,2'-(2-(2-Chlorophenyl)ethene-1,1-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (5.9)



5.9

Purified by flash column chromatography (pentane:ethyl ether = 100:3) yielded **5.9** (Method B: 62%, 48 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.92 (s, 1H), 7.60 – 7.54 (m, 1H), 7.35 – 7.29 (m, 1H), 7.23 – 7.11 (m, 2H), 1.28 (s, 12H), 1.25 (s, 12H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 151.7, 138.0, 133.8, 129.4, 129.4, 129.2, 126.2, 83.6, 83.3, 24.9, 24.5. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 30.9. **HRMS** (ESI) for **$C_{20}H_{29}B_2ClO_4$ [M+H]$^+$:** calculated: 391.2017, found: 391.2021.

2,2'-(2-(Cyclohex-1-en-1-yl)ethene-1,1-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (5.10)

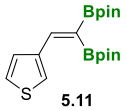


5.10

Purified by flash column chromatography (pentane:ethyl ether = 100:3) yielded **5.10** (Method B: 34%, 250 mg) as a pale yellowish solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.18 (s, 1H), 6.06 – 5.94 (m, 1H), 2.25 – 2.16 (m, 2H), 2.18 – 2.07 (m, 2H), 1.72 – 1.50 (m, 4H), 1.30 (s,

12H), 1.22 (s, 12H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 158.1, 138.9, 135.2, 83.5, 82.9, 26.3, 25.8, 24.9, 24.8, 24.8, 22.3, 22.1. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 30.8. **HRMS** (ESI) for **$C_{20}H_{40}NB_2O_4^+$[M+NH_4^+]$^+$:** calculated: 380.3143, found: 380.3149. **Melting point**: 42.3 °C.

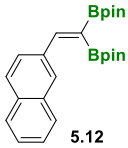
2,2'-(2-(Thiophen-3-yl)ethene-1,1-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (5.11)



5.11

Purified by flash column chromatography (pentane: diethyl ether = 100:3) yielded **5.11** (35%, 26 mg) as pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.64 (s, 1H), 7.44 (m, 1H), 7.31 (dd, *J* = 5.1, 1.3 Hz, 1H), 7.22 (ddd, *J* = 5.1, 3.0, 1.5 Hz, 1H), 1.33 (s, 12H), 1.27 (s, 12H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 148.2, 142.5, 127.2, 125.6, 125.3, 83.6, 83.1, 24.8, 24.8. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.9. **HRMS** (ESI) for **$C_{18}H_{29}B_2O_4S$ [M+H]$^+$:** calculated: 363.1972, found: 363.1973.

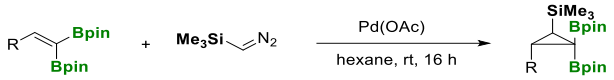
2,2'-(2-(Naphthalen-2-yl)ethene-1,1-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (5.12)



5.12

Purified by flash column chromatography (pentane: diethyl ether = 10:1) yielded **5.12** (57%, 47 mg) as pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.95 (s, 1H), 7.87 (s, 1H), 7.84 – 7.73 (m, 3H), 7.63 (dd, J = 8.5, 1.8 Hz, 1H), 7.50 – 7.40 (m, 2H), 1.34 (s, 12H), 1.30 (s, 12H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 155.1, 137.2, 133.3, 133.2, 128.3, 127.7, 127.7, 127.6, 126.2, 126.1, 125.9, 83.7, 83.2, 24.9, 24.7. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.8. **HRMS** (ESI) for **$C_{24}H_{33}B_2O_4$ [M+H]$^+$:** calculated: 407.2567, found: 407.2567.

