Pergamon

Tetrahedron 58 (2002) 9527–9540

TETRAHEDRON

Palladium-catalyzed hydrophenylation of bicyclic alkenes

Peter Mayo and William Tam*

Department of Chemistry and Biochemistry, Guelph-Waterloo Centre for Graduate Work in Chemistry and Biochemistry, University of Guelph, Guelph, Ont., Canada N1G 2W1

Received 15 August 2002; revised 2 October 2002; accepted 4 October 2002

Abstract—Palladium-catalyzed hydrophenylation reactions of bicyclic alkenes were investigated. These reactions were found to be completely chemo- and stereoselective, giving only *exo* products on the less substituted double bonds of bicyclic alkenes in moderate to good yields. For unsymmetrical bicyclic alkenes, regioselectivities of 52:48 to 100:0 were observed with various substituents on the bicyclic alkenes.

1. Introduction

Palladium-catalyzed coupling reactions of olefins represent an important strategy for carbon–carbon bond formation.[1] Both the inter- and intramolecular Heck-type hydroarylation and hydroalkenylation have been well studied and the asymmetric variant of these reactions has also been reported.[2–6] However, to our knowledge, no systematic study on the chemo-, stereo- and regioselectivities of palladium-catalyzed hydrophenylation of substituted bicyclic alkenes has been reported in the literature. There are several questions about the palladium-catalyzed hydrophenylation of substituted bicyclic alkenes that we would like to address: (i) the chemoselectivity (for the substituted norbornadienes **1** and **2**, will hydrophenylation occur on the C_5=C_6 or C_2=C_3 double bond, Fig. 1); (ii) the stereoselectivity (*exo* vs *endo* products); and (iii) the regioselectivity of unsymmetrical systems (**2**–**4**, Fig. 1). In the past few years, we have been focusing on the synthesis of substituted norbornadienes and norbornenes and studying different cycloaddition reactions and addition reactions to these bicyclic alkenes.[7–13] In this paper, we would like to report our study on the chemo-, stereo- and regioselectivities of these bicyclic alkenes in the palladium-catalyzed hydrophenylation reactions.

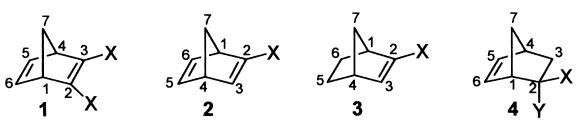


Figure 1. Substituted bicyclic alkenes.

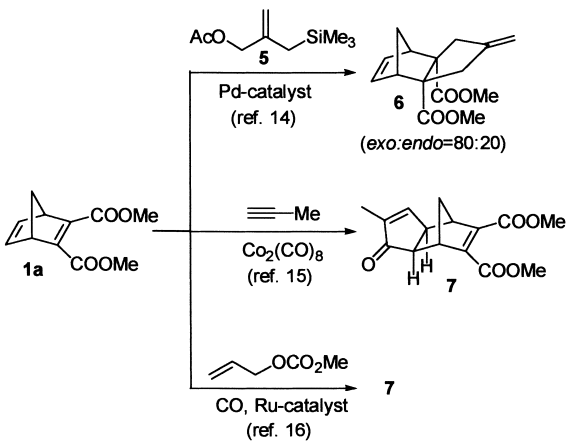
Keywords: palladium; hydrophenylation; heck coupling; bicyclic alkenes; chemoselectivity; stereoselectivity; regioselectivity.

* Corresponding author. Tel.: +1-519-824-4120x2268; fax: +1-519-766-1499; e-mail: wtam@uoguelph.ca

2. Results and discussion

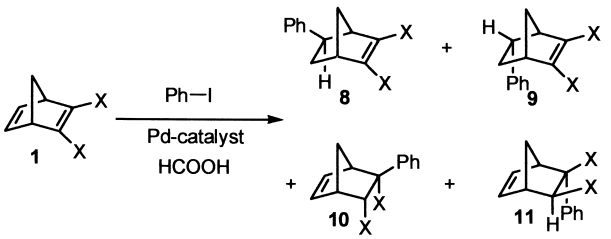
2.1. Palladium-catalyzed hydrophenylation of 2,3-disubstituted norbornadienes (1a–1c)

Only very few examples of the study of chemo- and stereoselectivity of transition metal-catalyzed cycloadditions and addition reactions of substituted norbornadienes can be found in the literature, and in all cases, the only substituted norbornadiene that has been used in these studies was the 2,3-dicarbomethoxynorbornadiene **1a** (Scheme 1). For example, the Pd-catalyzed [3+2] cycloaddition of palladium–trimethylenemethane (Pd–TMM) complex with **1a** occurs exclusively on the electron-deficient, tetrasubstituted double bond (with stereoselectivity *exo*/*endo*=80:20).[14] On the other hand, the opposite chemoselectivity was observed in the Co-catalyzed Pauson–Khand [2+2+1] cycloaddition of propyne and **1a**,[15] and in the Ru-catalyzed carbonylative cyclization of



Scheme 1. Literature examples of addition reactions of norbornadiene **1a**.

0040–4020/02/$ - see front matter
PII: S0040-4020(02)01277-2



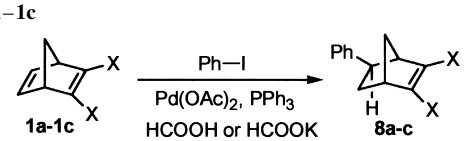
Scheme 2. Possible hydrophenylation products.

allylic carbonates,[16] in which the reactions occurred exclusively on the less substituted, less electron-deficient double bond.

Four possible hydrophenylation products are possible with 2,3-disubstituted norbornadienes (Scheme 2). Hydrophenylation can occur on the less substituted double bonds of the norbornadienes to give *exo* product **8** or *endo* product **9**, or occur on the more substituted double bonds of the norbornadienes, to give *exo* product **10** or *endo* product **11**. In order to study the chemo- and stereoselectivities of the palladium-catalyzed hydrophenylation of 2,3-disubstituted norbornadienes, several 2,3-disubstituted norbornadienes (**1a**–**1c**) were prepared[10,17] and their palladium-catalyzed hydrophenylation reactions were studied (Table 1).

Although four possible hydrophenylation products could be formed, single isomers were produced in all cases. Thus, excellent chemoselectivities were observed and hydrophenylations only occurred on the less hindered double bond of the norbornadienes regardless of the electronic nature of the substituents on the norbornadienes. The hydrophenylations were also highly stereoselective, giving only the *exo* products in moderate to good yields. With 2,3-disubstituted norbornadienes **1a** and **1b** (X=COOMe and $SiMe_3$), Pd-catalyzed hydrophenylations occurred smoothly using $Pd(OAc)_2$ (20 mol%), PPh_3 (40 mol%), formic acid (HCOOH) and piperidine in THF at 60°C (conditions A) afforded the products **8a** and **8b** in 91 and 80% yields, respectively (Table 1, entries 1 and 2). With 2,3-dibromonorbornadienes **1c**, under conditions A, less than 10% of the hydrophenylation product **8c** was isolated and a complicated mixture of inseparable products was obtained instead (Table 1, entry 3). Replacing the formic acid and piperidine

Table 1. Pd-catalyzed hydrophenylation of 2,3-disubstituted norbornadienes **1a**–**1c**



Entry	X	Conditions[a]	Product[b]	Yield (%)[c]
1	COOMe	A	**8a**	91
2	$SiMe_3$	A	**8b**	80
3	Br	A	**8c**	<10
4	Br	B	**8c**	33
5	Br	C	**8c**	58

[a] Reaction conditions: A=$Pd(OAc)_2$, PPh_3, HCOOH, piperidine, THF, 60°C. B=$Pd(OAc)_2$, PPh_3, HCOOK, DMF, 25°C. C=$Pd(OAc)_2$, PPh_3, HCOOK, Bu_4NCl, DMF, 25°C.

[b] No other isomers were detected by ^1H NMR (400 MHz) in the crude reaction mixture.

[c] Isolated yields after column chromatography.

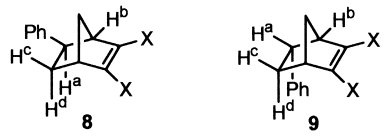
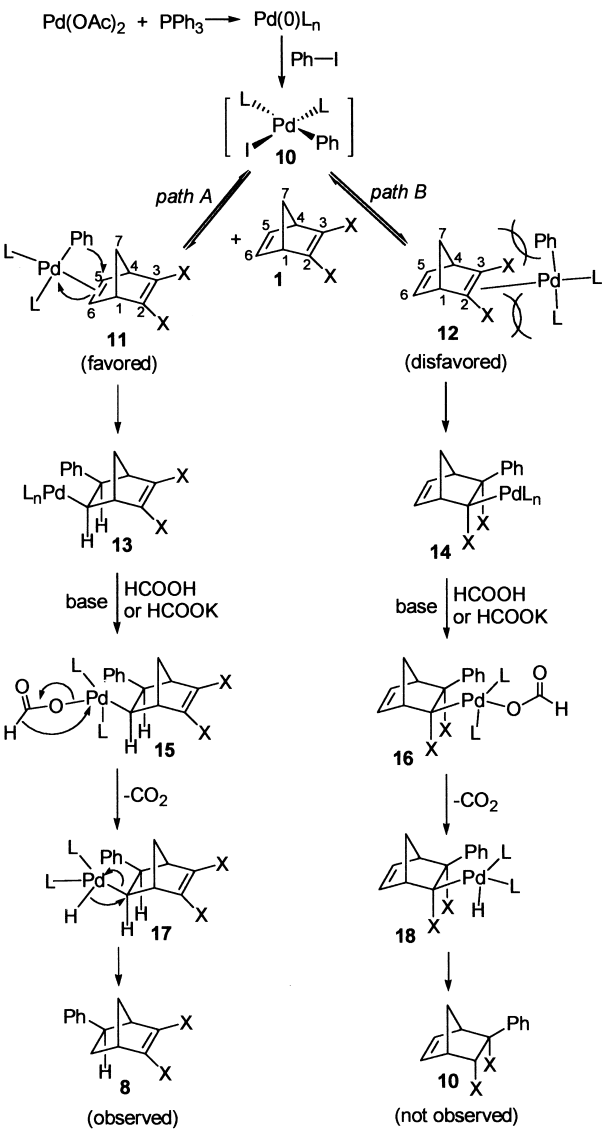


Figure 2. Assignment of stereochemistry of **8** and **9**.

with potassium formate (HCOOK) and using DMF as solvent at 25°C (conditions B) improved the yield of **8c** to 33% (Table 1, entry 4). Further improvement of the yield to 58% was achieved by the addition of tetrabutylammonium chloride (Bu_4NCl, conditions C, Table 1, entry 5).

The chemoselectivity and stereochemistry of the hydrophenylation products **8a** and **8c** were easily assigned by ^1H NMR. Since the ^1H NMR of the products do not contain any vinylic protons of the norbornadiene and therefore products **10** and **11** are not possible (Scheme 2). Examining the coupling pattern of H^a in **8** and **9** is sufficient to distinguish these *exo* and *endo* stereoisomers (Fig. 2). As the dihedral angle between H^a and H^b in the *exo* isomer **8** is close to 90°, the coupling constant between H^a and H^b is close to 0 Hz.[18]



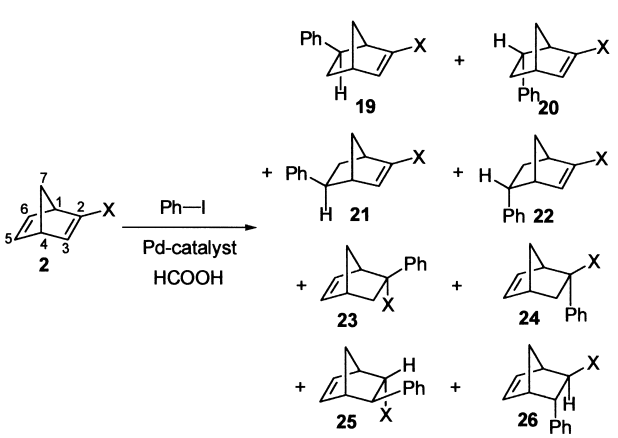
Scheme 3. Proposed mechanism.

Thus, H^a of the *exo* isomer **8** is a dd as it only couples to H^c and H^d but not with H^b. On the other hand, the corresponding dihedral angle between H^a and H^b in the *endo* isomer **9** is approximately 42° and would give a coupling constant of ~5 Hz.[18,19] Thus, H^a of the *endo* isomer **9** would be expected to have a ddd pattern as it couples to H^c, H^d as well as H^b. Since H^a in all the products **8a** and **8c** showed a dd coupling pattern (**8a**: δ 3.05 ppm, dd; **8b**: δ 2.55 ppm, dd; **8c**: δ 3.03 ppm, dd), they all therefore must possess the *exo* stereochemistry.

The excellent levels of chemoselectivities can be explained by the mechanism proposed in Scheme 3. Addition of PhI to the active Pd(0) complex will lead to the formation of Pd-complex **10**. Coordination of the less substituted double bond (C_5=C_6) of a 2,3-disubstituted norbornadiene to the Pd-complex **10** would lead to the formation of the olefin complex **11**, whereas coordination of the more substituted double bond (C_2=C_3) would provide the olefin complex **12**. Due to the steric hindrance of the X substitutents on the norbornadiene with the ligands on the Pd, complex **12** is highly disfavored. *syn*-Carbopalladation of the favorable Pd-complex **11** across the C_5=C_6 double bond would provide the intermediate **13**. Substitution of one of the ligands on the Pd-complex **13** with the formate (HCOO) group would generate intermediate **15**. Elimination of CO_2 followed by reductive elimination would provide the observed product **8** and regenerate the Pd(0) catalyst.

