Synthesis and Reactions of Allylic, Allenic, Vinylic, and Arylmetal Reagents from Halides and Esters via Transient Organopalladium Intermediates

James A. Marshall

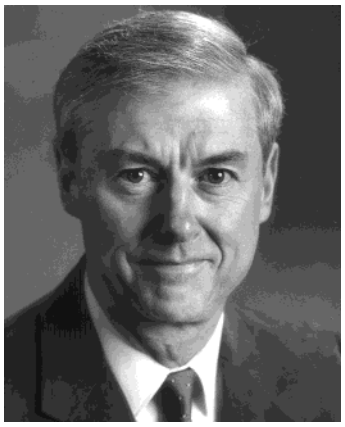
Department of Chemistry, University of Virginia, Charlottesville, Virginia 22904

Received February 2, 2000

Contents

I. Introduction

The value of organometallic reagents to organic synthesis can hardly be overstated. Every student of organic chemistry is aware of the virtually unlimited number of compounds that can be synthesized through use of Grignard reagents. Traditionally, such organometallic reagents have been prepared from organic halides and active metals such as Mg, Li, or Zn. However, in recent years the expansion of synthetic methodology to include organosilanes, boranes, boronates, tin, samarium, indium, and zinc reagents has led to the development of alternative routes to such compounds. Allylic, vinylic, and arylmetal compounds have proven to be particularly useful in carbon−carbon bond-forming reactions. These can often be prepared by transmetalation of organolithium intermediates. Unfortunately, this approach is not possible with base-sensitive materials and substances for which an appropriate halide precursor is not available.



James A. Marshall received his B.S. degree from the University of Wisconsin and his Ph.D. degree from the University of Michigan, where he studied with Robert E. Ireland. He was an NIH postdoctoral fellow in William S. Johnson's laboratory at Stanford University after which, in 1962, he joined the faculty at Northwestern University. He was promoted to Professor in 1968 and subsequently moved, in 1980, to the University of South Carolina, where he held the Guy Lipscomb Chair until 1995 when he accepted an appointment as Thomas Jefferson Professor of Chemistry at the University of Virginia. His professional interests lie in the area of natural products synthesis and stereocontrolled synthetic methodology.

In certain cases it has been found that organopalladium compounds derived from halides or esters undergo transmetalation with a number of metal salts, active metals, or readily available organometal compounds, such as Et_2Zn and Me_6Sn_2 (Figure 1). These reactions are carried out with 5−10 mol % or less of recoverable palladium catalysts under mild conditions. The reaction transforms electrophilic palladium intermediates into nucleophilic organometal compounds. These organometal compounds may be isolable or formed as transient intermediates that react with an electrophilic partner in situ. Such reactions can take place by either inter- or intramolecular pathways. Although relatively few examples have been reported to date, these transmetalations hold great promise for the in situ formation of extremely useful allylic, allenic, vinylic, and arylmetal compounds. This review will summarize the evolution of this emerging synthetic methodology.

A significant number of vinylmetal and 1,2-vinyldimetal compounds have been prepared by palladium-catalyzed additions of organometal or diorganodimetal compounds to alkynes (Figure 2). The process presumably involves oxidative addition of the palladium catalyst to the organometal species and

10.1021/cr000003u CCC: $35.00
Published on Web 06/30/2000

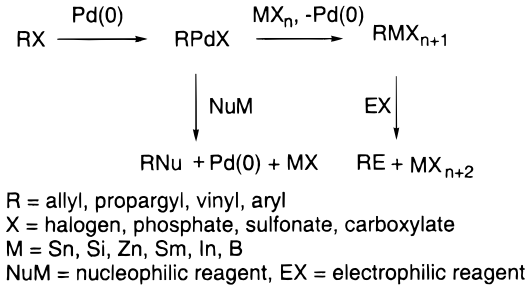


Figure 1. Substitution and transmetalation reactions of organopalladium intermediates.

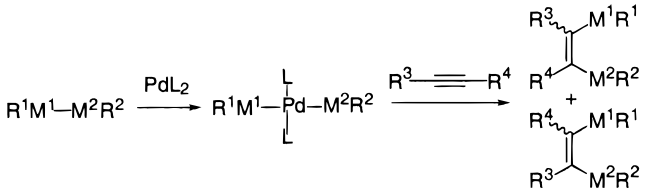


Figure 2. Synthesis of vinylmetal compounds by addition of metallopalladium compounds to alkynes.

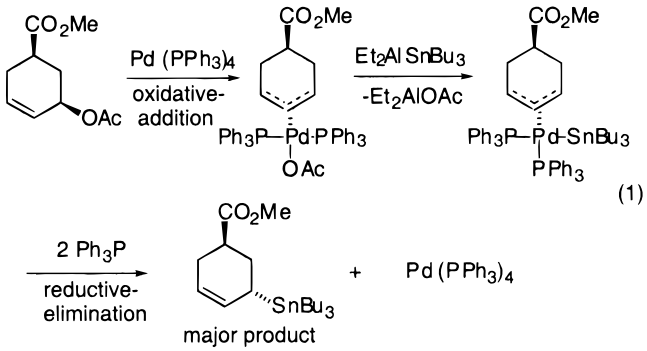
subsequent electrophilic addition to the triple bond and reductive elimination. This topic is covered elsewhere in this issue by Y. Ito and M. Suginome (Si) and M. Lautens (Sn). The present review mainly surveys reactions involving an initial oxidative addition of a Pd catalyst to a C−X bond.

II. Allylmetal Reagents

A. Allylic Stannanes

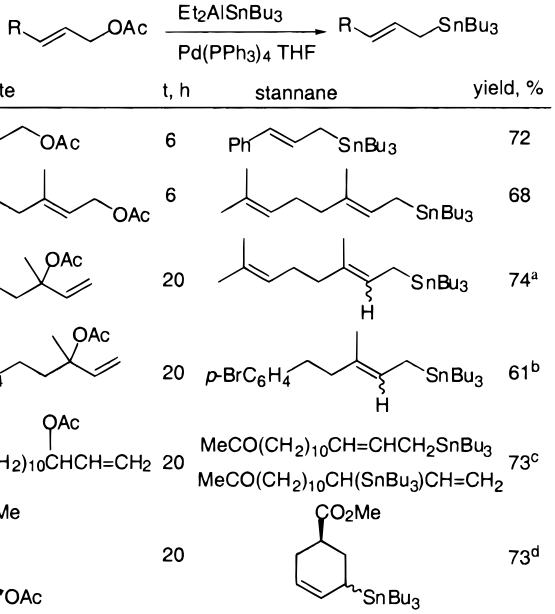
Initial developments came from three independent groups. Trost and Herndon reported the successful conversion of allylic acetates to allylic stannanes by way of π-allylpalladium intermediates (Table 1).[1] The reaction proceeds by attack of the nucleophilic tin reagent $Et_2AlSnBu_3$ on the π-allylpalladium acetate. In the case of unsymmetrical allylic acetates, substitution occurs at the less hindered terminus of the allylic system.

Whereas carbon nucleophiles tend to react with π-allylpalladium intermediates with overall retention of configuration, relative to the stereochemistry of the allylic acetate precursor, the stannylation reaction proceeds mainly with inversion. Thus, it can be concluded that the stannane initially attacks the electron-deficient Pd center rather than the allylic carbon of the π-allyl intermediate (eq 1). Reductive



elimination occurs at the less hindered terminus to regenerate the catalyst. It is worth noting that

Table 1



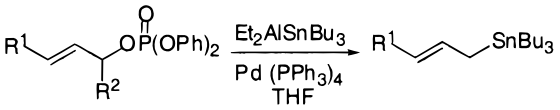
acetate	t, h	stannane	yield, %
Ph, OAc	6	Ph, $SnBu_3$	72
OAc	6	$SnBu_3$	68
OAc	20	$SnBu_3$, H	74[a]
OAc, p-BrC_6H_4	20	p-BrC_6H_4, $SnBu_3$, H	61[b]
OAc, $MeCO(CH_2)_{10}CH{=}CH_2$	20	$MeCO(CH_2)_{10}CH{=}CHCH_2SnBu_3$ + $MeCO(CH_2)_{10}CH(SnBu_3)CH{=}CH_2$	73[c]
CO_2Me, OAc	20	CO_2Me, $SnBu_3$	73[d]

[a] 50:50 (*E*)/(*Z*). [b] 60:40 (*E*)/(*Z*). [c] 82:18 mixture of regioisomers. [d] 70:30 trans:cis.

allylstannanes react with allylic acetates in the presence of a Pd(0) catalyst to afford 1,5-dienes. However, this reaction must be significantly slower than the stannane coupling as none of these byproducts are observed.