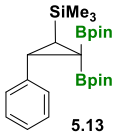
8.4.6. General procedure for the cyclopropanation of 1.1-diborylalkenes



In a glove box, a Schlenk-tube equipped with a magnetic stir bar was charged with $Pd(OAc)_2$ (15 mol%). Then the 1,1-diborylakene substrate (0.2 mmol, 1 equiv) and hexane (1 mL) were added. The mixture was stirred for 5 minutes and (diazomethyl)trimethylsilane 2M (1.4 mmol, 7 equiv) was added dropwise and the reaction was stirred for 5 minutes in the glovebox. The Schlenck-tube was closed with a Teflon cap and was allowed to react for 16 h, at room temperature, with magnetic stirring. The mixture was flirted through Celite® and washed with Et_2O. The solvent was evaporated and the crude was purified by silica gel chromatography.

8.4.7. Characterisation of cyclopropane products

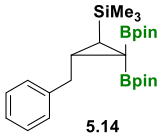
Trimethyl(3-phenyl-2,2-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclopropyl)silane (5.13)



5.13

Purified by flash column chromatography (pentane:ethyl ether = 100:3) yielded **5.13** (79%, 70 mg) as a pale yellowish solid **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.31 – 7.27 (m, 2H), 7.23 – 7.15 (m, 2H), 7.13 – 7.04 (m, 1H), 2.46 (d, J = 7.2 Hz, 1H), 1.27 (s, 6H), 1.25 (s, 6H), 0.97 (s, 6H), 0.92 (d, J = 7.2 Hz, 1H), 0.81 (s, 6H), 0.10 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 142.2, 129.0, 127.7, 125.8, 83.1, 82.9, 30.6, 25.3, 25.1, 25.1, 24.2, 14.2, -0.6. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.9. **HRMS** (ESI) for **$C_{24}H_{41}B_2O_4Si^+[M+H^+]^+$:** calculated: 443.2960, found: 443.2966. **Melting point**: 74.7 °C.

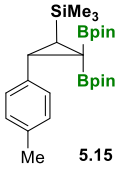
(3-Benzyl-2,2-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclopropyl)trimethylsilane (5.14)



5.14

Purified by flash column chromatography (pentane:ethyl ether = 100:3) yielded **5.14** (53%, 48 mg) as a pale yellowish solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.28 – 7.24 (m, 4H), 7.19 – 7.15 (m, 1H), 3.16 (dd, J = 14.3, 4.4 Hz, 1H), 2.34 (dd, J = 14.3, 9.5 Hz, 1H), 1.44 – 1.37 (m, 1H), 1.25 (s, 6H), 1.23 (s, 6H), 1.23 (s, 6H), 1.21 (s, 6H), 0.21 (d, J = 6.7 Hz, 1H), -0.07 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 142.9, 128.6, 128.2, 125.7, 83.2, 83.0, 40.0, 28.3, 25.5, 25.3, 25.2, 24.5, 17.3, 0.7, -0.8. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 33.1. **HRMS** (ESI) for **$C_{25}H_{43}B_2O_4Si^+[M+H^+]^+$:** calculated: 457.3116, found: 457.3118. **Melting point:** 73.7 °C.

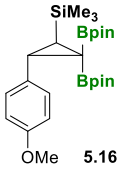
2,2-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-3-(p-tolyl)cyclopropyl)trimethylsilane (5.15)



5.15

Purified by flash column chromatography (pentane:ethyl ether = 10:1) yielded **5.15** (67%, 69 mg) as a pale yellowish solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.17 (d, J = 8.0 Hz, 2H), 6.99 (d, J = 8.0 Hz, 2H), 2.42 (d, J = 7.2 Hz, 1H), 2.26 (s, 3H), 1.26 (s, 6H), 1.25 (s, 6H), 0.98 (s, 6H), 0.88 (d, J = 7.2 Hz, 1H), 0.83 (s, 6H), 0.10 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 139.1, 135.2, 128.9, 128.4, 83.1, 82.9, 30.3, 25.3, 25.2, 25.1, 24.2, 21.1, 14.3, -0.6. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 31.9. **HRMS** (ESI) for **$C_{25}H_{43}B_2O_4Si^+[M+H^+]^+$:** calculated: 457.3117, found: 457.3118. **Melting point:** 75.2°C.