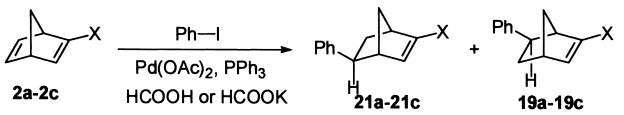
2.2. Palladium-catalyzed hydrophenylation of 2-substituted norbornadienes (2a–2c)

Unlike hydrophenylation of symmetrical 2,3-disubstituted norbornadienes **1a**–**1c** in which only four possible hydrophenylation products are possible (Scheme 2), for unsymmetrical 2-substituted norbornadienes **2**, eight hydrophenylation products are theoretically possible (Scheme 4). Hydrophenylation could occur on the less substituted double bond (C_5=C_6) to give products **19**–**22** (chemoselectivity), or on the more substituted double bond to give products **23**–**26**. In either case, both *exo* and *endo* products are possible e.g. **19** vs **20**, **21** vs **22** etc. (stereoselectivity). Other than chemo- and stereoselectivities, regioselectivity is also another question that we would like to address for unsymmetrical systems. Either *syn* or *anti* products could be formed (*syn*/*anti* with respect to the position of the substituent X, and *exo*/*endo* refers to the stereochemistry of the Ph group), e.g. *syn-exo*-**19** vs *anti-exo*-**21**; *syn-exo*-**23** vs *anti-exo*-**25**.



Scheme 4. Possible hydrophenylation products.

Table 2. Pd-catalyzed hydrophenylation of 2-substituted norbornadienes **2a**–**2c**



Entry	X	Conditions[a]	Product ratio **21**/**19**[b]	Yield (%)[c]
1	COOMe	A	**21a**/**19a**=nd[d]	< 10
2	COOMe	C	**21a**/**19a**=nd[d]	N.R.[e]
3	COOMe	D	**21a**/**19a**=62:38	56
4	Si^{t}BuMe$_2$	A	**21b**/**19b**=67:33	60
5	*n*Hexyl	A	**21c**/**19c**=62:38	57

[a] Reaction conditions: A=Pd(OAc)$_2$, PPh$_3$, HCOOH, piperidine, THF, 60°C. C=(OAc)$_2$, PPh$_3$, HCOOK, Bu$_4$NCl, DMF, 25°C. D=Pd(OAc)$_2$, PPh$_3$, HCOOK, Bu$_4$NCl, THF, 60°C.
[b] Determined by ^{1}H NMR (400 MHz) in the crude reaction mixture.
[c] Combined (**21**+**19**) isolated yields after column chromatography.
[d] nd=not determined.
[e] N.R.=no reaction was observed as indicated by TLC.

In order to carry out this study, 2-substituted norbornadienes **2a**–**2c** were synthesized[10] and their Pd-catalyzed hydrophenylation reactions were studied (Table 2). Similar to hydrophenylation of 2,3-disubstituted norbornadienes **1a**–**1c**, high levels of chemo- and stereoselectivities were observed with 2-substituted norbornadienes **2a**–**2c**. Although eight possible isomers could be formed in the reactions (Scheme 4), only the two regioisomers **19** and **21** were formed in all cases (Table 2). Thus, hydrophenylation of 2-substituted norbornadienes occurred only on the *exo*-face of the less substituted double bond of the norbornadienes, regardless of the electronic nature of the substituent X. Low levels of regioselectivities were observed (~2:1) with all the substituents tested (X=COOMe, Si^{t}BuMe$_2$ or ^{n}hexyl). With 2-silyl-substituted norbornadiene **2b** and 2-alkyl-substituted norbornadiene **2c**, Pd-catalyzed hydrophenylations occurred smoothly using Pd(OAc)$_2$ (20 mol%), PPh$_3$ (40 mol%), formic acid (HCOOH) and piperidine in THF at 60°C (conditions A) providing products **21b**/**19b** and **21c**/**19c** in 60 and 57% yields, respectively (Table 2, entries 4 and 5). With 2-ester-substituted norbornadiene **2a**, under conditions A, less than 10% of the hydrophenylation products were isolated and a complicated mixture of inseparable products was obtained instead (Table 2, entry 1). Although no reaction was observed using conditions C (Table 2, entry 2), carrying out the reaction using conditions D (Pd(OAc)$_2$, PPh$_3$, HCOOK and Bu$_4$NCl in THF at 60°C) improved the yield of **21a**/**19a** to 56% (Table 2, entry 3).

The chemo-, stereo- and regiochemistry of the hydrophenylation products were easily assigned by ^{1}H NMR. Since the ^{1}H NMR of the products contain only one (not two) vinylic proton of the norbornadiene and therefore only isomers (**19**–**22**) are possible (Scheme 4). To distinguish between *exo* and *endo* isomers (e.g. **19** vs **20**), a similar method to that used for the assignments of the structure of **8** and **9** (Fig. 2) was used (examining the coupling pattern of H^a). Regioisomers **19** and **21** were found to be the products

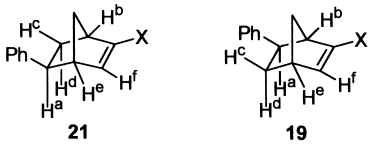


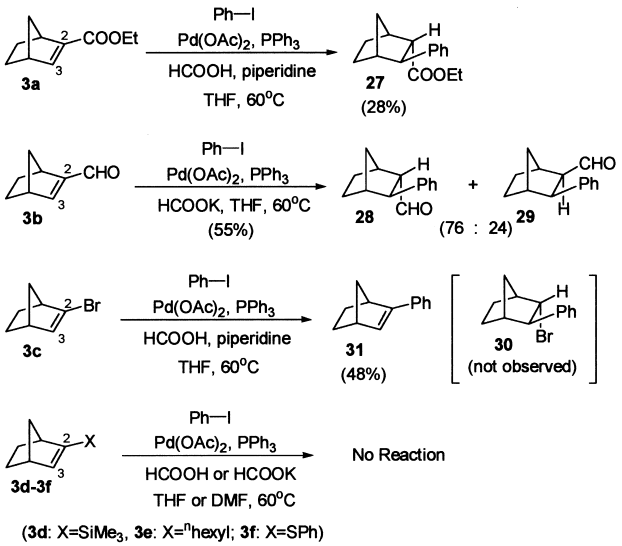
Figure 3. Assignment of regiochemistry of **21** and **19**.

formed in the Pd-catalyzed hydrophenylation of all of the 2-substituted norbornadienes **2a**–**2c**. To determine which isomer (**19** or **21**) was the major product, ^{1}H NMR and/or HCOSY experiments were used. In the major product **21**, H^b is a doublet (coupled only to H^c but not with H^d) and H^e is also a doublet (coupled only to the vinylic proton H^f, but not with H^a). In the minor product **19**, H^b is a singlet (not coupled to H^a) and H^e is a dd (coupled only to H^c and H^f but not with H^d) (Fig. 3).

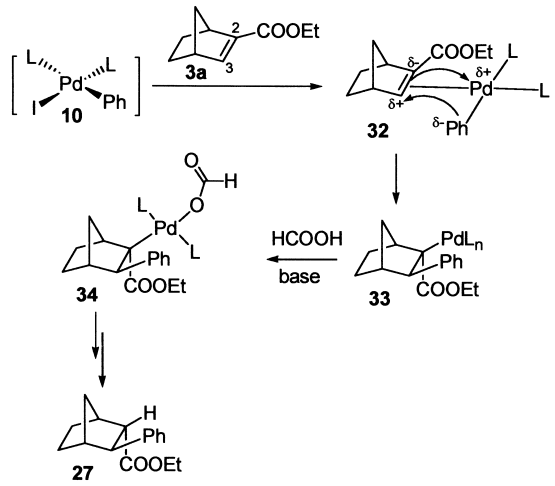
2.3. Palladium-catalyzed hydrophenylation of 2-substituted norbornenes (3a–3f)

Since hydrophenylation of 2-substituted norbornadienes **2a**–**2c** occurred only on the less substituted double bond of the norbornadienes, regardless of the electronic nature of the substituent X, we would like to determine if hydrophenylation can ever occur on the substituted double bond of norbornene **3**. The results of the hydrophenylation of 2-substituted norbornenes **3a**–**3f** are shown in Scheme 5.

Pd-catalyzed hydrophenylation of both **3a** and **3b** were highly regioselective, with the Ph group adding only to C_3. Pd-catalyzed hydrophenylation of **3a** using $Pd(OAc)_2$, PPh_3, formic acid (HCOOH) and piperidine in THF at 60°C (conditions A) afforded product **27** as the only isolated product in 28% yield. No improvement of the yield was observed using other conditions (B–D, Tables 1 and 2). Pd-catalyzed hydrophenylation of **3b** using HCOOK (condition D, Table 2) provided two stereoisomers **28** and **29** in a ratio of 76:24 with a combined yield of 55%. For all the Pd-catalyzed hydrophenylation reactions that we have studied so far, the hydrophenylations are always *syn-exo*-addition processes (both Ph and H added *syn* across the double bond on the *exo* face of the bicyclic structure), thus compound **29**



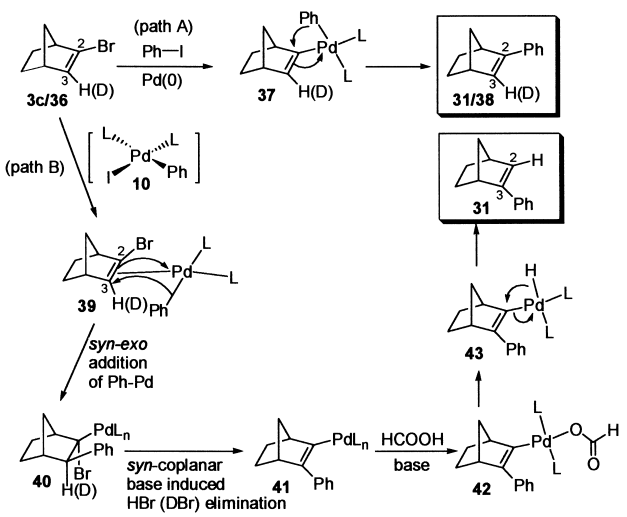
Scheme 5. Hydrophenylation of 2-substituted norbornenes **3a**–**3f**.



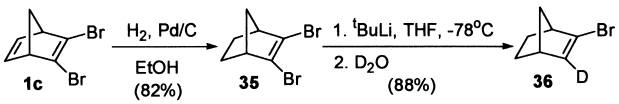
Scheme 6. Proposed mechanism.

may not be a direct hydrophenylation product. It could be formed from compound **28** via epimerization of the *exo* proton α to the CHO group under the reaction conditions. The regiochemistry of the Pd-catalyzed hydrophenylation of both **3a** and **3b** can be explained by the mechanism shown in Scheme 6. Coordination of Pd complex **10** with **3a** would lead to the formation of Pd-complex **32**. Carbopalladation will occur in such a way that the δ-Ph group will add to the $\delta+C_3$ of the norbornene, as in Heck-type reactions,[1] to give intermediate **33** which will eventually lead to the formation of the observed regioisomer **27**.

2-Bromonorbornene **3c** did not undergo the expected hydrophenylation (**30**, Scheme 5) under the reaction conditions and coupling product **31** was formed instead. Coupling product **31** could be formed via two different mechanisms (Scheme 7). The Ph group could either end up attached to C_2 or on C_3 of **3c**. The coupling product **31** with the Ph group attached to C_2 could be formed via intermediate **37** (path A, this intermediate has been proposed in the cyclotrimerization of **3c**).[20] The coupling product **31** with the Ph group attached to C_3 could be formed via hydrophenylation of **3c** with Pd complex **10** (path B).



Scheme 7. Proposed mechanism for the formation of **38/31**.



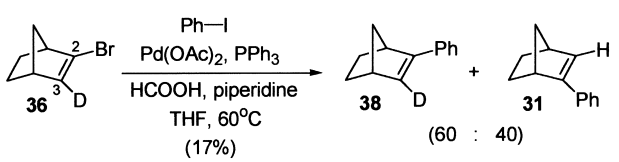
Scheme 8. Synthesis of deuterium labelled compound **36**.

syn-exo-Addition of **10** across the C_2=C_3 double bond would lead to the formation of **40**. *syn*-Coplanar base induced HBr elimination[20] would give **41** and upon addition of HCOOH would eventually generate the product **31** with the Ph group attached to C_3.

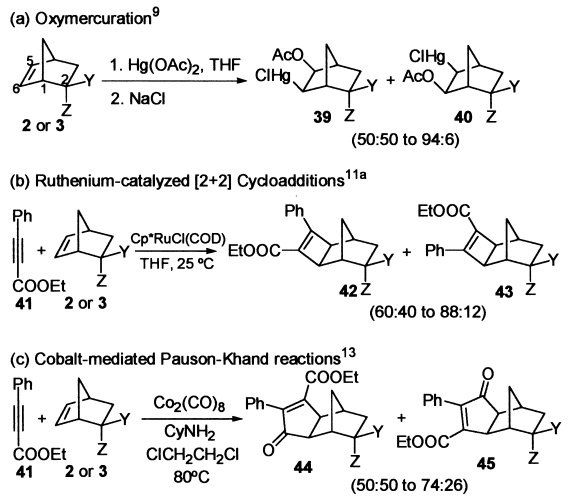
In order to distinguish these two mechanisms, we have prepared the deuterated compound **36** via hydrogenation of 2,3-dibromonorbornadiene **1c** followed by mono lithium–halide exchange[10] and trapping the resulting anion with D_2O (Scheme 8). The structure of the deuterated compound **36** was proven by ^{1}H, ^{13}C and ^{2}H (deuterium) NMR. ^{1}H NMR showed that there is no vinylic H in the deuterated compound **36**, ^{13}C NMR showed a triplet of the alkene carbon attached to the deuterium (D), and ^{2}H (deuterium) NMR showed only one peak of D. With the deuterated compound **36** (Scheme 7), path A will lead to the formation of a deuterated product **38**, with the Ph group attached to C_2, whereas path B will give a non-deuterated product **31** with the Ph group attached to C_3. When the deuterated compound **36** was subjected to the Pd-catalyzed hydrophenylation conditions, we obtained a 60:40 mixture of the deuterated product **38** and the non-deuterated product **31** (Scheme 9). Since we obtained both **38** and **31**, both mechanisms (path A and path B) may be operating in the reaction of **3c** to form **31** (Scheme 5). Unlike 2-substituted norbornenes **3a**–**3c**, with an electron-withdrawing substitutent attached to the double bond of the norbornenes, which reacted with PhI under Pd-catalysis, 2-substituted norbornenes **3d**–**3f** were found to be inert under the reaction conditions (Scheme 5).