In a closely related investigation, Oshima and coworkers reported on the use of allylic phosphates as precursors to allylic stannanes in a reaction catalyzed by $Pd(PPh_3)_4$ (Table 2).[2] As expected, the regiochem-

Table 2



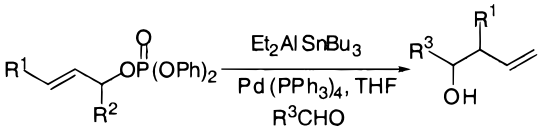
R^1	R^2	yield, %
H	H	57
Me	H	58
H	Me	55[a]

[a] R^1 = Me in the product.

istry of this substitution process parallels that of the related acetates.

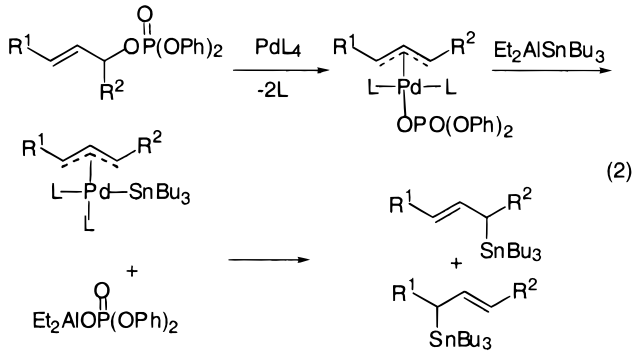
The Oshima group also showed that the stannylation could be conducted in the presence of aldehydes whereupon homoallylic alcohol adducts are produced in high overall yield (Table 3). As such additions are known to require stoichiometric amounts of Lewis acids to proceed, it can be concluded that the diethylaluminum phosphate byproduct of the transmetalation reaction fulfills this role (eq 2). Additions of crotyltributyltin to aldehydes, initiated by $BF_3{\cdot}OEt_2$, favor syn adducts in a process involving an acyclic transition state. In the present case, anti products are favored. However, as syn:anti ratios are sensitive to the nature of the Lewis acid, in the absence of evidence to the contrary, it is quite possible that the foregoing additions also proceed through an acyclic transition state.

Table 3



R^1	R^2	R^3	yield, %	*syn*:*anti*
H	H	Ph	82	
H	H	C_5H_{11}	70	
Me	H	Ph	70	40:60
Me	H	C_5H_{11}	65	47:53
H	Me	Ph	82	38:62[a]

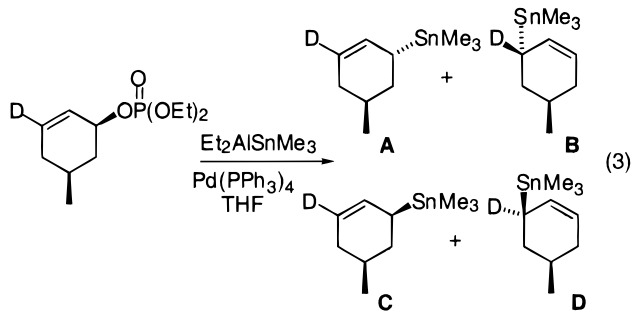
[a] R^1 = Me in the product.



(2)

The in situ transmetalation−aldehyde addition was also examined with $Et_2AlSnClF_2$ as the stannylation reagent (Table 4). Yields of homoallylic alcohols were high but diastereoselectivity was poor. Additions of allylic trihalostannanes to aldehydes are known to proceed via cyclic transition states whereby the (*E*)-isomers give rise to anti products and vice-versa. Thus, the formation of significant amounts of syn products may reflect the production of both (*E*)- and (*Z*)-allylic stannane intermediates.

The predominate stereochemical course of the allylic phosphate stannylation reaction was shown to be anti, as was the case with allylic acetates (eq 3). The intermediacy of a symmetrical π-allylpalladium complex is borne out by the formation of a 50:50 mixture of deuterated regioisomeric allylic stannane products **A**:**B** and **C**:**D.**

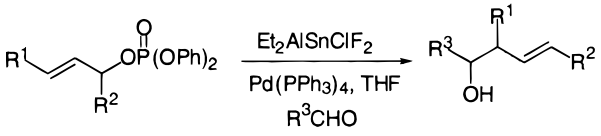


(3)

A/B:C/D = 72:28; **A:B** = 50:50, **C:D** = 50:50

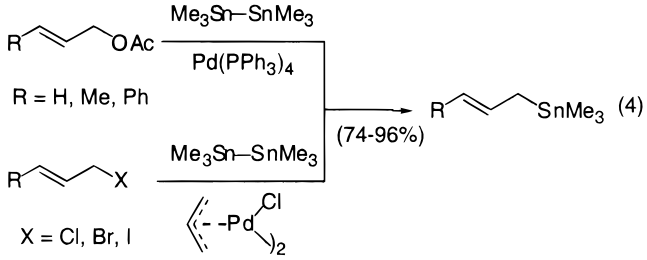
A third approach to allylic stannanes via π-allylpalladium intermediates was reported by Bumagin and co-workers.[3] They found that allylic acetates react with hexamethylditin in the presence of catalytic $Pd(PPh)_3)_4$ (eq 4). The reaction could also be carried out on allylic halides with bis-π-allylpalladium chloride as catalyst.

Table 4



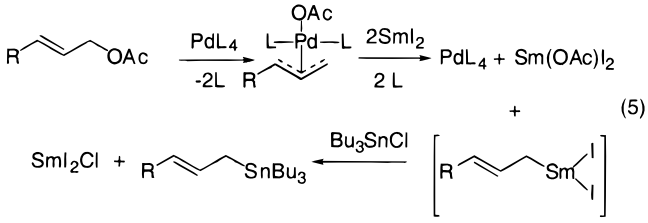
R^1	R^2	R^3	yield, %	*syn*:*anti*
H	H	Ph	95	
H	H	C_5H_{11}	69	
Me	H	Ph	96	33:67
Me	H	C_5H_{11}	80	50:50
H	Me	Ph	78 [a]	25:75
H	Me	C_5H_{11}	77 [a]	55:45

[a] R^1 = Me, R^2 = H in the product.



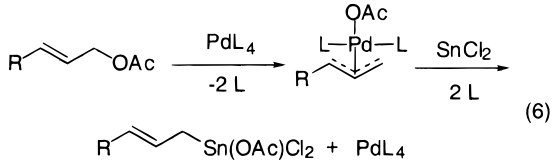
(4)

A somewhat different synthesis of allylic stannanes from allylic acetates was disclosed by Inanaga and co-workers.[4] In this case the electrophilic tin reagent Bu_3SnCl was employed to stannylate an allylic samarium intermediate which, in turn, was produced from a transient π-allylpalladium species and SmI_2 (eq 5). These transmetalations exhibit similar regio- and stereochemical features to those of the direct nucleophilic substitutions involving $Et_2AlSnBu_3$ (Table 5). However, the formation of identical ratios of cis and trans stannanes from isomeric cyclohexenyl acetates (Table 5, last two entries) suggests that the allylsamarium intermediates undergo rapid equilibration prior to stannylation. Quite possibly the intermediate allylsamarium iodide could be transmetalated with other metal halides leading to, e.g., allylic zinc or indium reagents.



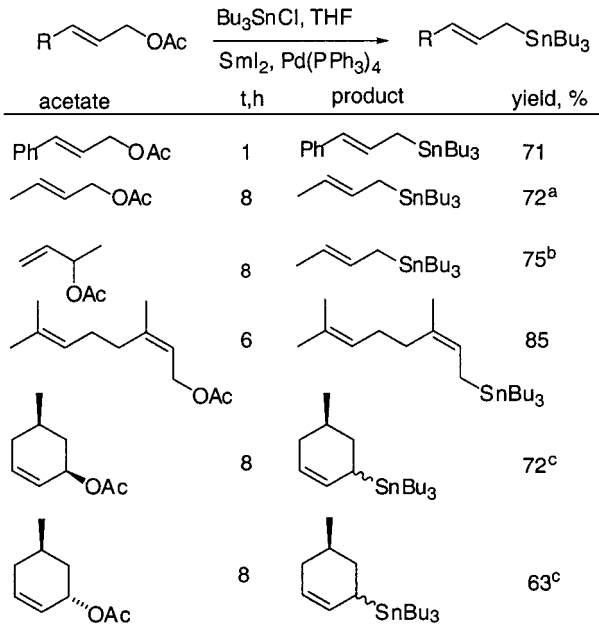
(5)

A series of studies on the use of $SnCl_2$ to transmetalate π-allylpalladium intermediates was carried out by Masuyama and co-workers (eq 6).[5] These



(6)

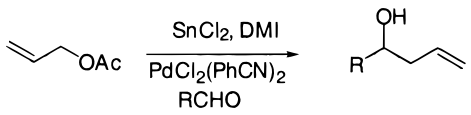
Table 5



acetate	t,h	product	yield, %
Ph, OAc	1	Ph, $SnBu_3$	71
OAc	8	$SnBu_3$	72[a]
OAc	8	$SnBu_3$	75[b]
OAc	6	$SnBu_3$	85
OAc	8	$SnBu_3$	72[c]
OAc	8	$SnBu_3$	63[c]

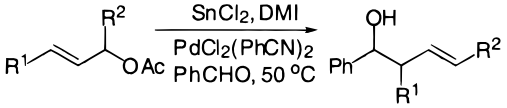
[a] (*E*)/(*Z*) = 53:47. [b] (*E*)/(*Z*) = 52:48. [c] trans:cis = 68:32.