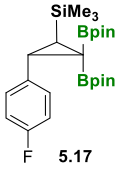
(3-(4-Methoxyphenyl)-2,2-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclopropyl)trimethylsilane (5.16)



5.16

Purified by flash column chromatography (pentane:ethyl ether = 100:3) yielded **5.16** (76%, 63 mg) as a pale yellowish solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.23 – 7.17 (m, 2H), 6.78 – 6.70 (m, 2H), 3.75 (s, 3H), 2.40 (d, J = 7.2 Hz, 1H), 1.26 (s, 6H), 1.24 (s, 6H), 0.99 (s, 6H), 0.85 (d, J = 7.2 Hz, 1H), 0.82 (s, 6H), 0.10 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 158.0, 134.4, 130.0, 113.2, 83.0, 82.8, 55.5, 29.8, 25.3, 25.1, 24.2, 14.3, -0.6. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.2. **HRMS** (ESI) for **$C_{25}H_{43}B_2O_5Si^+[M+H^+]^+$:** calculated: 473.3065, found: 473.3064. **Melting point:** 76.1°C.

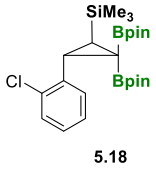
3-(4-Fluorophenyl)-2,2-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclopropyl)trimethylsilane (5.17)



5.17

Purified by flash column chromatography (pentane:ethyl ether = 10:1) yielded **5.17** (79%, 73 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.26 – 7.20 (m, 2H), 6.92 – 6.84 (m, 2H), 2.41 (d, J = 7.2 Hz, 1H), 1.26 (s, 6H), 1.25 (s, 6H), 0.99 (s, 6H), 0.87 – 0.84 (m, 1H), 0.82 (s, 6H), 0.10 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 161.5 (d, J = 243.2 Hz), 137.9 (d, J = 3.0 Hz), 130.5 (d, J = 7.9 Hz), 114.3 (d, J = 21.1 Hz), 83.1, 82.9, 29.7, 25.3, 25.1, 24.2, 14.5, -0.7. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.4. **^{19}F NMR** ($CDCl_3$, 376.5 MHz) δ -117.9. **HRMS** (ESI) for **$C_{24}H_{40}B_2FO_4Si^+[M+H^+]^+$:** calculated: 461.2866, found: 461.2868. **Melting point:** 77.7°C.

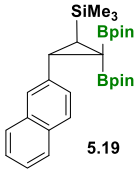
(3-(2-Chlorophenyl)-2,2-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclopropyl)trimethylsilane (5.18)



5.18

Purified by flash column chromatography (pentane:ethyl ether = 10:1) yielded **5.18** (51%, 49 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.30 – 7.27 (m, 1H), 7.18 – 7.13 (m, 1H), 7.12 – 7.04 (m, 2H), 2.53 (d, J = 7.5 Hz, 1H), 1.26 (s, 6H), 1.26 (s, 6H), 0.99 (d, J = 10.6 Hz, 1H), 0.93 (s, 6H), 0.78 (s, 6H), 0.13 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 140.7, 137.6, 130.1, 129.2, 127.7, 126.4, 83.5, 83.1, 31.2, 25.8, 25.5, 25.3, 24.9, 15.5, 0.0. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.2. **HRMS** (ESI) for **$C_{24}H_{40}B_2ClO_4Si$ [M+H]$^+$:** calculated: 477.2572, found: 477.2575. **Melting point:** 76.7°C.

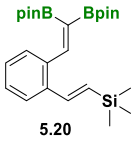
Trimethyl(3-(naphthalen-2-yl)-2,2-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclopropyl)silane (5.19)



5.19

Purified by flash column chromatography (pentane:ethyl ether = 10:1) yielded **5.19** (82%, 81 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.77 – 7.71 (m, 2H), 7.70 – 7.64 (m, 2H), 7.48 (m, 1H), 7.43 – 7.33 (m, 2H), 2.61 (d, J = 7.2 Hz, 1H), 1.29 (s, 6H), 1.27 (s, 6H), 1.07 (d, J = 7.2 Hz, 1H), 0.89 (s, 6H), 0.69 (s, 6H), 0.15 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 140.0, 133.4, 132.2, 128.4, 127.6, 127.5, 127.1, 126.0, 125.6, 124.9, 83.1, 82.9, 30.8, 25.3, 25.2, 25.0, 24.1, 14.6, -0.6. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 33.3. **HRMS** (ESI) for **$C_{28}H_{43}B_2O_4Si^+$[M+H$^+$]$^+$:** calculated: 493.3117, found: 493.3118. **Melting point:** 80.1 °C.