2.4. Palladium-catalyzed hydrophenylation of 2-disubstituted 5-norbornenes (4a–4i)

The study of long-range stereoelectronic effect of a remote substituent in controlling regio- and stereoselectivities on nucleophilic and electrophilic additions to π-bonds has attracted considerable interest.[21] On the other hand, very few examples of the study of remote substituent effects on transition metal-catalyzed reactions can be found in the literature.[11a,13,22,23] We have recently reported the remote substituent effects on the regioselectivity in some metal-catalyzed and non-metal-catalyzed reactions of 2-substituted 5-norbornenes (Scheme 10).[9,11a,12,13,24] For example, the remote substituents showed strong long-range stereoelectronic effect on oxymercuration reactions (regioselectivity up to 94:6, Scheme 10(a)), whereas moderate levels of long-range stereoelectronic effect on Ru-catalyzed [2+2] cycloadditions (regioselectivity up to 88:12,



Scheme 9. Coupling reaction of **36**.

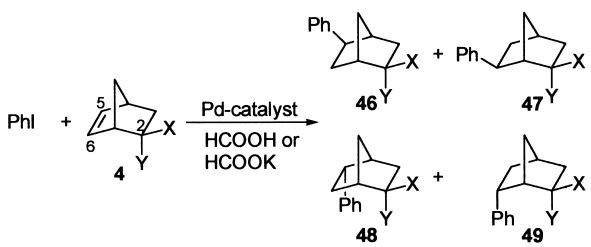


Scheme 10. Examples of some previous studies on the remote substituent effects of 2-substituted 5-norbornenes from our research group.

Scheme 10(b)) and Co-mediated Pauson–Khand reactions (regioselectivity up to 74:26, Scheme 10(c)) were observed. To the best of our knowledge, there is no systematic study on the effect of a remote substitutent on the regioselectivity of the Pd-catalyzed hydrophenylation reactions of unsymmetrical norbornene systems has been reported in the literature.

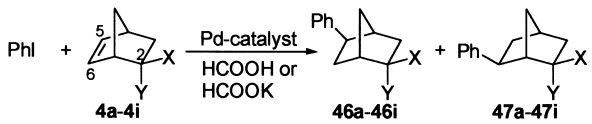
In order to study the remote substituent effects on regioselectivity in the Pd-catalyzed hydrophenylation reactions of 2-substituted 5-norbornenes, *exo*-2-substituted 5-norbornenes **4a**–**4d**, *endo*-2-substituted 5-norbornenes **4e**–**4h** and 5-norbornen-2-one **4i** were prepared (see preceding paper).[24] Four different hydrophenylation products are theoretically possible in the coupling between iodobenzene and a 2-substituted 5-norbornene (Scheme 11). Carbon–carbon bond formation could occur between the Ph group with one of the two olefinic carbons (C_5 or C_6) of the 2-substituted 5-norbornene **4**, and *exo* and *endo* coupling products are also possible. Based on the above studies of norbornenes and norbornadienes, we anticipated that only the *exo*-coupling products **46** and **47** would be formed. It has proven to be true and in all the 2-substituted 5-norbornenes that we examined, only the *exo*-coupling products **46** and **47** were obtained.

The results of the palladium-catalyzed hydrophenylation reactions of *exo*-2-substituted norbornenes **4a**–**4d** (Y=H) with iodobenzene are shown in Table 3, entries 1–9, and those of *endo*-2-substituted norbornenes **4e**–**4h** (X=H) are shown in entries 10–13. Hydrophenylation of **4a** (X=COOMe, Y=H, entry 1) under conditions A, $(Pd(OAc)_2$



Scheme 11. Possible hydrophenylation products.

Table 3. Pd-catalyzed hydrophenylation of 2-substituted 5- norbornenes **4a–4i**



Entry	X	Y	Conditions[a]	**46/47**[b]	Yield (%)[c]
1	COOMe	H	A	(**a**) 62:38	74
2	OH	H	A	(**b**) 67:33	87
3	OTBS	H	A	(**c**) 72:28	83
4	OTBS	H	C	(**c**) 66:34	87
5	OTBS	H	E	(**c**) 74:26	82
6	OTBS	H	F	(**c**) 72:28	92
7	OTBS	H	G	(**c**) 74:26	76
8	OAc	H	A	–[d]	–[d]
9	OAc	H	C	(**d**) 71:29	41
10	H	COOMe	A	(**e**) 75:25	70
11	H	OH	A	(**f**) 62:38	85
12	H	OTBS	A	(**g**) 58:42	89
13	H	OAc	A	(**h**) 67:33	81
14	X=Y=O (ketone)		A	–[d]	–[d]
15	X=Y=O (ketone)		C	(**i**) 85:15	38

[a] Reaction conditions: A=$Pd(OAc)_2$, PPh_3, HCOOH, piperidine, THF, 60°C. C=$Pd(OAc)_2$, PPh_3, HCOOK, Bu_4NCl, DMF, 25°C. E=$Pd(OAc)_2(PPh_3)_2$, HCOOH, piperidine, THF, 60°C. F=$Pd(OAc)_2$-$(PPh_3)_2$, HCOOH, piperidine, DMF, 60°C. G=$Pd(OAc)_2(PPh_3)_2$, HCOOH, piperidine, DMF, 25°C.

[b] Determined by ^{1}H NMR (400 MHz) and/or GC in the crude reaction mixture.

[c] Combined (**46**+**47**) isolated yields after column chromatography.

[d] Complicated mixture of products was obtained.

(20 mol%), PPh_3 (40 mol%), HCOOH (5 equiv.), piperidine (7 equiv.) in THF at 60°C) gave two regioisomers **46a** and **47a** in a ratio of 62:38. With oxy-substituents (OH, OTBS and OAc), the regioselectivities increased slightly (67:33 to 74:26). We have examined several different reaction conditions with **4c** (X=OTBS, Y=H, entries 3–7). Using $Pd(OAc)_2(PPh_3)_2$ instead of $Pd(OAc)_2$ and PPh_3 under the same solvent (THF) and temperature (60°C) provided almost identical yields and regioselectivities (entries 3 and 5). With $Pd(OAc)_2(PPh_3)_2$ as catalyst in DMF similar regioselectivities were observed (entries 6 and 7) and a higher yield was obtained when the reaction was carried out at 60°C (entry 6) than at room temperature (entry 7). We have also examined the use of other solvents using the catalytic system $Pd(OAc)_2$ and PPh_3 (not shown in Table 1). Very little effect was observed on the yield as well as the regioselectivity with different solvents (hexanes, Et_2O, CH_2Cl_2 and toluene). Using potassium formate (HCOOK) instead of formic acid (HCOOH) in the coupling reaction of **4c** with PhI led to a lower regioselectivity (entry 4). With X=OAc (**4d**), a complicated mixture of products was obtained using formic acid (HCOOH) with $Pd(OAc)_2$, PPh_3, and piperidine in THF at 60°C (entry 8). The same catalytic system using potassium formate (HCOOK) instead of formic acid (HCOOH) provided a much cleaner reaction of **4d** and the regioselectivity was 71:29 with a combined yield of 41% (entry 9). Similar trends in regioselectivities were observed in the palladium-catalyzed hydrophenylation reactions of *endo*-2-substituted norbornenes **4e–4h** (X=H) with iodobenzene (entries 10–13). Regioselectivities of 58:42 to 75:25 were observed. The lowest regioselectivity was observed with Y=OTBS (**4g**) and the highest regioselectivity was observed with Y=COOMe (**4e**). Similar to

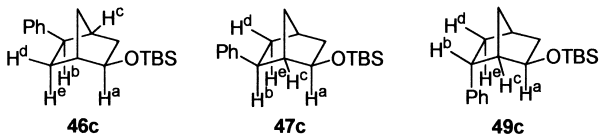
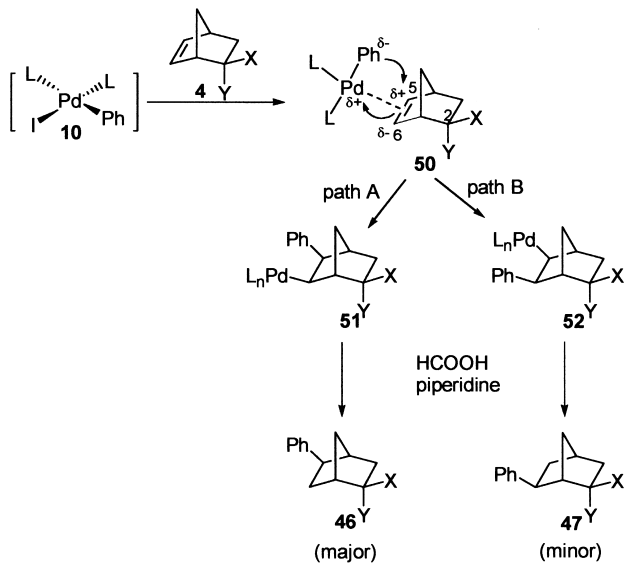


Figure 4. Determination of regio- and stereochemistry of the coupling products.

the *exo*-OAc-norbornene **4d**, a complicated mixture of products was obtained from the Pd-catalyzed coupling between 2-norbornenone **4i** (X=Y=O, ketone) and PhI using formic acid (HCOOH) with $Pd(OAc)_2$, PPh_3, and piperidine in THF at 60°C (entry 14). When potassium formate (HCOOK) was used instead of formic acid (HCOOH), a much cleaner reaction was observed and the highest regioselectivity was obtained (85:15, entry 15).

The regiochemistry and stereochemistry of the coupling products were determined by various NMR techniques. The *exo* stereochemistry of the products was proven by the coupling pattern of H^b in ^{1}H NMR spectra (Fig. 4). For example, in **46c**, as the dihedral angles between H^b and the bridge head proton H^c in the *exo* product are close to 90°, their coupling constants would be very small (J~0–2 Hz). For the *endo* product **49c**, the dihedral angles between H^b and H^c are approximately 42° and would give coupling constants of ~5 Hz.[25] In all the coupling products (major and minor) that we obtained, all the H^b are doublets of doublets (dd) (coupled only with H^d and H^e but not with the bridge head proton H^c), therefore all the coupling products must possess *exo* stereochemistry.[19] The regiochemistry of the coupling products was then determined by NMR GOESY experiments (a gradient NOE experiment).[26] For example, in the major regioisomer **46c**, H^a showed +ve NOE effect with H^e but not with H^b, whereas for the minor isomer **47c**, H^a showed +ve NOE effect with H^b but not with H^e. In all of the cases that we examined, the major isomers were the ones with the Ph group attached to C_5 (regioisomers **46**).

A proposed mechanism to account for the formation of the



Scheme 12. Proposed mechanism.

major product **46** is shown in Scheme 12. Coordination of the double bond of 2-substituted 5-norbornene **4** to the Pd-complex **10** would lead to the formation of the olefin complex **50**. According to our previous density function theory (DFT) study of 2-substituted 5-norbornene systems, C_6 of 2-substituted 5-norbornenes (**4a**–**4i**) is always more 'negative' than C_5.[9b] Thus the δ-Ph group in the Pd-complex **50** will have the preference to add to the $\delta+C_5$ of the double bond, to give intermediate **51** which will eventually lead to the formation of the major regioisomer **46** with the Ph group attached to C_5.

3. Conclusions

We have studied the palladium-catalyzed hydrophenylation reactions of substituted norbornadienes and norbornenes. The reactions with symmetrical 2,3-disubstituted norbornadienes (**1a**–**1c**) were found to be completely chemo- (100:0) and stereoselective (100:0), with the palladium-catalyzed hydrophenylation reactions occurring only on the less substituted or less sterically hindered double bonds regardless of the electronic nature of the substituents. The reactions with unsymmetrical 2-substituted norbornadienes (**2a**–**2c**) were also found to be completely chemo- (100:0) and stereoselective (100:0), with low levels of regioselectivity (up to 67:33). Palladium-catalyzed hydrophenylation of 2-substituted norbornadienes **3a** and **3b**, with an electron-withdrawing group attached to the double bond of the norbornenes, was highly regioselective, whereas 2-substituted norbornenes that do not contain an electron-withdrawing group attached to the double bond were found to be inert in the hydrophenylation. We have also investigated the long-range electronic effect of a remote substituent on unsymmetrical norbornenes **4a**–**4i** in the palladium-catalyzed hydrophenylation reaction. Moderate levels of regioselectivities (remote substituent effects) were observed (58:42 to 85:15) with various remote substituents on the norbornenes.