Table 6



R	T, °C	t, h	yield, %
Ph	60	15	82
PhCH=CH	25	57	60
C_5H_{11}	60	19	54
CH_2=CH$(CH_2)_8$	60	17	76

Table 7



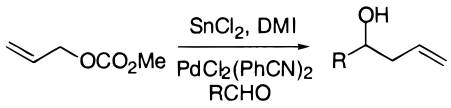
R^1	R^2	yield, %	*syn*:*anti*
Me	H	69	61:39
H	Me	46[a]	69:31
Ph	H	53	28:72
H	Ph	73[b]	5:95

[a] R^1 = Me, R^2 = H in product. [b] R^1 = Ph, R^2 = H in product.

reactions were conducted in the presence of aldehydes to afford homoallylic alcohol adducts (Table 6). They are assumed to involve a formal oxidative addition by $SnCl_2$ to the transient π-allylpalladium intermediate to produce an allylic SnX_3 reagent which adds to the aldehyde in situ. The use of 1,3-dimethylimidazolidin-2-one (DMI) as a solvent facilitated these relatively slow reactions.

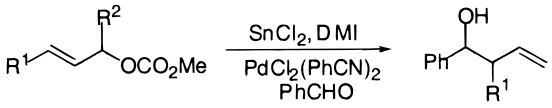
A curious crossover in stereoselectivity was reported for additions involving crotyl and cinnamylstannanes (Table 7). In the former case the reaction favors the syn adduct to nearly the same extent when the stannane reagent is generated from regioisomeric crotyl and α-methylallyl acetates, suggestive of a common intermediate. However, the adducts derived

Table 8



R	t,h	yield, %
C_5H_{11}	10	49
C_7H_{15}	10	57
CH_2=CH$(CH_2)_8$	10	75
PhCH=CH	7	92

Table 9



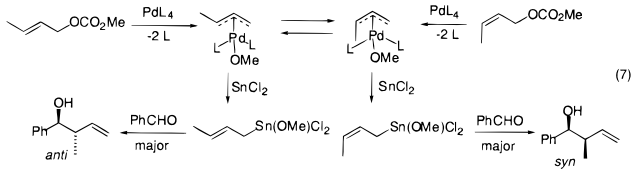
R^1	R^2	T, °C	t,h	yield, %	*syn*:*anti*
Me	H	25	48	80	33:67
Me	H	10	72	90	27:73
Me[a]	H	25	60	42	48:52
H	Me	10	84	95	31:69[b]

[a] The (*Z*)-allylic carbonate was used. [b] R^1 = Me in the product.

from the isomeric cinnamyl and α-phenylallyl acetates both favor anti adducts and the anti:syn ratios are quite different. These latter results are inconsistent with the formation of a common π-allylpalladium intermediate from both acetate regioisomers.

In related studies, Masuyama et al. found that allylic carbonates are more reactive than acetates (compare Table 6 with Table 8).[6] The diastereoselectivity of the subsequent additions to benzaldehyde showed a dependence on temperature and the structure of the allylic carbonate precursor (Table 9). Thus, *trans*-crotyl (entry 1) afforded somewhat more of the anti adduct than *cis*-crotyl (entry 3) and α-methallyl (entry 4). Product ratios were also temperature dependent.

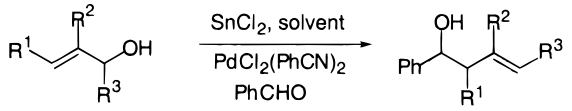
This result was interpreted in terms of competitive isomerization and addition reactions of the π-allylpalladium intermediates (eq 7). The initial π-allyl



(7)

species from *cis*-crotyl presumably isomerizes to *trans*-π-allyl and transmetalates at comparable rates, whereas trans-cis isomerization of the *trans*-crotyl species would likely be slower than addition of $SnCl_2$. Thus, assuming a cyclic transition state, more of the syn adduct would be formed from *cis*- vs *trans*-crotyl acetate. α-Methallyl acetate would expectedly give rise to mainly the *trans*-π-allylpalladium intermediate. It is also possible that through coordination with DMI, the allylic stannane intermediate reacts with benzaldehyde, at least in part, via an acyclic transition state. This pathway would favor the syn adduct.

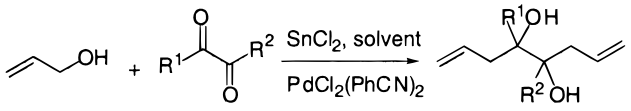
Table 10



R^1	R^2	R^3	solvent	T, °C	t, h	yield,%	*syn*:*anti*
Me	H	H	DMF	25	63	89	30:70
Me	H	H	THF	-10	130	81	10:90
Me	H	H	DMSO-H_2O[a]	25	88	84	86:14
Me	H	H	DMSO-H_2O[b]	25	70	70	16:84
H	H	Me	DMSO-H_2O	25	92	95	84:16
Me[c]	H	H	DMSO-H_2O	25	95	51	84:16
Me	Me	H	DMSO-H_2O	25	109	83	27:73
Me[c]	Me	H	DMSO-H_2O	25	113	87	38:62

[a] 3 mmol of H_2O. [b] 170 mmol of H_2O. [c] The *(Z)*-allylic alcohol.

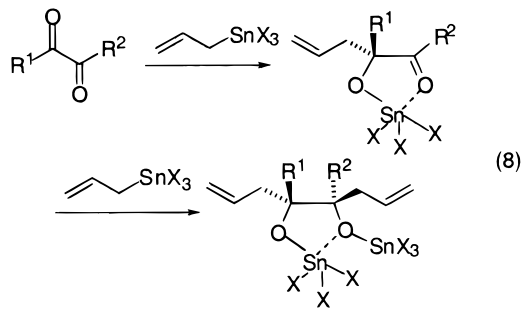
Table 11



R^1	R^2	solvent	T, °C	t, h	yield, %	*syn*:*anti*
Me	Me	DMI	25	48	59	70:30
Me	Me	THF-H_2O	25	48	53	61:39
Me	Me	DMSO-H_2O	25	88	33	89:11
Me	Et	DMI	25	48	47	62:38
Me	Et	THF-H_2O	25	48	51	55:45
$(CH_2)_4$		DMI	25	48	46	100:0

Masuyama et al. also found that allylic alcohols could be used as precursors of allylic stannanes for in situ additions to benzaldehyde (Table 10).[7] These reactions could be conducted in DMF, THF, or DMSO, but long reaction times were required. Water was found to have a beneficial effect. Moreover, the amount of water cosolvent influenced the ratio of syn and anti adducts with small amounts favoring syn and vice-versa. These results were explained by assuming a cyclic transition state for reactions employing large amounts of water and an acyclic transition state for those in which small amounts were present.

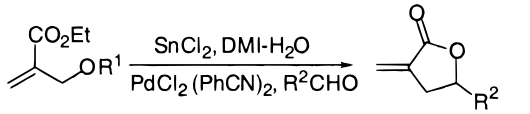
Additions to α-diketones by allylic stannanes generated from allylic alcohols favor syn diol adducts (Table 11).[8] This preference may result from addition of the second allyl group to an intermediate chelated α-hydroxy ketone (eq 8).