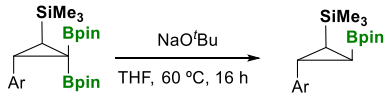
(*E*)-(2-(2,2-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)vinyl)styryl)trimethylsilane (5.20)



5.20

Purified by flash column chromatography (pentane:ethyl ether = 10:1) yielded **5.20** (41%, 37 mg) as a brown-yellowish solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 8.00 (s, 1H), 7.44 (td, J = 7.6, 1.5 Hz, 2H), 7.24 (td, J = 7.5, 1.3 Hz, 1H), 7.17 (td, J = 7.5, 1.4 Hz, 1H), 7.12 (d, J = 19.1 Hz, 1H), 6.32 (d, J = 19.1 Hz, 1H), 1.28 (s, 12H), 1.24 (s, 12H), 0.14 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 154.8, 141.5, 138.3, 137.6, 133.5, 128.4, 128.4, 127.3, 126.0, 83.7, 83.3, 25.0, 24.7, -1.1. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 29.9. **Melting point:** 76.9°C.

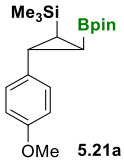
8.4.8. General procedure for the protodeboronation of 1,1-diborylcyclopropanes



A Schlenk-tube equipped with a magnetic stir bar was charged with NaO^{t}Bu (0.6 mmol, 3 equiv), the corresponding 1,1-diborylcyclopropane (0.2 mmol, 1 equiv) and THF (2 mL). The Schlenk-tube was closed with a Teflon cap and the reaction was stirred for 16 h at 60 °C. The solvents were evaporated at the rotatory evaporator and the crude was purified by silica gel chromatography to obtain the desired product.

8.4.9. Characterisation of borylcyclopropanes

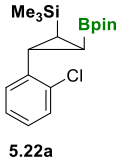
(2-(4-Methoxyphenyl)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclopropyl)trimethylsilane (5.21a)



5.21a

Purified by flash column chromatography (pentane:ethyl ether = 10:1) yielded **5.21a** (80%, 55 mg) as a pale yellowish solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.03 (d, J = 8.7 Hz, 2H), 6.79 (d, J = 8.7 Hz, 2H), 3.77 (s, 3H), 2.07 (dd, J = 7.1, 5.9 Hz, 1H), 1.24 (s, 12H), 0.42 (dd, J = 11.5, 5.9 Hz, 1H), 0.27 (dd, J = 11.5, 7.1 Hz, 1H), 0.09 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 157.7, 136.8, 126.8, 113.8, 83.2, 77.4, 77.1, 76.8, 55.4, 26.5, 25.3, 24.8, 17.1, -0.5. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 33.2. **HRMS** (ESI) for **$C_{19}H_{32}BO_3Si^+$[M+H$^+$]$^+$:** calculated: 347.2213, found: 347.2214. **Melting point:** 60.2°C.

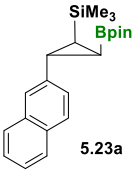
(2-(4-Methoxyphenyl)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclopropyl)trimethylsilane (5.22a)



5.22a

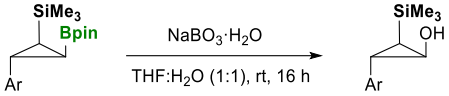
Purified by flash column chromatography (pentane:ethyl ether = 10:1) yielded **5.22a** (76%, 53 mg) as a pale yellowish solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.32 (dd, J = 7.7, 1.5 Hz, 1H), 7.12 (m, 2H), 7.05 – 6.99 (m, 1H), 2.36 (dd, J = 7.3, 6.1 Hz, 1H), 1.26 (s, 12H), 0.53 (dd, J = 11.4, 6.1Hz 1H), 0.27 (dd, J = 11.4, 7.4 Hz, 1H), 0.14 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 142.3, 136.2, 129.6, 127.4, 127.3, 127.1, 83.9, 26.4, 25.9, 25.3, 16.1, 0.0. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 33.4. **HRMS** (ESI) for **$C_{18}H_{29}BClO_2Si$ [M+H]$^+$**calculated: 351.1716, found: 351.1717. **Melting point:** 61.0°C.