4. Experimental

4.1. General information

All reactions were carried out in an atmosphere of dry nitrogen at ambient temperature unless otherwise stated. Standard column chromatography was performed on 230–400 mesh silica gel (obtained from Silicycle) by use of flash column chromatography techniques.[27] Analytical thin-layer chromatography (TLC) was conducted on Merck precoated silica gel 60 F_{254} plates. All glassware was flame dried under an inert atmosphere of dry nitrogen. Infrared spectra were taken on a Bomem MB-100 FTIR spectrophotometer. ^1H and ^{13}C NMR spectra were recorded on a Bruker-400 spectrometer. Chemical shifts for ^1H NMR spectra are reported in parts per million (ppm) from tetramethylsilane with the solvent resonance as the internal standard (chloroform: δ 7.26). Chemical shifts for ^{13}C NMR spectra are reported in parts per million (ppm) from tetramethylsilane with the solvent as the internal standard (deuterochloroform: δ 77.0). High-resolution mass spectra were done by McMaster Regional Centre for Mass Spectrometry at McMaster University, Hamilton, Ontario. Elemental analyses were performed by Canadian Microanalytical Service Ltd., British Columbia or by Quantitative Technologies Inc., New Jersey.

4.2. Materials

Unless stated otherwise, commercial reagents were used without purification. The palladium catalysts were purchased from Strem Chemicals and were stored in an inert atmosphere dry box. THF was purified by distillation from potassium/benzophenone under dry nitrogen. DMF and piperidine were purified by distillation from CaH_2 under dry nitrogen. Norbornadienes **1a**,[17] **1c**,[10] **2a**,[28] **2c**[29] and norbornenes **3d**,[12] **3e**,[12] **3f**,[29] **4a**–**4i**[24] were prepared according to literature procedures.

4.3. Synthesis of substituted norbornadienes and norbornenes

4.3.1. 2,3-Bis(trimethylsilyl)bicyclo[2.2.1]hepta-2,5-diene (1b). To a flame-dried round-bottom flask containing 2-bromo-3-trimethylsilyl)bicyclo[2.2.1]hepta-2,5-diene[10] (1.00 g, 4.11 mmol) and THF (12.0 mL) was added ^{t}BuLi (7.50 mL, 12.8 mmol, 1.7 M in pentane) dropwise at −78°C under nitrogen. The reaction mixture was stirred at −78°C for 1 h. The lithiated norbornadiene was trapped with TMSCl (2.6 mL, 20.5 mmol) at −78°C and stirred for 30 min. The reaction mixture was reacted at 0°C for 1 h before being quenched with saturated $NaHCO_3$ and H_2O. The aqueous layer was extracted with Et_2O, washed with saturated NaCl, then H_2O and dried over $MgSO_4$. The crude product was purified by column chromatography (hexanes) to give norbornadiene **1b** (0.964 g, 4.08 mmol, 99%) as a colourless liquid. R_f 0.66 (hexanes); IR (neat) 3065 (m), 2957 (s), 2898 (m), 2864 (m), 1523 (s), 1405 (m), 1301 (s), 1249 (s), 1193 (m), 1169 (s), 1052 (s), 1011 (s), 966 (s), 898 (s) cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 6.60 (t, 2H, J=1.9 Hz), 3.92 (m, 2H), 1.63 (m, 2H), 0.15 (s, 18H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ 165.0, 141.9, 71.5, 58.0, 0.09. HRMS calcd for $C_{13}H_{24}Si_2$: m/z 236.1417, found m/z 236.1428.

4.3.2. 2-(*tert*-Butyldimethylsilyl)bicyclo[2.2.1]hepta-2,5-diene (2b). Bicyclo[2.2.1]hepta-2,5-diene (5.0 mL, 46.3 mmol) was added to a flame-dried round-bottom flask containing ^{t}BuOK (2.86 g, 25.5 mmol) and THF (30 mL) at −78°C. nBuLi (10.0 mL, 25.0 mmol, 2.5 M in hexanes) was then added to the flask via a dropping funnel and the temperature was maintained below −65°C. The reaction mixture was warmed to −40°C over 1 h. TBSCl (3.61 g, 23.9 mmol) in THF (8 mL) was then added via a cannula to the reaction mixture at −78°C. The reaction mixture was stirred at −40°C for 30 min and at 25°C for 30 min. After quenching the reaction with water, the aqueous layer was extracted with diethyl ether and the combined organic layers were washed sequentially with water and saturated NaCl, and dried over $MgSO_4$. The solvent was removed by rotary evaporation and the crude product was purified by vacuum distillation (75°C, 5 Torr) to give norbornadiene **2b** (4.23 g, 20.5 mmol, 82%) as a clear, colourless liquid. R_f 0.80 (hexanes); IR (neat) 3065 (m), 2931 (s), 2856 (s), 1539 (s), 1471 (s), 1389 (m), 1361

(s), 1299 (s), 1248 (s), 1206 (m), 1190 (m), 1022 (m), 1008 (s), 929 (m) cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 7.06 (d, 1H, J=2.8 Hz), 6.68 (m, 2H), 3.75 (br s, 1H), 3.63 (br s, 1H), 1.89 (d, 1H, J=5.9 Hz), 1.86 (d, 1H, J=5.9 Hz), 0.85 (s, 9H), 0.038 (s, 3H), 0.0077 (s, 3H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ 155.2, 153.5, 143.3, 142.2, 74.2, 54.3, 52.0, 26.7, 17.2, −6.2, −6.7. HRMS calcd for $C_{13}H_{22}Si$: m/z 206.1491, found m/z 206.1499.

4.3.3. 2-Ethoxycarbonylbicyclo[2.2.1]hept-2-ene (3a). A solution of norbornene (520 mg, 5.52 mmol) in THF (1 mL) was added to a flame-dried flask containing KO^{t}Bu (310 mg, 2.76 mmol) in THF (2 mL) at −78°C via cannula and rinsed with THF (2×0.25 mL). The temperature was maintained below −60°C during this addition. nBuLi (1.1 mL, 2.75 mmol, 2.5 M in hexanes) was added to the reaction mixture over 15 min, with the temperature maintained below −70°C. The reaction mixture was warmed to −40°C and stirred for 1 h, then re-cooled to −78°C. A solution of LiBr (360 mg, 4.14 mmol) in THF (2 mL) was added to the reaction mixture via cannula and rinsed with THF (2×0.25 mL). The temperature was maintained below −60°C during this addition. The reaction mixture was warmed to −40°C and stirred for 45 min, then re-cooled to −78°C. The reaction mixture was transferred to a solution of ethyl chloroformate (0.470 mL, 4.92 mmol) in THF (1 mL) at −78°C via cannula and rinsed with THF (2×0.25 mL). The reaction mixture was stirred at −78°C for 15 min, then warmed to room temperature and stirred for 45 min. After quenching with water (10 mL), the layers were separated and the aqueous layer was extracted with Et_2O (3×10 mL). The combined organic layers were washed with brine (10 mL) and dried ($MgSO_4$). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (EtOAc/hexanes=1:19) to give **3a** (93.0 mg, 0.559 mmol, 20%) as a clear, transparent liquid. R_f 0.31 (EtOAc/hexanes=1:19); IR (neat) 2977 (s), 2874 (m), 1743 (w), 1712 (s), 1596 (w), 1449 (w), 1370 (w), 1342 (w), 1279 (s), 1260 (s), 1220 (w), 1160 (s), 1117 (w), 1079 (s), 1023 (w) cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 6.91 (d, 1H, J=3.1 Hz), 4.18 (ABX_3, 2H), 3.25 (d, 1H, J=1.0 Hz), 2.99–3.01 (m, 1H), 1.61–1.79 (m, 2H), 1.47 (dt, 1H, J=8.4, 2.0 Hz), 1.28 (t, 3H, J=7.1 Hz), 1.19 (dd, 1H, J=8.5, 1.0 Hz), 1.09 (dd, 1H, J=5.1, 2.3 Hz), 1.06 (dd, 1H, J=5.4, 2.8 Hz); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ 164.9, 146.6, 141.0, 60.0, 48.2, 43.4, 41.8, 24.6, 24.5, 14.3. Spectral data were identical to those reported in the literature.[30]

4.3.4. 2-Formylbicyclo[2.2.1]hept-2-ene (3b). A solution of norbornene (3.80 g, 40.4 mmol) in THF (5 mL) was added to a flame-dried flask containing KO^{t}Bu (1.25 mg, 11.2 mmol) in THF (6 mL) at −78°C via cannula and rinsed with THF (2×0.5 mL). The temperature was maintained below −60°C during this addition. nBuLi (4.40 mL, 11.0 mmol, 2.5 M in hexanes) was added to the reaction mixture over 45 min, with the temperature maintained below −70°C. The reaction mixture was warmed to −40°C and stirred for 1.5 h, then re-cooled to −78°C. A solution of LiBr (1.30 mg, 14.9 mmol) in THF (4 mL) was added to the reaction mixture via cannula over 30 min and rinsed with THF (2×0.5 mL). The temperature was maintained below −70°C during this addition. The reaction mixture was warmed to −40°C and stirred for 1 h, then re-cooled to −78°C. The reaction mixture was transferred to a solution of DMF (1.80 mL, 23.2 mmol) in THF (5 mL) at −78°C via cannula over 45 min and rinsed with THF (2×0.5 mL). The reaction mixture was warmed to room temperature and quenched with saturated NH_4Cl (30 mL), the layers were separated and the aqueous layer was extracted with CH_2Cl_2 (3×30 mL). The combined organic layers were washed with brine (30 mL) and dried ($MgSO_4$). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (EtOAc/hexanes=1:9) to give **3b** (209.0 mg, 1.70 mmol, 16%) as a clear, transparent liquid. R_f 0.40 (EtOAc/hexanes=1:9). Spectral data were identical to those reported in the literature.[31]

4.3.5. 2-Bromobicyclo[2.2.1]hept-2-ene (3c). A solution of norbornene (3.84 g, 40.7 mmol) in THF (5 mL) was added to a flame-dried flask containing KO^{t}Bu (1.24 g, 11.0 mmol) in THF (6 mL) cooled to −78°C via cannula and rinsed with THF (2×0.5 mL). The temperature was maintained below −72°C during this addition. nBuLi (4.40 mL, 11.0 mmol, 2.5 M in hexanes) was added to the reaction mixture over 45 min, with the temperature maintained below −72°C. The reaction mixture was slowly warmed to −40°C and stirred for 1.5 h, then re-cooled to −70°C. 1,2-Dibromoethane (0.950 mL, 11.0 mmol) was added to the reaction mixture dropwise over 30 min, with the temperature maintained between −40 and −50°C. The reaction mixture was warmed to −40°C and stirred for 2 h, then it was warmed to room temperature and quenched with saturated NH_4Cl (30 mL). The layers were separated and the aqueous layer was extracted with 1:9 CH_2Cl_2/hexanes (3×30 mL). The combined organic layers were washed with brine (30 mL) and dried ($MgSO_4$). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (hexanes) to give **3c** (622.7 mg, 3.60 mmol, 33%) as a clear, transparent liquid. R_f 0.83 (Hexanes); IR (neat) 2970 (s), 2950 (s), 2920 (s), 2872 (s), 1577 (s), 1469 (w), 1448 (m), 1305 (s), 1274 (m), 1252 (w), 1208 (w), 1158 (s), 1122 (m), 1037 (s), 1032 (m) 1017 (w) cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 6.02 (d, 1H, J=3.1 Hz), 2.89 (m, 2H), 1.64–1.70 (m, 2H), 1.58–1.61 (m, 1H), 1.11–1.22 (m, 3H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ 134.8, 125.5, 50.5, 48.1, 43.9, 25.9, 24.4. This is a known compound in the literature.[32]

4.3.6. 2,3-Dibromobicyclo[2.2.1]hept-2-ene (35). A flame-dried, round-bottom flask was charged with norbornadiene **1c** (310.2 mg, 1.24 mmol), ethanol (10 mL), 5% Pd/C (1.9 mg, 0.893 mmol), and a balloon of H_2 was attached to the flask. The reaction mixture was stirred at 25°C for 24 h and filtered. The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (hexanes) to give the product **35** (257 mg, 1.02 mmol, 82%) as a clear, colourless liquid. R_f 0.82 (hexanes); ^1H NMR ($CDCl_3$, 400 MHz) δ 3.00 (s, 2H), 1.77–1.79 (m, 1H), 1.68–1.71 (m, 2H), 1.26–1.33 (m, 2H), 1.22 (dd, 1H, J=8.4, 1.5 Hz); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ 125.5, 51.6, 46.9, 25.7. This is a known compound in the literature.[33]

4.3.7. 2-Bromo-3-deuterobicyclo[2.2.1]hept-2-ene (36). ^{t}BuLi (0.60 mL, 1.0 M in pentane, 0.60 mmol) was added

to a solution of norbornene **35** (83.4 mg, 0.331 mmol) in THF (2 mL) cooled to −78°C. The reaction mixture was stirred at −78°C for 30 min, then D_2O (0.50 mL, 27.6 mmol) was added and the reaction mixture was stirred at −78°C for 45 min. The reaction mixture was then warmed to 25°C, quenched with H_2O (5 mL), and extracted with Et_2O (4×5 mL). The combined extractions were dried ($MgSO_4$), the solvent was removed by rotary evaporation and the crude product was purified by column chromatography (hexanes) to give the product **36** (50.8 mg, 0.292 mmol, 88%) as a clear, colourless liquid. R_f 0.84 (hexanes); IR (neat) 2958 (s), 2915 (s), 2872 (s), 1712 (w), 1558 (m), 1467 (m), 1447 (m), 1378 (w), 1294 (s), 1272 (w), 1252 (w), 1162 (m), 1120 (w), 1083 (s), 1032 (m) cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 2.89 (s, 2H), 1.61–169 (m, 2H), 1.60 (dt, 1H, J=8.3, 2.3 Hz), 1.17 (ddd, 2H, J=10.4, 3.7, 2.4 Hz), 1.12 (dm, 1H, J=8.3 Hz); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ 134.5 (t, J_{CD}=26.5 Hz), 125.3, 50.4, 48.0, 43.7, 25.8, 24.3. ^2H (deuterium) NMR ($CDCl_3$, 65 MHz) δ 6.37 (s).