(8)

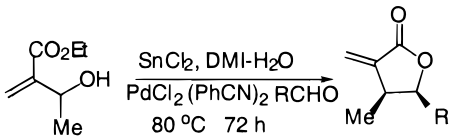
Both ethyl α-(hydroxymethyl)acrylate and the methyl carbonate derivative undergo stannylation with $SnCl_2$ and $PdCl_2(PhCN)_2$ in DMI.[9] Addition of the intermediate halostannanes in situ to aldehydes affords α-methylene-γ-butyrolactones in moderate yields (Table 12). The α-(α-hydroxyethyl) analogue affords *cis* adducts, in accord with a chelated acyclic transition state (Table 13).

Table 12



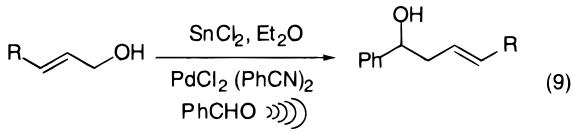
R^1	R^2	T, °C	t, h	yield, %
H	Ph	80	47	33
H	C_7H_{15}	80	70	36
H	*c*-C_6H_{11}	80	90	30
H	PhCH=CH	80	120	44
CO_2Me	Ph	50	52	36
CO_2Me	C_7H_{15}	50	60	51
CO_2Me	*c*-C_6H_{11}	50	48	61
CO_2Me	PhCH=CH	50	80	47

Table 13



R	yield, %	*cis*:*trans*
Bu	40	95:5
c-C_6H_{11}	38	96:4
p-$C_6H_4CO_2Me$	40	95:5

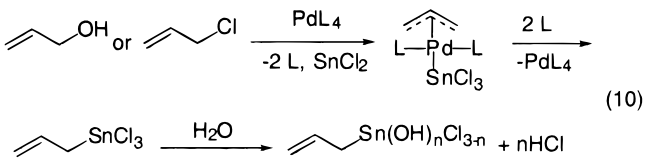
The allylation can be conducted in diethyl ether with ultrasonication.[10] Remarkably, the regiochemistry strongly favors the unbranched adduct under these conditions (eq 9).



(9)

R=Pr 57% 67:33 (*E*):(*Z*)
R=*c*-C_6H_{11} 69% 99:1 (*E*):(*Z*)

Through use of proton and carbon NMR, Masuyama and co-workers demonstrated that the reactions of allylic alcohols with $SnCl_2$ and Pd(0) catalysts proceeds by way of an allylic trichlorostannane.[11] In the presence of water, the trichlorostannane is hydrated (eq 10).

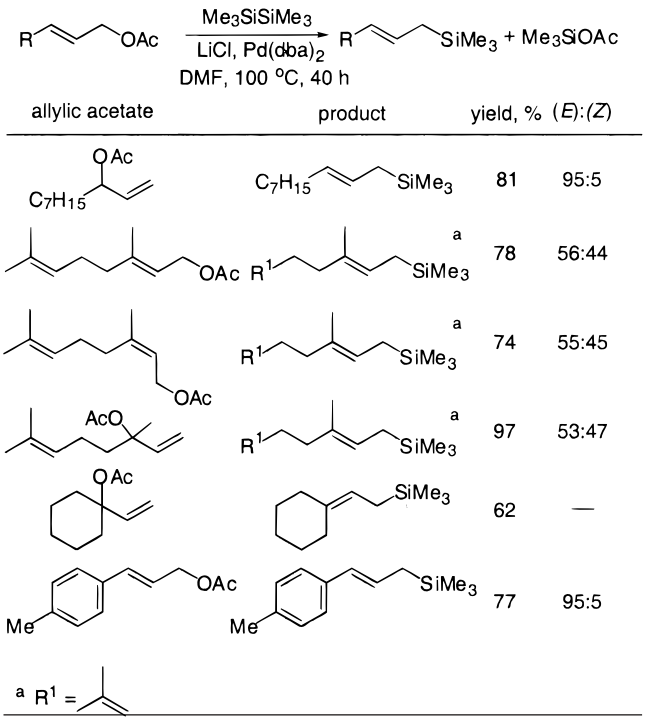


(10)

B. Allylic Silanes

Tsuji et al. found that allylic acetates can be converted to the corresponding silanes with hexamethyldisilane and a Pd(0) catalyst derived in situ from $Pd(dba)_2$ in DMF in the presence of LiCl (Table 14).[12] No reaction took place at room temperature, and even at 100 °C prolonged reaction times were required.

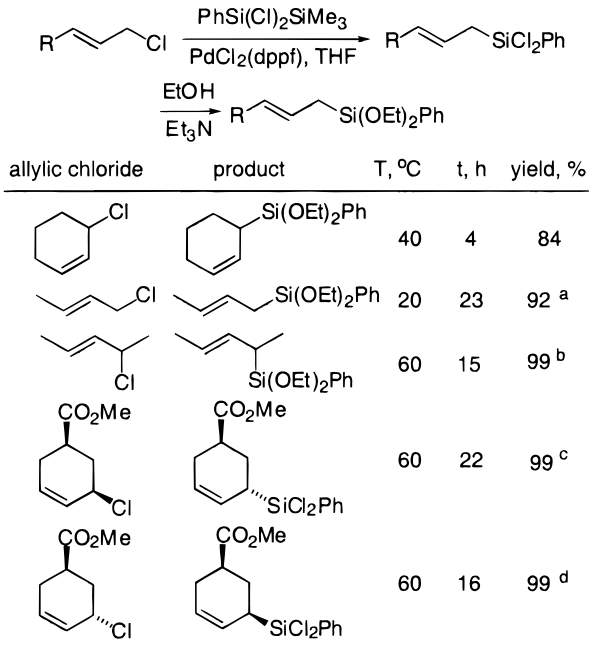
Table 14



The use of NaCl in place of LiCl gave the products in comparable yields, but KCl and KBr were less efficient as additives. No product was formed in the absence of added chloride salts. A more facile substitution took place with $Bu_3SnSiMe_3$ as the silyl source. These reactions, which could be conducted at room temperature, gave only products of silyl transfer. Allylic stannanes were not detected.

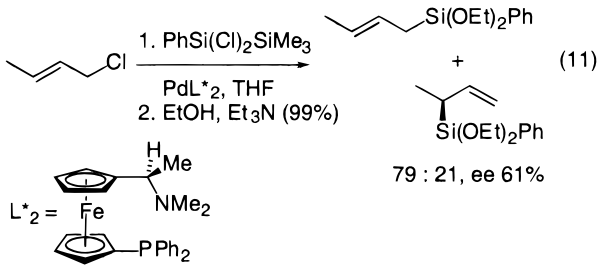
The mixed disilane reagent $PhSiCl_2SiMe_3$ was used by Hayashi and co-workers[13] to effect Pd-catalyzed silylation of allylic chlorides leading to allylic $SiCl_2$-Ph derivatives (Table 15). These labile products were converted to the diethoxysilanes with ethanol and Et_3N. The bidentate ligand dppf proved more effective than Ph_3P for this transformation. The substitution proceeded with predominant inversion of configuration in accord with a π-allylpalladium intermediate.

Table 15



[a] 82:18 (*E*):(*Z*). [b] 90:10 (*E*):(*Z*). [c] 85:15 trans:cis. [d] 59:41 cis:trans from a 79:21 trans:cis mixture of chlorides.

Crotyl chloride was converted to an α-methallylsilane of 61% ee through use of a chiral bidentate ferrocene ligand (eq 11). However, this product was the minor regioisomer of a 79:21 mixture.

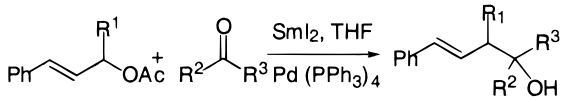


(11)

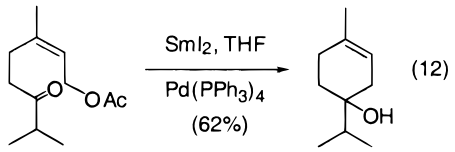
C. Allylic Samarium Halides

The use of SmI_2 in the transmetalation of π-allylpalladium intermediates was reported by Inanaga and co-workers.[14] When carried out in the presence of ketones or aldehydes with as little as 1 mol % of $Pd(PPh_3)_4$ as catalyst, the addition produced homoallylic alcohols in moderate to high yield from allylic acetates (Table 16). Aromatic or conjugated carbonyl substrates could not be employed owing to their facile reduction. An intramolecular application of the process led to terpinen-4-ol from neryl acetate (eq 12). The in situ reaction of the intermediate allylic samarium compounds with Bu_3SnCl has already been discussed (see eq 4 and Table 5).