Trimethyl((1S,2S,3S)-2-(naphthalen-2-yl)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclopropyl)silane (5.23a)



Purified by flash column chromatography (pentane:ethyl ether = 10:1) yielded **5.23a** (80%, 58 mg) as a white solid. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.79 – 7.72 (m, 3H), 7.63 – 7.57 (m, 1H), 7.46 – 7.36 (m, 2H), 7.19 (dd, J = 8.6, 1.8 Hz, 1H), 2.30 (dd, J = 7.0, 5.9 Hz, 1H), 1.28 (s, 6H), 1.27 (s, 6H), 0.66 (dd, J = 11.6, 5.9 Hz, 1H), 0.47 (dd, J = 11.6, 7.0 Hz, 1H), 0.14 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 142.3, 133.6, 132.0, 127.9, 127.6, 127.3, 126.0, 124.9, 124.2, 124.1, 83.3, 27.4, 25.3, 24.9, 17.9, -0.5. **^{11}B NMR** ($CDCl_3$, 128.3 MHz) δ 32.9. **HRMS** (ESI) for **$C_{22}H_{32}BO_2Si^+[M+H^+]^+$:** calculated: 367.2264, found: 367.2267. **Melting point:** 63.5°C.

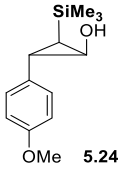
8.4.10. General procedure for the oxidation of borylcyclopropanes



In an opened-air flask, charged with a magnetic stir bar, were added the corresponding borylcyclopropane (0.1 mmol, 1 equiv), $NaBO_3 \cdot H_2O$ (0.3 mmol, 3 equiv), THF (2 mL) and distilled water (1 mL). The reaction was closed with a septum with a needle to avoid over pressures and was stirred for 16h at room temperature. After this period of time, the mixture was extracted with Et_2O (3 x 15 mL), the organic layer was dried with anhydrous magnesium sulphate, filtered and the solvents were evaporated. The resulting crude was purified by silica gel chromatography to obtain the corresponding alcohol.

8.4.11. Characterisation of cyclopropanols

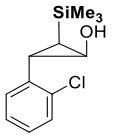
2-(4-Methoxyphenyl)-3-(trimethylsilyl)cyclopropan-1-ol (5.24)



5.24

Purified by flash column chromatography (pentane:ethyl ether = 10:2) yielded **5.24** (92%, 21 mg) as a pale yellowish oil. **^{1}H NMR** (CDCl3, 400 MHz) δ 6.96 (d, J = 8.7 Hz, 2H), 6.80 (d, J = 8.7 Hz, 2H), 3.80 (dd, J = 7.4, 2.4 Hz, 1H), 3.78 (s, 3H), 2.00 (dd, J = 8.2, 2.4 Hz, 1H), 0.24 (dd, J = 8.2, 7.4 Hz, 1H), 0.13 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 157.8, 134.3, 126.9, 113.9, 59.7, 55.4, 29.8, 28.5, 18.8, -0.2.