4.4. Pd-catalyzed hydrophenylation reactions

4.4.1. *exo*-2,3-Bis(methoxycarbonyl)-5-phenylbicyclo-[2.2.1]hept-2-ene (8a) (Table 1, entry 1). A flame-dried vial was charged with norbornadiene **1a** (58.6 mg, 0.281 mmol), THF (2 mL), PPh_3 (27.8 mg, 0.106 mmol), $Pd(OAc)_2$ (12.1 mg, 0.0539 mmol), iodobenzene (30 μL, 0.268 mmol), piperidine (180 μL, 1.82 mmol), and formic acid (50 μL, 1.33 mmol). The reaction mixture was stirred for 24 h at 60°C. After quenching with water (5 mL), the reaction mixture was extracted with Et_2O (4×5 mL), and the combined organic layers were dried ($MgSO_4$). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (EtOAc/hexanes=1:4) to give the product **8a** (73.0 mg, 0.255 mmol, 91%) as orange–white crystals. R_f 0.41 (EtOAc/hexanes=1:4); IR (neat) 3060 (w), 3026 (w), 2991 (m), 2952 (s), 2879 (w), 2844 (w), 2257 (w), 1736 (s), 1625 (s), 1602 (m), 1486 (m), 1448 (m), 1436 (s), 1340 (s), 2275 (s), 1259 (s), 1193 (m), 1155 (s), 1093 (s), 1020 (m) cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 7.19–7.35 ($AA'MM'X$, 5H), 3.813 (s, 3H), 3.811 (s, 3H), 3.38 (m, 1H), 3.36 (br s, 1H), 3.05 (dd, 1H, J=8.4, 5.4 Hz), 1.93–2.03 (m, 2H), 1.68–1.74 (m, 2H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ 165.2, 165.1, 145.6, 145.1, 143.9, 128.5, 127.5, 126.1, 52.0, 51.6, 45.9, 44.8, 43.5, 33.1. HRMS calcd for $C_{17}H_{18}O_4$: m/z 286.1205, found m/z 286.1222.

4.4.2. *exo*-2,3-Bis(trimethylsilyl)-5-phenylbicyclo[2.2.1]-hept-2-ene (8b) (Table 1, entry 2). A flame-dried vial was charged with norbornadiene **1b** (61.4 mg, 0.260 mmol), THF (2 mL), PPh_3 (28.6 mg, 0.109 mmol), $Pd(OAc)_2$ (12.3 mg, 0.0548 mmol), iodobenzene (30 μL, 0.268 mmol), piperidine (180 μL, 1.82 mmol), and formic acid (50 μL, 1.33 mmol). The reaction mixture was stirred for 24 h at 60°C. After quenching with water (5 mL), the reaction mixture was extracted with 1:9 CH_2Cl_2/hexanes (4×5 mL), and the combined organic layers were dried ($MgSO_4$). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (hexanes) to give the product **8b** (65.3 mg, 0.208 mmol, 80%) as a clear, colourless liquid. R_f 0.79 (hexanes); IR (neat) 3062 (w), 3025 (w), 2956 (s), 2900 (m), 2867 (m), 1601 (w), 1496 (m), 1446 (m), 1405 (w), 1248 (s), 1172 (w), 1023 (s) cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 7.17–7.33 ($AA'MM'X$, 5H), 3.19 (m, 1H), 3.09 (d, 1H, J=1.3 Hz), 2.55 (dd, 1H, J=8.9, 4.7 Hz), 1.74 (ddd, 1H, J=11.9, 4.7, 3.8 Hz), 1.54 (dt, 1H, J=8.7, 1.2 Hz), 1.49 (ddd, 1H, J=11.9, 9.3, 2.6 Hz), 1.24 (dm, 1H, J=8.6 Hz), 0.22 (s, 9H), 0.20 (s, 9H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ 160.5, 160.3, 146.4, 128.2, 127.6, 125.5, 55.4, 48.9, 44.5, 43.4, 33.0, 0.9, 0.6. Anal. calcd for $C_{19}H_{30}Si_2$: C, 72.54; H, 9.61. Found C, 72.81; H, 9.28.

4.4.3. *exo*-2,3-Dibromo-5-phenylbicyclo[2.2.1]hept-2-ene (8c) (Table 1, entry 5). A flame-dried vial was charged with norbornadiene **1c** (65.5 mg, 0.262 mmol), DMF (2 mL), iodobenzene (30 μL, 0.268 mmol), PPh_3 (14.2 mg, 0.0541 mmol), tetrabutylammonium chloride (TBAC, 75.3 mg, 0.271 mmol), KO_2CH (77.5 mg, 0.921 mmol), $Pd(OAc)_2$ (6.5 mg, 0.0290 mmol). The reaction mixture was stirred for 24 h at room temperature. After quenching with water (15 mL), the reaction mixture was extracted with 1:9 CH_2Cl_2/hexanes (8×15 mL), and the combined organic layers were dried ($MgSO_4$). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (Hexanes) to give the product **8c** (50.1 mg, 0.153 mmol, 58%) as a clear, colourless liquid. R_f 0.47 (hexanes); IR (neat) 3061 (w), 3026 (w), 2982 (s), 2951 (s), 2874 (w), 1586 (s), 1497 (s), 1463 (m), 1448 (s), 1294 (s), 1278 (m), 1264 (m), 1066 (s) cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 7.20–7.35 ($AA'MM'X$, 5H), 3.11 (m, 1H), 3.07 (dd, 1H, J=3.3, 1.6 Hz), 3.03 (dd, 1H, J=8.3, 4.8 Hz), 1.98 (ddd, 1H, J=11.6, 8.9, 1.9 Hz), 1.84–1.91 (m, 2H), 1.71 (dt, 1H, J=8.9, 1.8 Hz); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ 143.4, 128.5, 127.6, 127.5, 126.9, 126.2, 57.5, 52.0, 44.30, 44.27, 38.8. Anal. calcd for $C_{13}H_{12}Br_2$: C, 47.60; H, 3.69. Found C, 47.36; H, 3.75.

4.4.4. *exo*-2-Methoxycarbonyl-5-phenylbicyclo[2.2.1]-hept-2-ene (21a) and *exo*-2-methoxycarbonyl-6-phenylbicyclo[2.2.1]hept-2-ene (19a) (Table 2, entry 3). A flame-dried vial was charged with norbornadiene **2a** (40.7 mg, 0.271 mmol), THF (2 mL), iodobenzene (30 μL, 0.268 mmol), PPh_3 (14.3 mg, 0.0545 mmol), tetrabutylammonium chloride (TBAC, 76.9 mg, 0.277 mmol), KO_2CH (78.3 mg, 0.931 mmol), $Pd(OAc)_2$ (6.3 mg, 0.0281 mmol). The reaction mixture was stirred for 2 d at room temperature. After quenching with water (5 mL), the reaction mixture was extracted with Et_2O (4×5 mL), and the combined organic layers were dried ($MgSO_4$). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (EtOAc/hexanes=1:9) to give an inseparable mixture of **21a** and **19a** (34.6 mg, 0.152 mmol, 56%, **21a/19a**=62:38 measured by integration on 400 MHz ^1H NMR spectrum and GC) as a clear, colourless liquid. R_f 0.51 (EtOAc/hexanes=1:9); IR (neat) 3061 (w), 3026 (m), 2977 (s), 2950 (s), 2876 (m), 1720 (s), 1600 (s), 1495 (m), 1435 (m), 1346 (m), 1278 (s), 1258 (s), 1234 (m), 1191 (m), 1156 (s), 1089 (s) cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 7.26–7.32 (m, 4H), 7.18–7.22 (m, 1H), 7.15 (d, 0.38H, J=3.2 Hz), 7.09 (d, 0.62H, J=3.1 Hz), 3.77 (s, 1.14H), 3.76 (s, 1.86H), 3.35 (m, 1H), 3.13 (br s, 0.62H), 3.08 (ddd, 0.38H, J=7.8, 6.2, 0.9 Hz), 2.84 (dd, 0.62H, J=8.8, 4.7 Hz),

2.80 (dd, 0.38H, J=8.9, 4.9 Hz), 1.86–1.96 (m, 1H), 1.57–1.79 (m, 3H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) major isomer (**21a**): δ 165.1, 148.9, 144.8, 142.6, 128.3, 127.6, 125.8, 51.4, 48.2, 45.4, 44.0, 43.3, 33.0; minor isomer (**19a**): δ 165.2, 148.2, 144.7, 142.4, 128.4, 127.5, 125.9, 51.4, 50.0, 45.5, 43.3, 42.4, 33.0. HRMS calcd for $C_{15}H_{16}O$: m/z 228.1150, found m/z 228.1128.

4.4.5. *exo*-2-*tert*-Butyldimethylsilyl-5-phenylbicyclo-[2.2.1]hept-2-ene (21b) and *exo*-2-*tert*-butyldimethyl-silyl-6-phenylbicyclo[2.2.1]hept-2-ene (19b) (Table 2, entry 4). A flame-dried vial was charged with norbornadiene **2b** (57.4 mg, 0.278 mmol), THF (2 mL), PPh_3 (27.9 mg, 0.106 mmol), $Pd(OAc)_2$ (12.0 mg, 0.0535 mmol), iodobenzene (30 μL, 0.268 mmol), piperidine (180 μL, 1.82 mmol), and formic acid (50 μL, 1.33 mmol). The reaction mixture was stirred for 24 h at 60°C. After quenching with water (5 mL), the reaction mixture was extracted with Et_2O (4×5 mL), and the combined organic layers were dried ($MgSO_4$). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (hexanes) to give an inseparable mixture of **21b** and **19b** (47.4 mg, 0.167 mmol, 60%, **21b/19b**=67:33 measured by integration on 400 MHz ^{1}H NMR spectrum and GC) as a clear, colourless liquid. R_f 0.70 (hexanes); IR (neat) 3061 (w), 3027 (m), 2956 (s), 2927 (s), 2890 (s), 2855 (s), 1554 (m), 1494 (m), 1470 (s), 1463 (s), 1361 (m), 1297 (w), 1248 (s), 1048 (s) cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.27–7.33 (m, 4H), 7.16–7.20 (m, 1H), 6.60 (d, 0.67H, J=3.0 Hz), 6.50 (d, 0.33H, J=2.9 Hz), 3.10 (br s, 0.67H), 2.99 (br s, 0.67H), 2.93 (m, 0.66H), 2.71 (dd, 0.67H, J=8.7, 4.7 Hz), 2.63 (dd, 0.33H, J=8.7, 4.8 Hz), 1.71–1.80 (m, 1H), 1.55–1.64 (m, 2H), 1.38–1.42 (m, 1H), 0.923 (s, 6.03H), 0.915 (s, 1.49H), 0.914 (s, 1.48H), 0.070 (s, 4.02H), 0.069 (s, 0.99H), 0.064 (s, 0.99H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ major isomer (**21b**): δ 148.9, 148.8, 146.4, 128.2, 127.6, 125.5, 49.7, 46.1, 46.0, 43.4, 33.8, 26.8, 16.9, −1.8; minor isomer (**19b**): 148.9, 148.8, 146.3, 128.3, 127.6, 125.5, 52.6, 45.9, 43.78, 43.75, 33.1, 26.8, 16.9, −5.8, −6.1. HRMS calcd for C19H28Si: m/z 285.2038, found m/z 285.2011.

4.4.6. *exo*-2-Hexyl-5-phenylbicyclo[2.2.1]hept-2-ene (21c) and *exo*-2-hexyl-6-phenylbicyclo[2.2.1]hept-2-ene (19c) (Table 2, entry 5). A flame-dried vial was charged with norbornadiene **2c** (47.1 mg, 0.267 mmol), THF (2 mL), PPh_3 (27.9 mg, 0.106 mmol), $Pd(OAc)_2$ (12.3 mg, 0.0548 mmol), iodobenzene (30 μL, 0.268 mmol), piperidine (180 μL, 1.82 mmol), and formic acid (50 μL, 1.33 mmol). The reaction mixture was stirred for 15 h at 60°C. After quenching with water (5 mL), the reaction mixture was extracted with Et_2O (4×5 mL), and the combined organic layers were dried ($MgSO_4$). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (hexanes) to give an inseparable mixture of **21c** and **19c** (38.4 mg, 0.151 mmol, 57%, **21c/19c**=62:38 measured by integration on 400 MHz ^{1}H NMR spectrum and GC) as a clear, colourless liquid. R_f 0.86 (hexanes); IR (neat) 3060 (m), 3025 (m), 2959 (s), 2927 (s), 2871 (s), 2857 (s), 1600 (m), 1494 (m), 1463 (m), 1448 (m), 1378 (w), 1262 (w), 1076 (w) cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.29–7.31 (m, 4H), 7.26–7.28 (m, 1H), 5.77 (br s, 0.62H), 5.69 (br s, 0.38H), 2.89 (br s, 0.38H), 2.85 (d, 0.62H, J=1.4 Hz), 2.71–2.80 (m, 2H), 2.11–2.19 (m, 2H), 1.72–1.78 (m, 1.38H), 1.65 (ddd, 0.62H, J=11.3, 8.9, 2.2 Hz), 1.57–1.61 (m, 1H), 1.44–1.54 (m, 3H), 1.32–1.37 (m, 6H), 0.89–0.93 (m, 3H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ major isomer (**21c**): δ 152.2, 146.6, 128.6, 128.2, 127.6, 125.4, 48.6, 45.7, 45.6, 45.4, 33.4, 31.8, 30.3, 29.2, 27.5, 22.6, 14.1; minor isomer (**19c**): 152.2, 146.6, 128.9, 128.2, 127.5, 125.4, 51.6, 45.7, 43.7, 42.7, 36.2, 31.8, 29.8, 29.3, 27.6, 22.6, 14.1. Anal. calcd for $C_{19}H_{26}$: C, 89.70; H, 10.30. Found C, 89.98; H, 10.12.