Table 16



R^1	R^2	R^3	T, °C	t, h	yield, %
H	H	C_6H_{13}	0	2.5	63
H	$(CH_2)_5$		0	2.5	75
Me	$(CH_2)_5$		20	3	71
Me	Me	C_6H_{13}	20	3	84

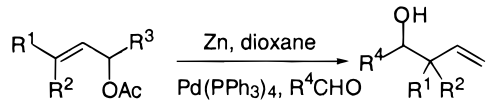


(12)

D. Allylic Zinc Reagents

The oxidative transmetalation of π-allylpalladium intermediates with zinc in dioxane was reported by Masuyama et al.[15] These transformations were carried out in the presence of aldehydes, leading to the formation of homoallylic alcohols from allylic acetates. The reactions were slow, requiring 4−6 days for completion, and with few exceptions, the adducts were formed in low to moderate yield with poor diastereoselectivity (Table 17). The process is thought

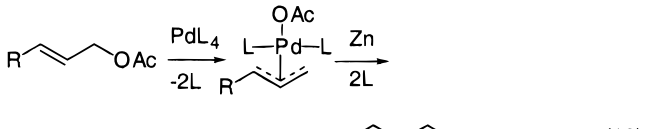
Table 17



R^1	R^2	R^3	R^4	t, d	yield, %	*syn*:*anti*
Me	H	H	Ph	4	71	55:45
H	H	Me	Ph	4	37[a]	53:47
Me	H	H	C_5H_{11}	5	51	58:42
Me	Me	H	Ph	4	99	–
Ph	H	H	Ph	5	70	13:87
H	H	Ph	Ph	5	57[b]	17:83
H	H	C_7H_{15}	C_5H_{11}	6	33[c]	58:42

[a] R^1 = Me, R^2 = H. [b] R^1 = Ph, R^2 = H. [c] R^1 = C_7H_{15}, R^2 = H.

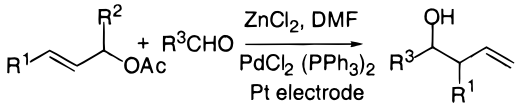
to involve an oxidative addition of Zn metal to the π-allylpalladium intermediate, most likely on the surface of the Zn (eq 13). Notably, an analogous reaction was not observed with Sn, $SnCl_2$, Mn, $CrCl_2$, or V. A Zn−Cu couple was also unreactive.



(13)

An analogous reaction was reported by Qui and Wang in which Zn metal was formed in situ by electrochemical reduction of $ZnCl_2$ on a divided cell fitted with Pt electrodes (Table 18).[16] It was initially

Table 18



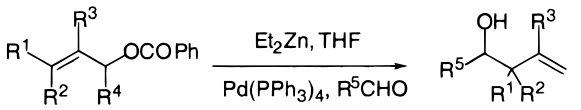
R^1	R^2	R^3	yield, %	*syn*:*anti*
H	H	Ph	77	
H	H	*p*-MeC_6H_4	84	
H	H	*p*-ClC_6H_4	68	
H	H	C_9H_{19}	79	
H	Me	Ph	62[a]	57:34
Me	H	Ph	56	57:34
Ph	H	Ph	71	69:31

[a] R^1 = Me in product.

proposed that electrochemical reduction of the π-allylpalladium intermediate leads to an allyl anion which then reacts with $ZnCl_2$ to form an allylic zinc halide. However, it was later found that $ZnCl_2$ is reduced to Zn(0) at the applied potential. Reduction of the $PdCl_2$ catalyst precursor also occurs in situ (eq 14).

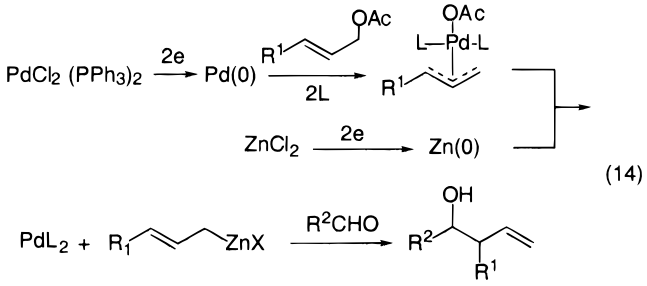
A significant improvement in the Pd(0)-catalyzed zincation was reported by Tamaru and co-workers, who found that Et_2Zn can serve as a source of zinc.[17,18] In situ allylations of aldehydes occur rapidly, and the homoallylic alcohol products are isolated in high yield (Table 19). However, diastereoselectivity is poor, at least in the case of crotylzinc and benzaldehyde. Interestingly, the reaction is most efficient

Table 19



R^1	R^2	R^3	R^4	R^5	Et_2Zn, eq	t, h	yield, %
H	H	H	H	Ph	1	3	88
Me	H	H	H	Ph	2	2	94[a]
H	H	H	Me	Ph	2	2	92[a,b]
H	H	Me	H	Ph	1	5	82
Me	Me	H	H	Ph	2	2	95
H	H	H	H	C_8H_{17}	2	6	89
H	H	H	H	PhCH=CH	2	4	97

[a] syn:anti = 30:70. [b] R^1 = Me, R^2 = R^3 = H in product.

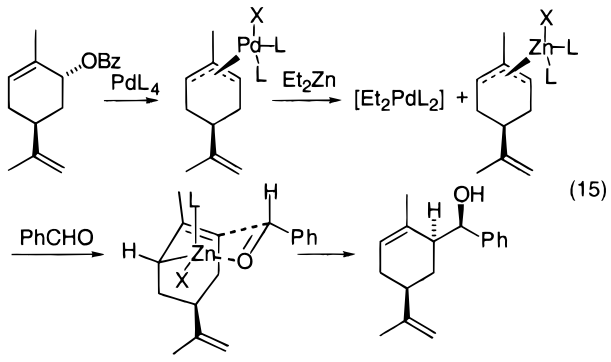


(14)

when allylic benzoates or phenyl ethers are employed. Acetates, carbonates, and bromides are less reactive.

In contrast to crotyl benzoate, cyclohexenyl and secondary acyclic allylic benzoates undergo the π-allylpalladium zincation and subsequent addition to benzaldehyde with high efficiency and diastereoselectivity (Table 20).[19] As expected, the transmetalation takes place with net anti displacement of the allylic substituent and subsequent syn addition to the aldehyde via a cyclic transition state.

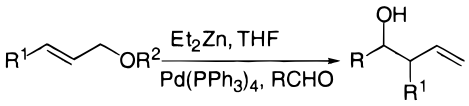
A likely pathway is shown in eq 15. Oxidative

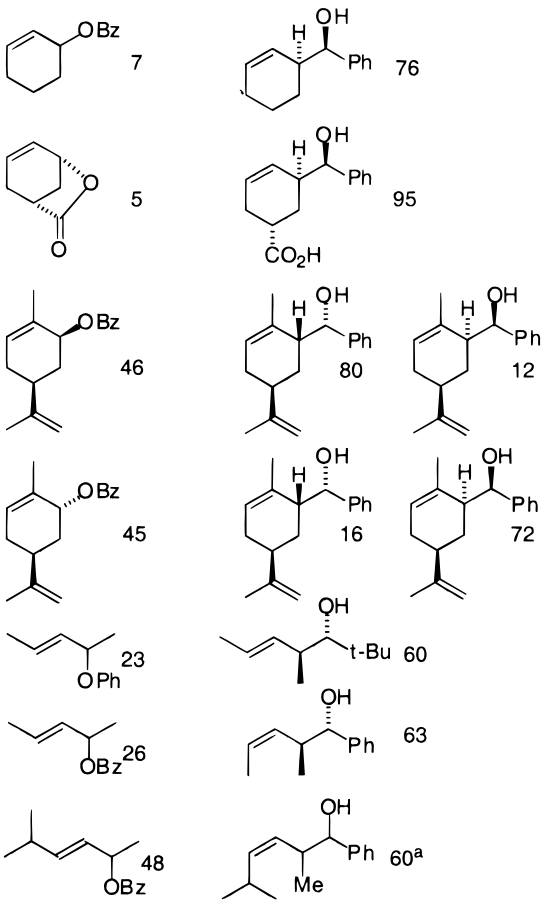


(15)

addition of the allylic benzoate affords a π-allylpalladium intermediate. Subsequent ligand transfer to Et_2Zn then yields the allylic zinc intermediate. Evidently the more typical alkyl addition−reductive elimination reaction sequence is unfavorable in this case. The presumed diethylpalladium intermediate undergoes β-hydride elimination and hydride transfer to generate ethylene, ethane, and the Pd(0) catalyst. It is also possible that butane is formed to some extent by reductive elimination of the putative

Table 20

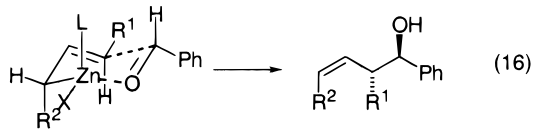




[a] anti:syn = 89:11.