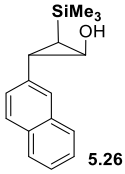
2-(4-Methoxyphenyl)-3-(trimethylsilyl)cyclopropan-1-ol (5.25)



5.25

Purified by flash column chromatography (pentane:ethyl ether = 10:2) yielded **5.25** (95%, 43 mg) as a pale yellowish oil. **^{1}H NMR** ($CDCl_3$, 400 MHz) δ 7.35 (dd, J = 7.5, 1.8 Hz, 1H), 7.18 – 7.08 (m, 2H), 6.92 – 6.83 (m, 1H), 3.85 (dd, J = 7.6, 2.6 Hz, 1H), 2.31 (dd, J = 8.5, 2.6, 1H), 1.58 (bs, 1H), 0.30 (dd, J = 8.5, 7.6 Hz, 1H), 0.17 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 139.7, 135.4, 129.5, 127.4, 127.1, 127.1, 59.1, 27.7, 18.3, -0.0.

2-(Naphthalen-2-yl)-3-(trimethylsilyl)cyclopropan-1-ol (5.26)



5.26

Purified by flash column chromatography (pentane:ethyl ether = 10:1) yielded **5.26** (96%, 49 mg) as a pale yellowish oil. **^{1}H NMR** (CDCl3, 400 MHz) δ 7.57 (ddd, J = 17.8, 8.2, 1.9 Hz, 3H), 7.28 – 7.18 (m, 3H), 6.98 (dd, J = 8.5, 1.9 Hz, 1H), 3.80 (dd, J = 7.5, 2.4 Hz, 1H), 2.02 (dd, J = 8.5, 2.4 Hz, 1H), 0.86 (m, 1H), -0.01 (s, 9H). **^{13}C NMR** ($CDCl_3$, 100 MHz) δ 140.1, 133.8, 132.2, 128.2, 127.9, 127.6, 126.4, 125.3, 125.1, 123.8, 60.4, 29.8, 19.8, -0.0.

8.5. References

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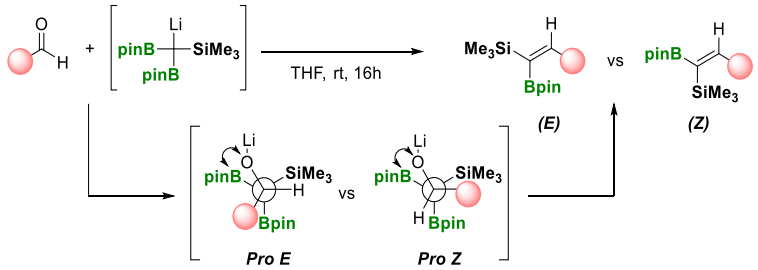
CHAPTER 9

Summary

Organoboron chemistry has been widely studied over the past decades due to its importance in organic synthesis, becoming a highly efficient tool since organoboron compounds can be transformed into a wide range of functional groups. Recently, *gem*-diboron compound have emerged as alternative bifunctional reagents for selective C-C bond formation. The present thesis contributes to the field with new methodologies that allow the synthesis of *gem*-diborylalkenes, as well as, conducting novel activation modes and reactivity trends towards the formation of unprecedented organoboron compounds.

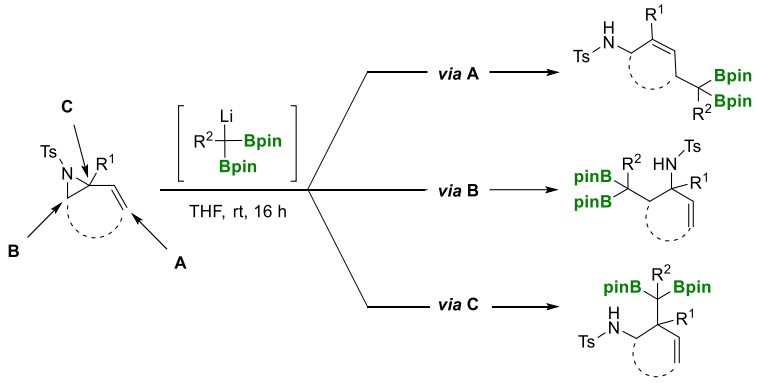
In Chapter 3 we have conducted the olefination reaction between aromatic or aliphatic aldehydes and $LiC[B]_2[Si]$ ([B] = Bpin or Bhex, [Si] = $SiMe_3$, $SiMe_2{}^tBu$ or $SiPh_2{}^tBu$) with a special focus on the challenging stereocontrol on the trisubstituted 1,1-silylborylated alkene formation. We have found that picolinaldehyde, thiophene-2-carbaldehyde and furan-2-carbaldehyde could be involved in stereodetermining intermediates via intramolecular interaction of N, S or O with B. A divergent stereocontrol has been observed, OMe *ortho* substituents in the aromatic moieties influences towards (*E*)-borylsilylalkane formation whereas bulky halide *ortho* substituents favours the condensation towards the (*Z*)-borylsilylalkanes. The boron-Wittig of α,β-unsaturated substrates with $LiC(Bpin)_2[Si]$ allows access to 1,1-silylborylated conjugated dienes and enynes, with relative high stereoselectivity (Scheme 9.1).