4.4.7. 2-*endo*-Ethoxycarbonyl-3-*exo*-phenylbicyclo-[2.2.1]heptane (27). A solution of norbornene **3a** (12.2 mg, 0.0734 mmol) in THF (1 mL) was added to a flame-dried vial containing $Pd(OAc)_2$ (3.6 mg, 0.0160 mmol) and PPh_3 (7.9 mg, 0.0301 mmol) via cannula and rinsed with THF (2×0.5 mL). Iodobenzene (30 μL, 0.268 mmol), piperidine (30 μL, 0.30 mmol), and formic acid (20 μL, 0.53 mmol) were added. The reaction mixture was stirred for 23 h at 60°C. After quenching with water (4 mL), the reaction mixture was extracted with Et_2O (4×4 mL) and dried ($MgSO_4$). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (EtOAc/hexanes=1:49) to give the product **27** (5.1 mg, 0.0209 mmol, 28%) as a clear, colourless liquid. R_f 0.27 (1:19 EtOAc/hexanes); IR (neat) 2960 (m), 2865 (w), 1724 (s), 1265 (s), 1178 (m), 1094 (m), 1029 (m) cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.17–7.30 (AA′MM′X, 5H), 4.16 (ABX_3, 2H), 3.21 (d, 1H, J=5.8 Hz), 2.84 (ddd, 1H, J=6.0, 4.2, 1.9 Hz), 2.67 (m, 1H), 2.49 (dm, 1H, J=4.1 Hz), 1.79 (dm, 1H, J=9.9 Hz), 1.52 (m, 1H), 1.46 (m, 1H), 1.42 (m, 1H), 1.41 (m, 1H), 1.39 (m, 1H), 1.27 (t, 3H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ 174.3, 145.9, 128.4, 126.9, 125.8, 60.4, 55.7, 48.8, 42.9, 41.0, 38.3, 30.1, 24.2, 14.4. HRMS calcd for $C_{16}H_{20}O_2$: m/z 244.1463, found m/z 244.1458.

4.4.8. 2-*endo*-Formyl-3-*exo*-phenylbicyclo[2.2.1]heptane (28) and 2-*exo*-formyl-3-*exo*-phenylbicyclo[2.2.1]heptane (29). A flame-dried vial was charged with norbornene **3b** (33.0 mg, 0.270 mmol), THF (2 mL), iodobenzene (40 μL, 0.357 mmol), PPh_3 (14.2 mg, 0.0541 mmol), $Pd(OAc)_2$ (6.0 mg, 0.0267 mmol), KO_2CH (27.0 mg, 0.321 mmol). The reaction mixture was stirred for 4 d at 60°C. After quenching with water (5 mL), the reaction mixture was extracted with Et_2O (4×5 mL), and the combined organic layers were dried ($MgSO_4$). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (EtOAc/hexanes=1:19) to give an inseparable mixture of **28** and **29** (29.8 mg, 0.149 mmol, 55%, **28/29**=76:24 measured by integration on 400 MHz ^{1}H NMR spectrum and GC) as a clear, colourless liquid. R_f 0.30 (EtOAc/hexanes=1:19); IR (neat) 2957 (m), 2874 (m), 2807 (w), 2717 (w), 1717 (s), 1602 (w), 1497 (w), 1400 (w), 1266 (s), 1071 (m), 1031 (m) cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 9.88 (s, 0.76H), 8.98 (d, 0.24H, J=3.6 Hz), 7.14–7.30 (m, 5H), 3.26 (d, 0.24H, J=10.0 Hz), 3.24 (d, 0.76H, J=3.7 Hz), 2.85–2.86 (m, 1.52H), 2.73 (dm, 0.24H, J=10.0 Hz), 2.67 (br s, 0.24H), 2.62 (br s, 0.24H), 2.57 (d, 0.76H, J=4.2 Hz), 1.98 (dm, 0.24H, J=10.6 Hz), 1.82 (dd, 0.76H, J=10.0, 0.7 Hz), 1.69 (m, 1H), 1.34–1.64 (m, 4H);

^{13}C NMR (APT, $CDCl_3$, 100 MHz) major isomer (**28**): δ 203.6, 145.4, 128.5, 126.8, 125.9, 63.8, 46.0, 42.9, 39.0, 38.2, 30.3, 24.2; minor isomer (**29**): δ 204.1, 140.6, 128.7, 127.7, 126.3, 60.2, 50.4, 41.2, 38.3, 36.6, 30.6, 28.2. HRMS calcd for $C_{15}H_{16}O$: *m/z* 200.1201, found *m/z* 200.1213.

4.4.9. 2-Phenylbicyclo[2.2.1]hept-2-ene (31). A flame-dried vial was charged with norbornene **3c** (46.3 mg, 0.268 mmol), THF (2 mL), iodobenzene (90 μL, 0.804 mmol), PPh_3 (27.8 mg, 0.106 mmol), piperidine (180 μL, 1.82 mmol), formic acid (50 μL, 1.33 mmol), and $Pd(OAc)_2$ (11.8 mg, 0.0526 mmol). The reaction mixture was stirred for 5 d at 60°C. After quenching with water (10 mL), the reaction mixture was extracted with CH_2Cl_2 (4×10 mL) and dried ($MgSO_4$). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (hexanes) to give the product **31** (22.0 mg, 0.129 mmol, 48%) as a clear, colourless liquid. R_f 0.64 (hexanes); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.16–7.43 (AA′MM′X, 5H), 6.29 (d, 1H, *J*=3.2 Hz), 3.32 (br s, 1H), 2.99 (m, 1H), 1.73–1.83 (m, 2H), 1.53 (dm, 1H, *J*=8.3 Hz), 1.25 (ddd, 1H, *J*=8.2, 1.4, 1.0 Hz), 1.11–1.19 (m, 2H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) δ 147.8, 135.8, 129.7, 128.4, 126.6, 124.8, 47.9, 43.3, 43.1, 26.8, 24.8. This is a known compound in the literature.[34]

4.4.10. 2-Deutero-3-phenylbicyclo[2.2.1]hept-2-ene (38). A flame-dried vial was charged with norbornene **36** (35.8 mg, 0.206 mmol), THF (2 mL), iodobenzene (120 μL, 1.07 mmol), PPh_3 (21.5 mg, 0.0820 mmol), piperidine (180 μL, 1.82 mmol), $Pd(OAc)_2$ (9.4 mg, 0.0419 mmol), and formic acid (36 μL, 0.95 mmol) were added. The reaction mixture was stirred for 3 d at 60°C. After quenching with water (5 mL), the reaction mixture was extracted with Et_2O (4×5 mL) and dried ($MgSO_4$). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (hexanes). ^{1}H NMR revealed the presence of the excess iodobenzene as well as the products **38** and **31** (**38/31**=60:40), so Zn dust (15.9 mg, 0.234 mmol) was added to a solution of the products in 1:1 EtOH/saturated NH_4Cl (2 mL) to remove the excess iodobenzene. The reaction mixture was stirred at 25°C for 24 h and then extracted with Et_2O (4×5 mL), dried ($MgSO_4$), and filtered to give an inseparable mixture of **38** and **31** (6.0 mg, 0.0351 mmol, 17%, **38/31**=60:40 measured by integration on 400 MHz ^{1}H NMR spectrum) as a clear, colourless liquid. Spectral data for **38**: R_f 0.67 (hexanes); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.17–7.43 (AA′MM′X, 5H), 3.32 (s, 1H), 3.00 (s, 1H), 1.74–1.83 (m, 2H), 1.52–1.53 (m, 1H), 1.24–1.29 (m, 1H), 1.12–1.22 (m, 2H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) visible peaks: δ 128.4, 126.6, 124.8, 47.9, 43.3, 43.0, 26.8, 24.8; ^{2}H (deuterium) NMR ($CDCl_3$, 65 MHz) δ 6.35 (s). HRMS calcd for $C_{13}H_{13}D$: *m/z* 171.1158, found *m/z* 171.1145.

4.4.11. 2-*exo*-Methoxycarbonyl-5-*exo*-phenylbicyclo[2.2.1]heptane (46a) and 2-*exo*-methoxycarbonyl-6-*exo*-phenylbicyclo[2.2.1]heptane (47a) (Table 3, entry 1). $Pd(OAc)_2$ (12.4 mg, 0.0552 mmol), PPh_3 (27.9 mg, 0.106 mmol), iodobenzene (90 μL, 0.804 mmol), piperidine (0.180 mL, 1.81 mmol), and formic acid (0.050 mL, 1.33 mmol) were added to a solution of norbornene **4a** (42.0 mg, 0.276 mmol) in THF (2 mL). The reaction mixture was stirred for 1 d at 60°C, then passed through a plug of silica gel (EtOAc/hexanes=1:49). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (EtOAc/hexanes=1:19) to give an inseparable mixture of **46a** and **47a** (46.7 mg, 0.203 mmol, 74%, **46a/47a**=62:38 measured by integration on 400 MHz ^{1}H NMR spectrum) as a colourless, transparent liquid. R_f 0.22 (EtOAc/hexanes=1:49); IR (neat) 3087 (w), 3060 (w), 3025 (w), 2952 (s), 2878 (m), 1729 (s), 1602 (w), 1494 (m), 1448 (m), 1435 (m), 1358 (m), 1305 (w), 1262 (w), 1195 (s), 1174 (s), 1042 (m) cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.15–7.31 (m, 5H), 3.70 (s, 1.86H), 3.68 (s, 1.14H), 2.82 (dd, 0.38H, *J*=8.7, 5.7 Hz), 2.77 (dd, 0.62H, *J*=8.7, 6.0 Hz), 2.70 (br s, 0.38H), 2.64 (d, 0.62H, *J*=3.8 Hz), 2.53 (dd, 0.38H, *J*=9.1, 4.8 Hz), 2.44–2.48 (m, 1.62H), 1.98 (dd, 0.38H, *J*=5.4, 4.4 Hz), 1.95 (dd, 0.62H, *J*=5.4, 4.2 Hz), 1.41–1.92 (m, 5H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) major isomer (**46a**): δ 176.4, 146.6, 128.28, 126.9, 125.6, 51.7, 46.4, 45.6, 42.5, 41.4, 38.6, 35.0, 34.3; minor isomer (**47a**): 176.1, 146.1, 128.26, 127.0, 125.7, 51.7, 47.1, 47.0, 46.9, 37.8, 36.4, 34.1, 33.4. HRMS calcd for $C_{15}H_{18}O_2$: *m/z* 230.1307, found *m/z* 230.1328.

4.4.12. 2-*exo*-Hydroxy-5-*exo*-phenylbicyclo[2.2.1]heptane (46b) and 2-*exo*-hydroxy-6-*exo*-phenylbicyclo[2.2.1]heptane (47b) (Table 3, entry 2). $Pd(OAc)_2$ (12.5 mg, 0.0557 mmol), PPh_3 (28.3 mg, 0.108 mmol), iodobenzene (0.090 mL, 0.80 mmol), piperidine (0.180 mL, 1.81 mmol), and formic acid (0.050 mL, 1.3 mmol) were added to a solution of norbornene **4b** (29.5 mg, 0.268 mmol) in THF (2 mL). The reaction mixture was stirred for 3 d at 60°C. After quenching with water (4 mL), the reaction mixture was extracted with 1:9 CH_2Cl_2 (4×4 mL) and dried ($MgSO_4$). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (EtOAc/hexanes=1:4) to give an inseparable mixture of **46b** and **47b** (44.1 mg, 0.234 mmol, 87%, **46b/47b**=67:33 measured by integration on 400 MHz ^{1}H NMR spectrum) as a yellow semi-solid. R_f 0.31 (EtOAc/hexanes=1:4); IR (neat) 3382 (br s), 3087 (w), 3060 (w), 3025 (w), 2957 (s), 2896 (m), 1653 (w), 1600 (w), 1494 (m), 1449 (m), 1345 (w), 1266 (w), 1151 (w), 1081 (m), 1064 (s), 1032 (m) cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.15–7.31 (m, 5H), 3.96 (d, 0.33H, *J*=6.7 Hz), 3.93 (d, 0.67H, *J*=6.7 Hz), 2.64 (dd, 0.67H, *J*=8.2, 5.6 Hz), 2.57 (dd, 0.33H, *J*=8.2, 6.7 Hz), 2.42 (s, 0.33H), 2.41 (s, 0.67H), 2.33 (s, 0.33H), 2.28 (d, 0.67H, *J*=3.8 Hz), 1.88 (ddd, 0.67H, *J*=13.2, 6.8, 2.4 Hz), 1.78 (ddd, 0.33H, *J*=13.2, 6.8, 2.2 Hz), 1.35–1.72 (m, 6H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) major isomer (**46b**): δ 146.6, 128.2, 127.0, 125.56, 74.6, 45.9, 44.9, 43.0, 42.0, 33.3, 31.9; minor isomer (**47b**): 146.2, 128.3, 127.0, 125.62, 75.2, 50.8, 42.4, 41.5, 37.9, 35.8, 32.6. HRMS calcd for $C_{13}H_{16}O$: *m/z* 188.1201, found *m/z* 188.1200.