Et_2Pd species. Other pathways can also be envisioned for the transmetalation whereby ethyl transfer from Et_2Zn to the Pd intermediate is followed by β-hydride elimination as illustrated in Figure 4.

The ensuing aldehyde addition occurs by a syn process involving a chairlike transition state. A similar sequence can be formulated for the acyclic allylic zinc additions (eq 16). In this case it is



assumed that the allylic substituent, R^2, adopts an axial orientation to minimize steric interactions with the ligands on zinc. The preferred formation of (*Z*)-double bonds in the homoallylic alcohol products is thereby accommodated.

An interesting crossover in the regioselectivity of additions involving an *o*-$Me_2NC_6H_4$-substituted allylic acetate was noted by Tamaru and co-workers.[20] They speculated that the Me_2N substituent might

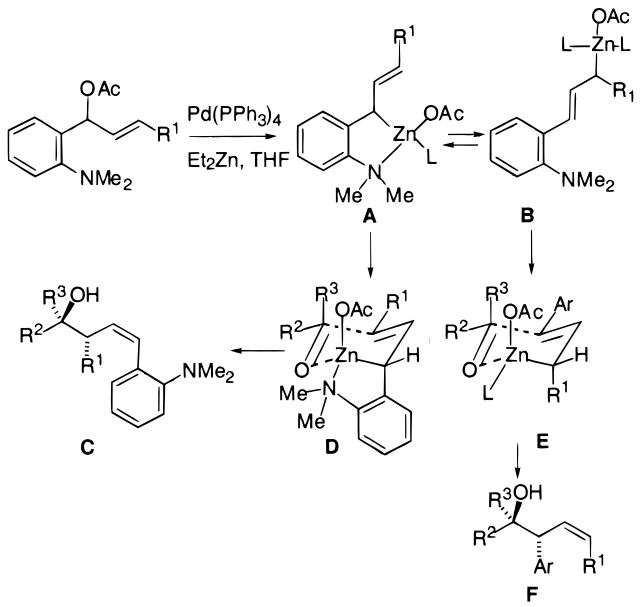
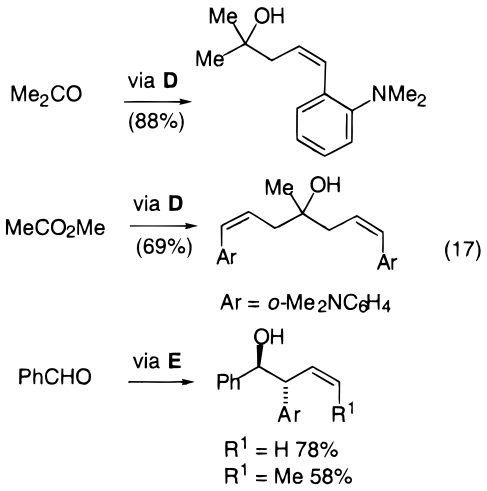


Figure 3. Pathways for regioselective formation of allylic zinc intermediates and ensuing addition to aldehydes.

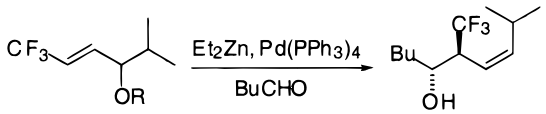
favor the chelated transition state **D** (Figure 3), thus leading to the formation of adducts such as **C**. In fact, this was the case in additions to acetone and methyl acetate (eq 17). However, benzaldehyde gave rise to



adducts **F** with the opposite regiochemistry via the proposed transition state **E**. They explain this divergent behavior in terms of carbonyl basicity. Accordingly, because of the lower Lewis acidity of complex **A** relative to **B**, aldehydes could not coordinate to the zinc effectively in transition state **D**. However, the greater carbonyl basicity of acetone and methyl acetate would allow these substrates to effectively bind to the zinc atom in this transition state, thereby affording adducts of type **C**.

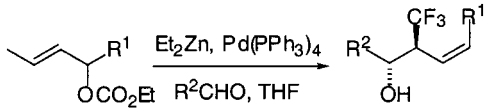
An application of these additions to fluorinated allylic esters was reported by Kitazume and coworkers.[21] They found that adducts were not formed in solvents such as CH_2Cl_2 or benzene (Table 21). In THF the additions proceeded comparably to the nonfluorinated counterparts. Additions to branched and unbranched aldehydes were highly diastereo-

Table 21



R	solvent	t, h	yield, %	*anti*:*syn*
COPh	THF	24	45	94:6
COPh	CH_2Cl_2	24	—	—
COPh	C_6H_6	24	—	—
CO_2Et	THF	20	66	97:3
Ms	THF	24	35	96:4

Table 22

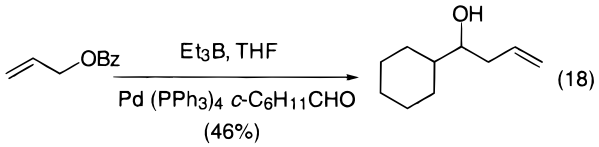


R^1	R^2	yield, %	*anti*:*syn*
i-Pr	*i*-Pr	46	95:5
i-Pr	*t*-Bu	—	—
i-Pr	Ph	83	> 99:1
Bu	Bu	46	> 99:1

selective favoring the anti adducts (Table 22). Interestingly, pivaldehyde failed to undergo the addition. This failure was attributed to unfavorable steric interactions between the aldehyde *tert*-butyl substituent and the CF_3 grouping of the allylic zinc reagent in the transition state (eq 16, *t*-Bu in place of Ph and $R^1 = CF_3$).

E. Allylic Boranes

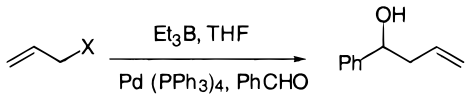
Applying the same concept, Tamaru and co-workers examined the reactions of π-allylpalladium intermediates and Et_3B in the presence of benzaldehyde (Table 23).[22] As with the zinc analogues, the allylborane intermediates were formed most efficiently with the benzoate, although phenyl and benzyl ethers also gave the addition product in reasonable yield, albeit more slowly. The bromide and chloride failed to react. Additions employing substituted allylic benzoates were relatively efficient but gave mixtures of syn and anti adducts favoring the latter by 1.5−2:1 (Table 24). Additions to aliphatic aldehydes, as exemplified by cyclohexanecarboxaldehyde, were somewhat less efficient (eq 18).



(18)

These transmetalations and ensuing additions are thought to proceed analogously to those involving Et_2Zn. The assumed ligand exchange involves a single ethyl group, leading to an ethyl palladium halide which undergoes β-hydride elimination and extrusion of HX to regenerate the Pd(0) catalyst (Figure 4). Though not detected in the zinc reactions, 1,5-dienes

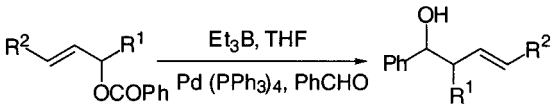
Table 23



X	t, h	yield, %
OCOPh	4	68
OPh	6	59
OBn	[a]	47
Cl	24	0
Br	38	0

[a] rt for 45 h, 50 °C for 17 h.

Table 24



R^1	R^2	yield, %	*anti*:*syn*
Ph	H	77	70:30
Me	H	60	65:35
$PhCH_2CH_2$	H	76	60:40
H	Ph	83 [a]	70:30
H	Me	64 [b]	73:27

[a] R^1 = Ph, R^2 = H in the product. [b] R^1 = Me, R^2 = H in the product.

were produced in the boron counterpart. These no doubt arise by allyl transfer from the intermediate allylic boranes to the π-allylpalladium precursor (eq 19).