Scheme 9.1 Boron-Wittig reaction between aldehydes and diborylsilylmethide lithium salts.

Chapter 4 discloses that α-diboryl carbanions formed from *gem*-diborylalkanes and LiTMP perform regioselective nucleophilic attack on vinyl aziridines.

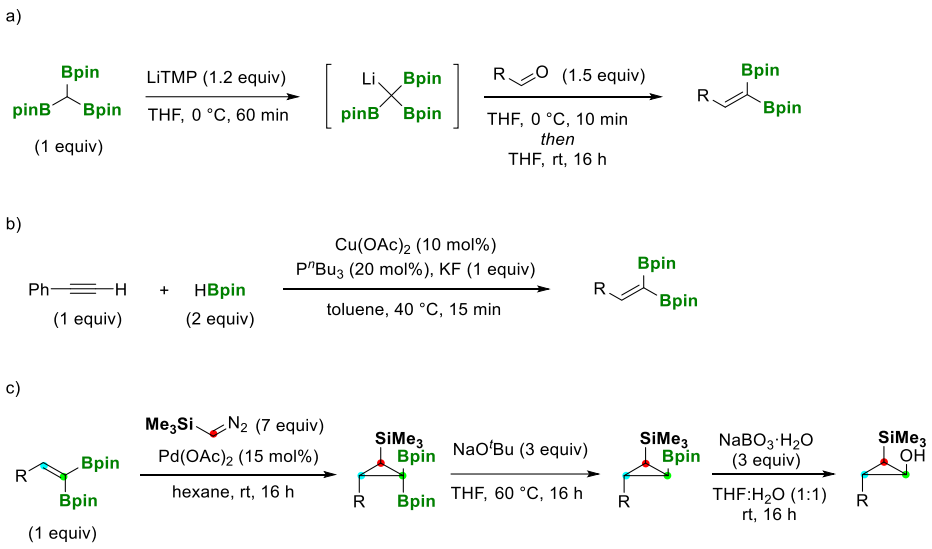
Preferred S_N2 ring opening/C−C bond forming on the less sterically hindered 1-tosyl-2vinylaziridine contrasts to the favoured S_N2' diborylalkylation on 2-methyl-1-tosyl-2-vinylaziridine. In contrast to the two previous examples, the allylic position of cyclic vinyl aziridines traps the α-diboryl carbanions along the diborylalkylation/ring opening to form exclusively homoallyldiboronate species with *trans* disposition of the amine and diborylalkyl groups. Despite the fact that the regioselectivity depends on the nature of vinyl aziridine substrate, the resulting product maintains the two boryl moieties unaltered, except for those reactions where $HCAr(Bpin)_2$ are involved, since protodeboronation seems to proceed under the basic reaction conditions, in order to diminish the steric hindrance around the tetrasubstituted C centres (Scheme 9.2).



Scheme 9.2 Nucleophilic diborylalkylation/ring-opening reaction between cyclic and non-cyclic vinyl aziridines and diborylmethide lithium salts.