4.4.13. 2-*exo*-(*tert*-Butyldimethylsilyloxy)-5-*exo*-phenylbicyclo[2.2.1]heptane (46c) and 2-*exo*-(*tert*-butyldimethylsilyloxy)-6-*exo*-phenylbicyclo[2.2.1]heptane (47c) (Table 3, entry 5). A solution of norbornene **4c** (57.7 mg, 0.257 mmol) in THF (1 mL) was added to a flame-dried vial containing $Pd(OAc)_2(PPh_3)_2$ (36.4 mg, 0.0486 mmol) via cannula and rinsed with THF (2×0.5 mL). Iodobenzene

(90 μL, 0.80 mmol), piperidine (0.180 mL, 1.81 mmol), and formic acid (50 μL, 1.3 mmol) were added. The reaction mixture was stirred for 16 h at 60°C. After quenching with water (4 mL), the reaction mixture was extracted with Et_2O (4×4 mL), and the combined organic layers were dried ($MgSO_4$). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (EtOAc/hexanes=1:19) to give an inseparable mixture of **46c** and **47c** (64.0 mg, 0.212 mmol, 82%, **46c/47c**=74:26 measured by integration on 400 MHz ^{1}H NMR spectrum) as a colourless, transparent liquid. R_f 0.44 (EtOAc/hexanes=1:9); IR (neat) 3088 (w), 3063 (w), 3026 (w), 2956 (s), 2930 (s), 2894 (s), 2856 (s), 1653 (w), 1604 (w), 1494 (w), 1471 (m), 1361 (m), 1256 (s), 1180 (w), 1152 (m), 1089 (s), 1018 (m) cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.15–7.31 (m, 5H), 3.85 (d, 0.26H, *J*=6.7 Hz), 3.82 (dd, 0.74H, *J*=8.5, 1.0 Hz), 2.62 (dd, 0.74H, *J*=8.5, 5.3 Hz), 2.52 (dd, 0.26H, *J*=8.6, 6.2 Hz), 2.37 (s, 0.26H), 2.36 (s, 0.74H), 2.26 (s, 0.26H), 2.20 (d, 0.74H, *J*=3.7 Hz), 1.78 (ddd, 0.74H, *J*=12.8, 6.6, 1.9 Hz), 1.60–1.69 (m, 3.26H), 1.43–1.46 (m, 2H), 0.90–0.91 (m, 9H), 0.07–0.08 (m, 6H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) major isomer (**46c**): δ 147.0, 128.2, 127.1, 125.48, 75.0, 46.3, 45.0, 43.9, 41.9, 33.4, 32.0, 25.94, 18.13, −4.6; minor isomer (**47c**): δ 146.7, 128.3, 127.1, 125.52, 75.5, 51.0, 42.5, 42.3, 38.5, 35.7, 32.8, 25.90, 18.10, −4.7. Anal. calcd for $C_{19}H_{30}OSi$: C, 75.43; H, 10.00. Found C, 75.63; H, 10.16.

4.4.14. 2-*exo*-Acetoxy-5-*exo*-phenylbicyclo[2.2.1]heptane (46d) and 2-*exo*-acetoxy-6-*exo*-phenylbicyclo[2.2.1]heptane (47d) (Table 3, entry 9). $Pd(OAc)_2$ (6.5 mg, 0.029 mmol), tetrabutylammonium chloride (81.4 mg, 0.293 mmol), potassium formate (165.6 mg, 1.97 mmol), and iodobenzene (40 μL, 0.36 mmol) were added to a solution of norbornene **4d** (41.2 mg, 0.271 mmol) in DMF (2 mL). The reaction mixture was stirred for 96 h at room temperature. After quenching with water (4 mL), the reaction mixture was extracted with 1:9 CH_2Cl_2/hexanes (4×4 mL) and dried ($MgSO_4$). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (EtOAc/hexanes=1:19) to give an inseparable mixture of **46d** and **47d** (25.5 mg, 0.111 mmol, 41%, **46d/47d**=71:29 measured by integration on 400 MHz ^{1}H NMR spectrum) as a colourless, transparent liquid. R_f 0.31 (EtOAc/hexanes=1:19); IR (neat) 3086 (w), 3060 (w), 3026 (m), 2965 (s), 2878 (m), 1740 (s), 1602 (w), 1495 (m), 1471 (m), 1449 (m), 1376 (s), 1360 (s), 1302 (m), 1240 (s), 1152 (w), 1048 (s), 1032 (s), 1015 (s) cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.15–7.31 (m, 5H), 4.79 (ddd, 0.29H, *J*=7.0, 1.2, 1.0 Hz), 4.73 (dd, 0.71H, *J*=7.2, 2.7 Hz), 2.70–2.72 (m, 1H), 2.69 (s, 0.29H), 2.44–2.48 (m, 1.71H), 2.04 (s, 2.13H), 2.03 (s, 0.87H), 1.95 (m, 0.71H), 1.85 (ddd, 0.29H, *J*=13.6, 6.8, 1.8 Hz), 1.50–1.76 (m, 5H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) major isomer (**46d**): δ 170.9, 146.3, 128.28, 127.0, 125.69, 77.2, 45.9, 42.0, 41.9, 40.3, 33.1, 32.7, 21.4; minor isomer (**47d**): δ 170.7, 145.6, 128.33, 127.1, 125.74, 77.6, 47.8, 42.2, 39.0, 37.8, 35.8, 33.3, 21.4. HRMS calcd for $C_{15}H_{18}O_2$: *m/z* 230.1307, found *m/z* 230.1285.

4.4.15. 2-*endo*-Methoxycarbonyl-5-*exo*-phenylbicyclo[2.2.1]heptane (46e) and 2-*endo*-methoxycarbonyl-6-*exo*-phenylbicyclo[2.2.1]heptane (47e) (Table 3, entry 10). A solution of norbornene **4e** (41.4 mg, 0.272 mmol) in THF (1 mL) was added to a flame-dried vial containing $Pd(OAc)_2$ (12.2 mg, 0.0543 mmol) and PPh_3 (28.3 mg, 0.108 mmol) via cannula and rinsed with THF (2×0.5 mL). Iodobenzene (0.090 mL, 0.80 mmol), piperidine (0.180 mL, 1.81 mmol), and formic acid (0.050 mL, 1.3 mmol) were added. The reaction mixture was stirred for 16 h at 60°C. After quenching with water (4 mL), the reaction mixture was extracted with EtOAc (4×4 mL) and dried ($MgSO_4$). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (EtOAc/hexanes=1:19) to give an inseparable mixture of **46e** and **47e** (44.1 mg, 0.191 mmol, 70%, **46e/47e**=75:25 measured by integration on 400 MHz ^{1}H NMR spectrum) as a colourless, transparent liquid. R_f 0.27 (EtOAc/hexanes=1:19); IR (neat) 3060 (w), 3025 (w), 2954 (s), 2878 (m), 1736 (s), 1601 (w), 1494 (m), 1448 (m), 1435 (m), 1351 (m), 1305 (m), 1201 (s), 1168 (s), 1117 (w), 1042 (m) cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.15–7.31 (m, 5H), 3.74 (s, 0.75H), 3.73 (s, 2.25H), 2.91–2.82 (m, 2H), 2.73 (d, 0.25H, *J*=3.4 Hz), 2.68 (br s, 0.75H), 2.42–2.45 (m, 1H), 1.59–1.89 (m, 5H), 1.35–1.41 (m, 1H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) major isomer (**46e**): δ 175.4, 146.8, 128.2, 126.9, 125.5, 51.56, 46.43, 45.2, 43.3, 40.9, 37.9, 34.3, 33.0; minor isomer (**47e**): δ 175.2, 146.2, 128.2, 127.1, 125.6, 51.64, 46.5, 46.39, 41.7, 38.0, 37.5, 37.4, 31.1. Anal. calcd for $C_{15}H_{18}O_2$: C, 78.23; H, 7.88. Found C, 77.93; H, 7.99.

4.4.16. 2-*endo*-Hydroxy-5-*exo*-phenylbicyclo[2.2.1]heptane (46f) and 2-*endo*-hydroxy-6-*exo*-phenylbicyclo[2.2.1]heptane (47f) (Table 3, entry 11). A solution of norbornene **4f** (29.8 mg, 0.270 mmol) in THF (1 mL) was added to a flame-dried vial containing $Pd(OAc)_2$ (12.1 mg, 0.0539 mmol) and PPh_3 (28.1 mg, 0.107 mmol) via cannula and rinsed with THF (2×0.5 mL). Iodobenzene (0.090 mL, 0.80 mmol), piperidine (0.180 mL, 1.81 mmol), and formic acid (0.050 mL, 1.3 mmol) were added. The reaction mixture was stirred for 21 h at 60°C. After quenching with water (4 mL), the reaction mixture was extracted with Et_2O (4×4 mL). The extractions were combined, and the solvent was removed by rotary evaporation. The crude product was purified by column chromatography (EtOAc/hexanes=1:4) to give an inseparable mixture of **46f** and **47f** (43.1 mg, 0.229 mmol, 85%, **46f/47f**=62:38 measured by integration on 400 MHz ^{1}H NMR spectrum) as a yellow solid. R_f 0.37 (EtOAc/hexanes=1:4); IR (neat) 3366 (br s), 3085 (w), 3059 (w), 3025 (w), 2954 (s), 2877 (m), 2493 (br w), 1601 (m), 1494 (m), 1472 (w), 1449 (m), 1344 (m), 1303 (m), 1266 (m), 1147 (m), 1121 (w), 1085 (m), 1054 (s), 1019 (s) cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.23–7.32 (m, 4H), 7.15–7.19 (m, 1H), 4.28–4.36 (m, 1H), 3.56 (dd, 0.62H, *J*=8.9, 6.0 Hz), 2.90 (dd, 0.38H, *J*=11.6, 5.4 Hz), 2.47 (ddd, 0.38H, *J*=12.9, 9.1, 2.3 Hz), 2.40 (s, 0.62H), 2.39 (s, 0.38H), 2.33–2.35 (m, 1H), 2.11 (ddd, 0.38H, *J*=13.1, 10.1, 4.8 Hz), 2.03 (ddd, 0.62H, *J*=9.6, 4.2, 1.9 Hz), 1.93 (ddd, 0.62H, *J*=12.0, 9.2, 2.3 Hz), 1.76 (m, 0.62H), 1.61–1.65 (m, 2H), 1.56 (d, 0.38H, *J*=4.1 Hz), 1.31–1.37 (m, 1H), 1.08 (dt, 0.38H, *J*=13.0, 3.4 Hz), 0.97 (dt, 0.62H, *J*=12.9, 3.6 Hz); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) major isomer (**46f**): δ 147.1, 128.3, 127.3, 125.4, 72.9, 49.2, 39.5, 38.4, 37.7, 36.3, 35.5; minor isomer (**47f**): δ 147.1, 128.3, 127.0, 125.5, 72.4, 47.1, 43.4, 43.0, 40.9, 35.3, 29.4. HRMS calcd for $C_{13}H_{16}O$: *m/z* 188.1201, found *m/z* 188.1208.

4.4.17. 2-*endo*-(*tert*-Butyldimethylsilyloxy)-5-*exo*-phenylbicyclo[2.2.1]heptane (46g) and 2-*endo*-(*tert*-butyldimethylsilyoxy)-6-*exo*-phenylbicyclo[2.2.1]heptane (47g) (Table 3, entry 12). A solution of norbornene **4g** (56.5 mg, 0.252 mmol) in THF (1 mL) was added to a flame-dried vial containing $Pd(OAc)_2$ (11.7 mg, 0.0521 mmol) and PPh_3 (27.3 mg, 0.104 mmol) via cannula and rinsed with THF (2×0.5 mL). Iodobenzene (0.090 mL, 0.80 mmol), piperidine (0.180 mL, 1.81 mmol), and formic acid (0.050 mL, 1.3 mmol) were added. The reaction mixture was stirred for 17 h at 60°C. After quenching with water (4 mL), the reaction mixture was extracted with Et_2O (4×4 mL). The extractions were combined, and the solvent was removed by rotary evaporation. The crude product was purified by column chromatography (EtOAc/hexanes=1:19) to give an inseparable mixture of **46g** and **47g** (67.9 mg, 0.224 mmol, 89%, **46g/47g**=58:42 measured by integration on 400 MHz ^{1}H NMR spectrum) as a colourless, transparent liquid. R_f 0.36 (hexanes); IR (neat) 3027 (w), 2955 (s), 2930 (m), 2884 (m), 2857 (m), 1653 (m), 1471 (m), 1361 (w), 1257 (m), 1151 (m), 1122 (w), 1095 (s), 1068 (s), 1029 (w) cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.24–7.32 (m, 4H), 7.15–7.19 (m, 1H), 4.18–4.23 (m, 1H), 3.62 (dd, 0.42, J=8.8, 6.3 Hz), 2.88 (dd, 0.58H, J=9.1, 5.2 Hz), 2.53 (ddd, 0.58H, J=12.2, 9.5, 2.0 Hz), 2.28–2.31 (m, 2H), 1.99 (ddd, 0.58H, J=13.4, 9.6, 4.5 Hz), 1.86–1.93 (m, 0.84H), 1.75 (m, 0.42H), 1.59 (dd, 0.42H, J=3.1, 1.5 Hz), 1.57 (dd, 0.58J, J=3.2, 1 Hz), 1.51 (dt, 0.58H, J=12.5, 4.9 Hz), 1.29 (t, 0.42H, J=1.1 Hz), 1.27 (t, 0.58H, J=1.1 Hz), 1.24 (t, 0.42H, J=1.0 Hz), 1.06 (ddd, 0.58H, J=12.8, 3.6, 2.9 Hz), 0.93–0.94 (m, 9H), 0.07–0.08 (m, 6H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) major isomer (**46g**): δ 147.65, 128.2, 127.1, 125.3, 72.4, 43.4, 43.3, 41.4, 37.6, 34.7, 29.6, 25.9, 18.2, −4.8; minor isomer (**47g**): δ 147.74, 128.2, 127.4, 125.2, 72.9, 50.0, 47.0, 39.2, 39.1, 36.5, 34.9, 25.9, 18.2, −4.65, −4.69. Anal. calcd for $C_{19}H_{30}OSi$: C, 75.43; H, 10.00. Found C, 75.41; H, 10.02.