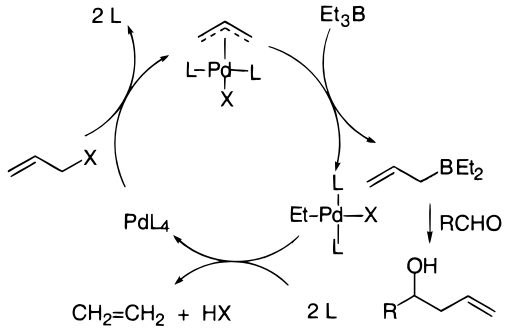
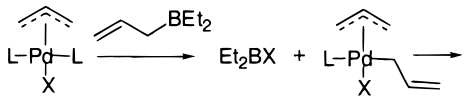


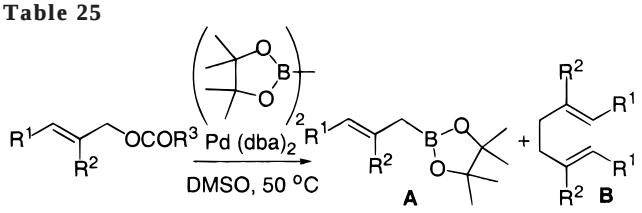
Figure 4. Catalytic cycle for palladium-catalyzed formation of allylboranes.



(19)

The synthesis of allylic boronates through transmetalation of π-allylpalladium acetates with bis(pinacolato)diborane was reported by Miyaura and co-workers (Table 25).[23] Of the various allylic esters examined, trifluoroacetates gave the best overall results, mainly because the 1,5-diene byproduct (**B**) was not formed. This byproduct is produced through coupling of the allylic boronate with its π-allylpalladium precursor along the lines of eq 19. Both *cis*- and *trans*-cinnamyl acetate yielded the *trans*-cinnamyl

Table 25



R^1	R^2	R^3	t, h	yield, % **A**	yield, % **B**
H	Ph	Me	16	89	10
H	Ph	CF_3	22	86	0
H	Ph	Ph	18	55	15
H	Ph	OMe	16	3	80
H	H	Me	16	68	[a]
H	Me	Me	16	70	[a]
Ph	H	Me	26	73	13
Ph [b]	H	Me	24	65	1

[a] Not determined. [b] *cis*-Cinnamyl acetate.

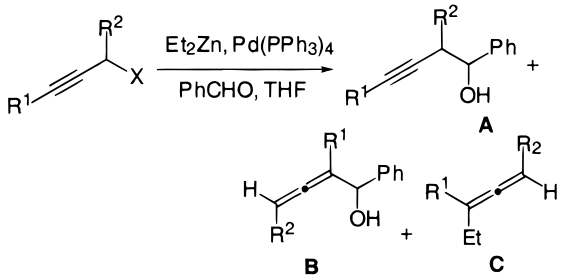
boronate. It would thus appear that equilibration of the π-allylpalladium intermediate precedes Pd−boron interchange.

III. Allenylmetal Reagents

A. Allenylzinc Reagents

Tamaru et. al. extended their studies on the transmetalation of π-allylpalladium intermediates with Et_2Zn to the corresponding allenyl/propargyl systems (Table 26).[24] Except for TMS, substituents

Table 26



R^1	R^2	X	**A**, %	**B**, %	**C**, %
H	H	OBz	57	—	—
H	Me	OBz	70 [a]	—	—
H	Me	OTs	55 [a]	—	—
H	Me	Br	88 [a]	—	—
H	Ph	OBz	79 [a]	—	20
Me	H	OBz	22	56	—
Ph	H	OBz	57	12	—
TMS	H	OBz	80	—	—

[a] Nearly 1:1 mixture of syn and anti products.

on the alkyne (R^1) caused mixtures of homopropargylic and allenic alcohols **A** and **B** to be produced (last three entries). In at least one case, reductive elimination of the presumed allenyl EtPd intermediate took place to afford the ethylated allene **C** as a minor product. Secondary propargylic esters and the bromide yielded only the propargylic adducts but with no stereocontrol. The adducts were isolated as 1:1 mixtures of syn and anti diastereomers.

Marshall and Adams adapted the Tamaru Et_2Zn transmetalation protocol to chiral propargylic mesylates.[25] They reasoned that the intermediate allenylpalladium species would be formed with inversion of configuration and the ensuing Pd−Zn transmetalation would occur with retention (Figure 5), by

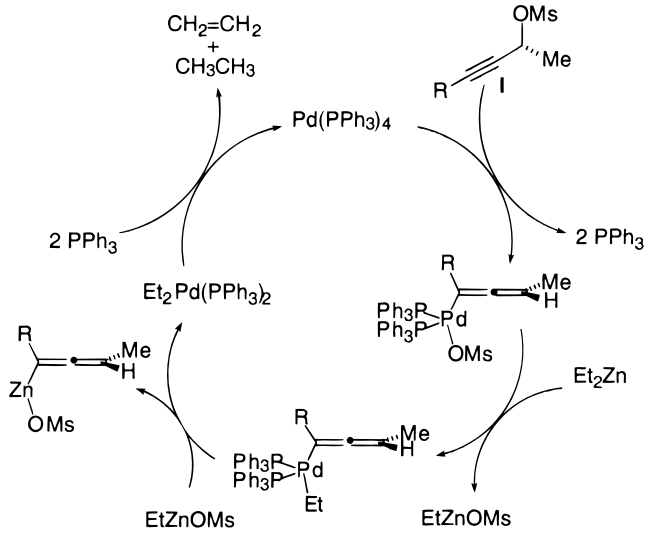
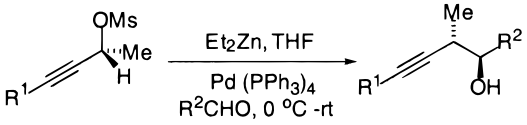


Figure 5. Catalytic cycle for the formation of chiral allenylzinc reagents.

analogy to their previous work on the alkoxycarbonylation of allenylpalladium species derived from enantioenriched propargylic mesylates.[26]

In fact, when the reaction was performed on mesylates of ~97% ee in the presence of various aliphatic aldehydes, homopropargylic alcohol adducts of 86−96% ee were isolated in moderate to high yield (Table 27). Diastereoselectivity was excellent with

Table 27

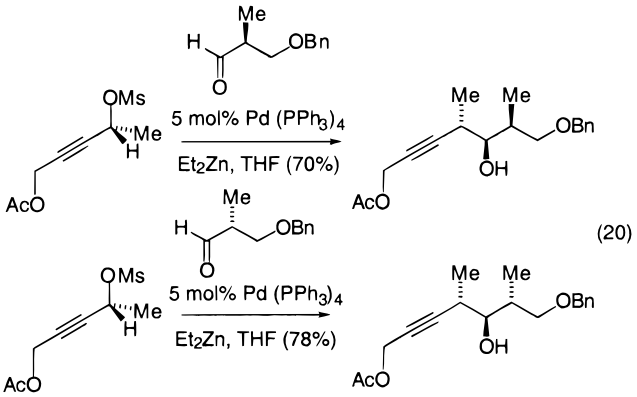


R^1	R^2	yield, %	*anti*:*syn*	ee
H	*c*-C_6H_{11}	85	95:5	95
H	C_6H_{13}	70	88:12	90
H	$TBSOCH_2CH_2$	56	86:14	86
H	(*E*)-BuCH=CH	71	77:23	88
H	1-octynyl	60	68:32	90
CH_2OAc	*c*-C_6H_{11}	51	95:5	96
CH_2OAc	C_6H_{13}	57	90:10	89
CH_2OAc	*i*-Pr	47	95:5	96

α-branched aldehydes. Unbranched and conjugated aldehydes yielded mixtures of diastereomers ranging from 3:1 to 7:1. In all cases the anti diastereomer was favored, as expected for a cyclic transition state.

Additions to prototype enantiomeric α-branched aldehydes afforded anti adducts with negligible

formation of diastereomers (eq 20). Thus, there

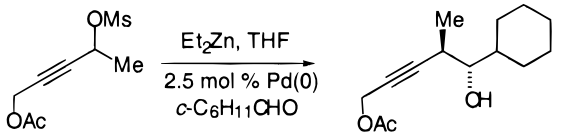


(20)

wouldappear to be little interaction between the chiral zinc reagent and the aldehyde substituent in the transition state, indicative of a reagent-controlled addition. The use of propargylic acetates or trifluoroacetates as the allenylzinc precursors gave no adduct with cyclohexanecarboxaldehyde. The methyl carbonate of 3-butyn-2-ol afforded an adduct of 29% ee in only 27% yield. These findings suggest that rapid catalyst turnover is essential to high enantioselectivity. It is known that allenylpalladium species racemize upon prolonged standing.[26] It is also possible that the allenylzinc reagent is susceptible to racemization.