In Chapter 5, two novel synthetic strategies for the preparation of 1,1-diborylalkenes have been described. One of them relies on a boron-Wittig reaction between aldehydes and triborylmethide lithium salt (Scheme 9.3a). The second one is based on a copper-catalysed dehydrogenative borylation/hydroboration of terminal alkynes with pinacolborane (HBpin) in the presence of KF (Scheme 9.3b). We have described a palladium-catalysed cyclopropanation of 2-substituted 1,1-diborylalkenes with

(trimethylsilyl)diazomethane. The relative stereoselectivity is controlled *via* carbene insertion sequence, generating an exclusive *anti* conformation between R and $SiMe_3$ substituents. The new 2,2-diboryl-1-silyl-cyclopropanes can be activated by NaO^tBu, *via* protodeboronation preferentially on the boryl moiety *syn* to the aryl group. Further oxidation enabled the formation of polyfuncional cylcopropanols with retention of the stereoselectivity (Scheme 9.3c).



Scheme 9.3 Strategic synthesis of 1,1-diborylalkenes through a) boron-Wittig reaction between aldehydes and tris(pinacolboryl)methane and b) Cu-catalysed dehydrogenative borylation/hydroboration of terminal alkynes and c) stereroselective cyclopropanation of 2-substituted 1,1-diborylalkenes to afford bis(pinacolboryl)cyclopropanes, with subsequent orthogonal protodeboronation and oxidation.

CHAPTER 10

Scientific contributions

10.1. List of publications

O. Salvado, R. Gava, E. Fernández, *"Diborylalkyllithium salts trigger regioselective ring opening of vinyl aziridines", Org. Lett.* **2019**, *21*, 9247-9250.

O. Salvado, E. Fernández, *"A modular olefination reaction between aldehydes and diborylsylilmethide lithium salts", Chem. Commun.* **2021**, *57*, 6300–6303.

O. Salvado, P. Dominguez-Molano, E. Fernández, *"Stereoselective cyclopropanation of 1,1-diborylalkenes via palladium-catalyzed (trimethylsilyl)diazomethane insertion", Org. Lett.* **2022**, *24*, 4949-4953.

P. Dominguez-Molano, G. Bru, O. Salvado, R. J. Maza, J. J. Carbó, E. Fernández, *"Transborylation of alkenylboranes with diboranes", Chem. Commun.* **2021**, *57*, 13361-13364.

S. González, O. Salvado, E. Fernández, *"1,2-Dialkylation of 1,1-arylboryl alkenes via borata-alkene intermediate", Adv. Synth.Catal.* **2022**, *364*, 1701-1707.

M. Pujol, R. J. Maza, O. Salvado, J. J. Carbó, E. Fernández, *"Site-selective (Z)-α-borylalkenyl copper systems for nucleophilic stereodefined allylic coupling", Angew. Chem. Int. Ed.* **2022**, *61*, e202208495.

O. Salvado, E. Fernández, *"Tri(boryl)alkanes and tri(boryl)alkenes: the versatile reagents", Molecules.* **2020**, *25*, 1578. Review by invitation.

M. Corro, O. Salvado, S. González, P. Dominguez-Molano, E. Fernández, *"Reactivity trends with borylalkyl copper(I) species", Eur. J. Inorg. Chem.* **2021**, *28*, 2802-2813. Review by invitation.

J. Sendra, O. Salvado, M. Pedrón, E. Reyes, T. Tejero, E. Fernández, P. Merino, J. L. Vicario, *"Switchable Brønsted acid-catalysed ring contraction of cyclooctatetraene oxide towards the enantioselective synthesis of cycloheptatrienyl-substituted homoallylic alcohols and oxaborinanes",* (submitted).

10.2. Contributions to scientific conferences

XXXVIII Reunión Bienal de la Real Sociedad Española de Química, Granada (Spain), June 2022 – Flash presentation. Oriol Salvadó

9th European Conference on Boron Chemistry (EuroBoron IX), Barcelona (Spain), July 2022 – Oral presentation. Oriol Salvadó

13th Spanish-Italian Symposium on Organic Chemistry (SISOC-XIII), Tarragona (Spain), September 2022 – Poster presentation. Oriol Salvadó

6th Edition of PhD Day ICIQ-URV (VI PhD Day), Tarragona (Spain), October 2022 – Organising committee. Oriol Salvadó

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