4.4.18. 2-*endo*-Acetoxy-5-*exo*-phenylbicyclo[2.2.1]heptane (46h) and 2-*endo*-acetoxy-6-*exo*-phenylbicyclo-[2.2.1]heptane (47h) (Table 3, entry 13). A solution of norbornene **4h** (36.3 mg, 0.238 mmol) in THF (1 mL) was added to a flame-dried vial containing $Pd(OAc)_2$ (12.4 mg, 0.0552 mmol) and PPh_3 (27.4 mg, 0.104 mmol) via cannula and rinsed with THF (2×0.5 mL). Iodobenzene (0.090 mL, 0.80 mmol), piperidine (0.180 mL, 1.81 mmol), and formic acid (0.050 mL, 1.3 mmol) were added. The reaction mixture was stirred for 18 h at 60°C. After quenching with water (4 mL), the reaction mixture was extracted with Et_2O (4×4 mL) and dried ($MgSO_4$). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (EtOAc/hexanes=1:9) to give an inseparable mixture of **46h** and **47h** (44.6 mg, 0.194 mmol, 81%, **46h/47h**=67:33 measured by integration on 400 MHz ^{1}H NMR spectrum) as a colourless, transparent liquid. R_f 0.38 (EtOAc/hexanes=1:19); IR (neat) 3087 (w), 3061 (w), 3026 (w), 2964 (s), 2879 (w), 1732 (s), 1602 (w), 1494 (w), 1448 (m), 1376 (m), 1360 (m), 1303 (w), 1208 (s), 1140 (w), 1091 (w), 1047 (m), 1027 (m) cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.15–7.32 (m, 5H), 4.99–5.06 (m, 1H), 3.39 (dd, 0.33H, J=8.8, 6.0 Hz), 2.88 (dd, 0.67H, J=8.9, 5.6 Hz), 2.67 (d, 0.33H, J=4.4 Hz), 2.63 (s, 67H), 2.39 (s, 0.33H), 2.88 (s, 0.67H), 2.31 (ddd, 0.67H, J=12.6, 9.0, 2.3 Hz), 2.15 (ddd, 0.67H, J=14.6, 10.3, 4.6 Hz), 2.095 (s, 0.99H), 2.092 (s, 2.01H), 1.92 (ddd, 0.33H, J=12.2, 8.8, 2.2 Hz), 1.80 (m, 0.33H), 1.56–1.68 (m, 2H), 1.34–1.38 (m, 1H), 1.21 (dt, 0.67H, J=13.5, 3.4 Hz), 1.11 (dt, 0.33H, J=13.4, 3.7 Hz); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) major isomer (**46h**): δ 171.2, 146.8, 128.3, 126.9, 125.62, 75.0, 46.7, 42.7, 40.7, 38.1, 34.99, 30.4, 21.2; minor isomer (**47h**): δ 171.1, 146.3, 128.3, 127.2, 125.56, 75.2, 46.4, 38.8, 37.2, 37.1, 36.0, 34.96, 21.2. Anal. calcd for $C_{15}H_{18}O_2$: C, 78.23; H, 7.88. Found C, 78.05; H, 7.97.

4.4.19. 5-*exo*-Phenylbicyclo[2.2.1]heptan-2-one (46i) and 6-*exo*-phenylbicyclo[2.2.1]heptan-2-one (47i) (Table 3, entry 15). $Pd(OAc)_2$ (6.4 mg, 0.029 mmol), tetrabutylammonium chloride (80.4 mg, 0.289 mmol), potassium formate (78.7 mg, 0.936 mmol), and iodobenzene (0.040 mL, 0.36 mmol) were added to a solution of norbornene **4i** (29.0 mg, 0.268 mmol) in DMF (2 mL). The reaction mixture was stirred for 3 d at room temperature. After quenching with water (4 mL), the reaction mixture was extracted with EtOAc (4×4 mL) and dried ($MgSO_4$). The solvent was removed by rotary evaporation and the crude product was purified by column chromatography (EtOAc/hexanes=1:9) to give an inseparable mixture of **46i** and **47i** (19.1 mg, 0.103 mmol, 38%, **46i/47i**=85:15 measured by integration on 400 MHz ^{1}H NMR spectrum and GC) as a colourless, transparent liquid. R_f 0.24 (EtOAc/hexanes=1:9); IR (neat) 3060 (w), 3027 (m), 2964 (s), 2909 (m), 2884 (m), 1756 (s), 1601 (m), 1494 (m), 1469 (m), 1449 (m), 1407 (m), 1294 (w), 1174 (m), 1126 (w), 1092 (w) cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.30–7.37 (m, 2H), 7.20–7.27 (m, 3H), 3.15 (dd, 0.15H, J=8.2, 6.3 Hz), 3.03 (dd, 0.85H, J=8.5, 6.1 Hz), 2.83 (m, 0.15H), 2.81 (m, 0.85H), 2.75 (m, 0.15H), 2.72 (d, 0.85H, J=4.3 Hz), 1.92–2.23 (m, 5H), 1.72–1.75 (m, 1H); ^{13}C NMR (APT, $CDCl_3$, 100 MHz) major isomer (**46i**): δ 217.5, 145.1, 128.46, 126.8, 126.1, 50.4, 46.0, 45.1, 41.7, 35.1, 32.3; visible peaks of minor isomer (**47i**): δ 143.6, 128.48, 127.0, 126.3, 56.5, 44.5, 41.0, 36.4, 35.8, 32.3. Anal. calcd for $C_{13}H_{14}O$: C, 83.83; H, 7.58. Found C, 83.59; H, 7.76.

Acknowledgements

We thank the Natural Sciences and Engineering Research Council (NSERC) of Canada, Boehringer Ingelheim (Canada) Ltd. and the University of Guelph for the generous financial support of our program. Peter Mayo thanks NSERC for postgraduate scholarships (PGS A and PGS B).

References

1. For recent reviews, see: (a) Beletskaya, I. P.; Cheprakov, A. V. *Chem. Rev.* **2000**, *100*, 3009, and references cited therein. (b) Amatore, C.; Jutand, A. *Acc. Chem. Res.* **2000**, *33*, 314.
2. (a) Larock, R. C.; Johnson, P. L. *J. Chem. Soc., Chem. Commun.* **1989**, 1368. (b) Arcadi, A.; Marinelli, F.; Bernocchi, E.; Cacchi, S.; Ortar, G. *J. Organomet. Chem.* **1989**, *368*, 249. (c) Clayton, S. C.; Regan, A. C. *Tetrahedron Lett.* **1993**, *34*, 7493.
3. (a) Larock, R. C.; Babu, S. *Tetrahedron Lett.* **1987**, *28*, 5291.

(b) Burns, B.; Grigg, R.; Ratananukul, P.; Sridharan, V.; Stevenson, P.; Worakun, T. *Tetrahedron Lett.* **1988**, *29*, 4329.
4. (a) Brunner, H.; Kramler, K. *Synthesis* **1991**, 1121. (b) Sakuraba, S.; Awano, K.; Achiwa, K. *Synlett* **1994**, 291. (c) Moinet, C.; Fiaud, J.-C. *Tetrahedron Lett.* **1995**, *36*, 2051.
5. Ozawa, F.; Kobatake, Y.; Kubo, A.; Hayashi, T. *J. Chem. Soc., Chem. Commun.* **1994**, 1323.
6. (a) Hay, L. A.; Koenig, T. M.; Ginah, F. O.; Copp, J. D.; Mitchell, D. *J. Org. Chem.* **1998**, *63*, 5050. (b) Jia, C.; Piao, D.; Kitamura, T.; Fujiwara, Y. *J. Org. Chem.* **2000**, *65*, 7516. (c) Jia, C.; Lu, W.; Oyamada, J.; Kitamura, T.; Matsuda, K.; Irie, M.; Fujiwara, Y. *J. Am. Chem. Soc.* **2000**, *122*, 7252.
7. (a) Yip, C.; Handerson, S.; Jordan, R.; Tam, W. *Org. Lett.* **1999**, *1*, 791. (b) Yip, C.; Handerson, S.; Tranmer, G. K.; Tam, W. *J. Org. Chem.* **2001**, *66*, 276.
8. (a) Tranmer, G. K.; Keech, P.; Tam, W. *Chem. Commun.* **2000**, 863. (b) Tranmer, G. K.; Tam, W. *J. Org. Chem.* **2001**, *66*, 5113.
9. (a) Mayo, P.; Poirier, M.; Rainey, J.; Tam, W. *Tetrahedron Lett.* **1999**, *40*, 7727. (b) Mayo, P.; Orlova, G.; Goddard, J. D.; Tam, W. *J. Org. Chem.* **2001**, *66*, 5182.
10. Tranmer, G. K.; Yip, C.; Handerson, S.; Jordan, R. W.; Tam, W. *Can. J. Chem.* **2000**, *78*, 527.
11. (a) Jordan, R. W.; Tam, W. *Org. Lett.* **2000**, *2*, 3031. (b) Jordan, R. W.; Tam, W. *Org. Lett.* **2001**, *3*, 2367.
12. Mayo, P.; Hecnar, T.; Tam, W. *Tetrahedron* **2001**, *57*, 5931.
13. Mayo, P.; Tam, W. *Tetrahedron* **2001**, *57*, 5943.
14. Trost, B. M.; Balkovec, J. M.; Angle, S. R. *Tetrahedron Lett.* **1986**, *27*, 1445.
15. Schore, N. E. *Comprehensive Organometallic Chemistry II*, Abel, E. W., Stone, F. G. A., Wilkinson, G., Eds.; Pergamon: Oxford, 1995; Vol. 12, p 721.
16. Morisaki, Y.; Kondo, T.; Mitsudo, T. *Org. Lett.* **2000**, *2*, 949.
17. Michieletto, I.; Fabris, F.; De Lucchi, O. *Tetrahedron: Asymmetry* **2000**, *11*, 2835.
18. The *exo* and *endo* cycloadducts **8** and **9** were modeled for energy minimization at PM3 level (CS Chem 3D Pro Version 3.5.1) using MOPAC for the assessment of the dihedral angles between H^a and H^b. These dihedral angles were then compared to the Karplus curve for the determination of the theoretical coupling constants.
19. Similar methods have been used for the assignment of *exo* and *endo* stereochemistry of bicyclic alkanes, see: (a) Flautt, T. J.; Erman, W. F. *J. Am. Chem. Soc.* **1963**, *85*, 3212. (b) Mazzocchi, P. H.; Stahly, B.; Dodd, J.; Rondan, N. G.; Domelsmith, L. N.; Rozeboom, M. D.; Caramella, P.; Houk, K. N. *J. Am. Chem. Soc.* **1980**, *102*, 6482. See also Refs. 8b,12, 13.
20. Cossu, S.; De Lucchi, O.; Paulon, A.; Peluso, P.; Zonta, C. *Tetrahedron Lett.* **2001**, *42*, 3515.
21. For recent reviews, see: (a) Cieplak, A. S. *Chem. Rev.* **1999**, *99*, 1265. (b) Ohwada, T. *Chem. Rev.* **1999**, *99*, 1337. (c) Mehta, G.; Chandrasekhar, J. *Chem. Rev.* **1999**, *99*, 1437.
22. MacWhorter, S. E.; Sampath, V.; Olmstead, M. M.; Schore, N. E. *J. Org. Chem.* **1988**, *53*, 203.
23. Lautens, M.; Tam, W.; Edwards, L. G. *J. Chem. Soc., Perkin Trans. 1* **1994**, 2143.
24. Mayo, P.; Tam, W. *Tetrahedron* **2002**, *58*, 9513–9525.
25. The *exo* and *endo* cycloadducts **46** and **47** were modeled for energy minimization at PM3 level (CS Chem 3D Pro Version 3.5.1) using MOPAC for the assessment of the dihedral angles between H^a and H^b. These dihedral angles were then compared to the Karplus curve for the determination of the theoretical coupling constants.
26. GOESY: Gradient enhanced nuclear Overhauser enhancement spectroscopy, see: (a) Stonehouse, J.; Adell, P.; Keeler, J.; Shaka, A. J. *J. Am. Chem. Soc.* **1994**, *116*, 6037. (b) Stott, K.; Stonehouse, J.; Keeler, J.; Hwang, T-L.; Shaka, A. J. *J. Am. Chem. Soc.* **1995**, *117*, 4199. (c) Dixon, A. M.; Widmalm, G.; Bull, T. E. *J. Magn. Reson.* **2000**, *147*, 266.
27. Still, W. C.; Kahn, M.; Mitra, A. *J. Org. Chem.* **1978**, *43*, 2923.
28. Lautens, M.; Edwards, L. G.; Tam, W.; Lough, A. J. *J. Am. Chem. Soc.* **1995**, *117*, 10276.
29. Verkruijsse, H. D.; Brandsma, L. *Recl. Trav. Chim. Pays-Bas* **1986**, *105*, 66.
30. Gassman, P. G.; Mansfield, K. T. *J. Am. Chem. Soc.* **1968**, *90*, 1517.
31. Rousseau, G.; Le Perchec, P.; Conia, J. M. *Synthesis* **1978**, 67.
32. (a) Cossu, S.; De Lucchi, O.; Paulon, A.; Peluso, P.; Zonta, C. *Tetrahedron Lett.* **2001**, *42*, 3515. (b) Gassman, P. G.; Gennick, I. *J. Org. Chem.* **1980**, *45*, 5211.
33. Gassman, P. G.; Gennick, I. *J. Org. Chem.* **1980**, *45*, 5211.
34. Kleinfelter, D. C.; Dye, T. E.; Mallory, J. E.; Trent, E. S. *J. Org. Chem.* **1967**, *32*, 1734.