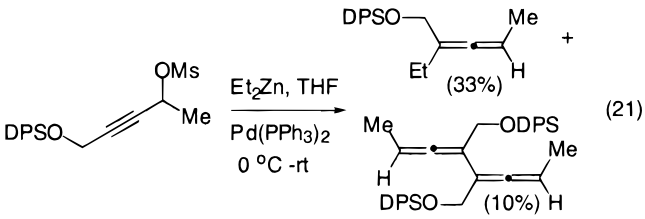
Subsequent studies of this methodology identified several superior catalyst precursor (Table 28).[27] The

Table 28



Pd(0)	t, h	T, °C	mesylate, eq.	conc, M	yield
$Pd(PPh_3)_4$	3	0	2	0.05	51
$PdCl_2(MeCN)_2$	2	0	1.5	0.05	dec
$PdCl_2(dppf)$	36	0 -rt	2	0.05	37
$Pd(OAc)_2$•PPh_3	12	-20	1.5	0.1	75
$PdCl_2(PPh_3)_2$	2	0	1.5	0.05	74
$Pd(OAc)_2(PPh_3)_2$	2	0 -rt	1.5	0.05	58

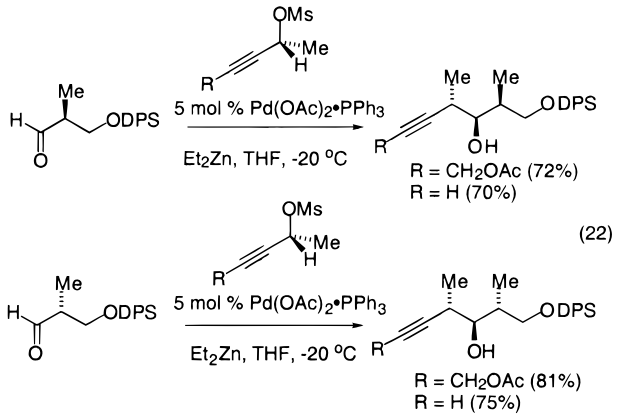
most effective precursor was found to be an equimolar mixture of $Pd(OAc)_2$ and Ph_3P. A 1:2 complex of $PdCl_2$ and Ph_3P was also effective. It was also established that small amounts of ethylated allene and allene dimer were produced (eq 21) and that ethyl addition to the aldehyde took place to some extent. These



(21)

byproducts could be minimized through proper choice of catalyst and by conducting the reaction at moderately high dilution without sacrifice in yield or selectivity.

Under optimized conditions the anti,syn and anti,-anti adducts of chiral α-methyl-β-ODPS aldehydes were produced in relatively high yield (eq 22). As



(22)

before, only traces of diastereomeric products could be detected in keeping with a reagent-controlled process.

A possible transition state for these additions is depicted in Figure 6. The high degree of reagent

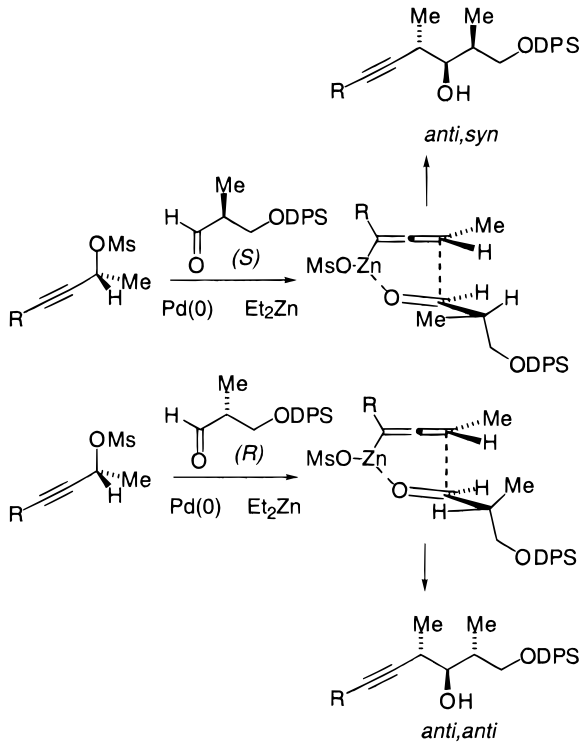


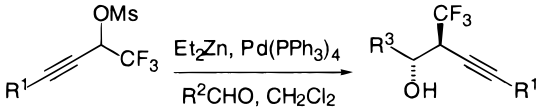
Figure 6. Transition states for additions of chiral allenylzinc reagents to chiral aldehydes.

control may be a consequence of an early transition state which minimizes interactions between the allenylzinc reagent and the aldehyde stereocenter. Alternatively, the attack angle on the aldehyde may be altered from the usual 110° because of constraints imposed by the presumed cyclic transition state. Such constraints would effectively minimize interactions (torsional strain) between the incoming

allenic reagent and aldehyde Me substituent in the "mismatched" transition state.

Analogous results were reported by Kitazume and co-workers for CF_3-substituted propargylic mesylates (Table 29).[21] These additions proceed with higher

Table 29



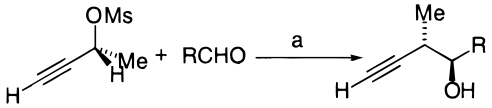
R^1	R^2	yield, %	*anti*:*syn*
CH_2OBn	Bu	76	91:9
CH_2OBn	*t*-Bu	60	> 99:1
CH_2OBn	Ph	55	87:13
Ph	Bu	56 [a]	93:7
Pr	Bu	33 [b]	93:7
t-Bu	Bu	70	95:5

anti:syn selectivity than the related CH_3 examples in Table 27. This difference may result from the greater steric requirements of a CF_3 substituent on the allenylzinc reagent.

B. Allenylindium Reagents

In a related study, Marshall and Grant showed that chiral allenylindium halides are formed from chiral propargylic mesylates through transmetalation of a transient allenylpalladium complex with InI.[28] In this case $PdCl_2$(dppf) or an equimolar mixture of $Pd(OAc)_2$ and PPh_3 were the catalyst precursors of choice. The indium reagents afford *anti*-homopropargylic alcohols when aldehydes are present in the reaction mixture (Table 30). No adducts were pro-

Table 30



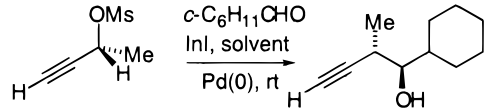
R	yield, %	*anti*:*syn*	ee, %
C_6H_{13}	73	82:18	96
$DPSOCH_2CH_2$	88	88:12	-
(*E*)-BuCH=CH	68	71:29	96
1-heptynyl	62	72:28	95
Ph	85	45:55	92

[a] 5 mol % $PdCl_2$(dppf), 1 equiv of InI, 3:1 THF−HMPA, rt.

duced when In powder was used in place of InI. It was also necessary to employ dipolar aprotic cosolvents (Table 31).

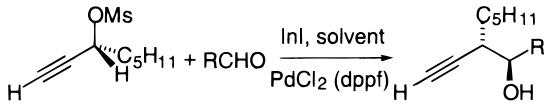
The diastereoselectivity of the addition was similar to that seen in the allenylzinc reactions. *anti*-Products were highly favored with α-branched aldehydes and less so with unbranched or conjugated aldehydes, but addition to benzaldehyde was nonselective (Table 32). However, the additions proceeded with virtually complete enantioselectivity. Additions to chiral α-methyl-*β*-ODPS aldehydes were strongly reagent controlled and proceeded in

Table 31



Pd(0) source	solvent	yield, %	*anti*:*syn*	ee, %
none	3:1 THF-HMPA	66	96:4	0
$PdCl_2$(dppf)	3:1 THF-HMPA	76	95:5	95
$PdCl_2$(dppf)	3:1 THF-DMPU	63	87:13	87
$PdCl_2$(dppf)	1:1 THF-DMPU	80	91:9	90
$PdCl_2$(dppf)	20:1 THF-DMPU	66	93:7	91
$Pd(OAc)_2$•PPh_3	3:1 THF-HMPA	75	95:5	91

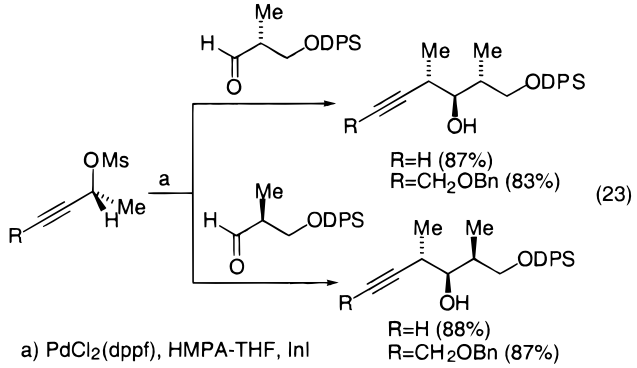
Table 32



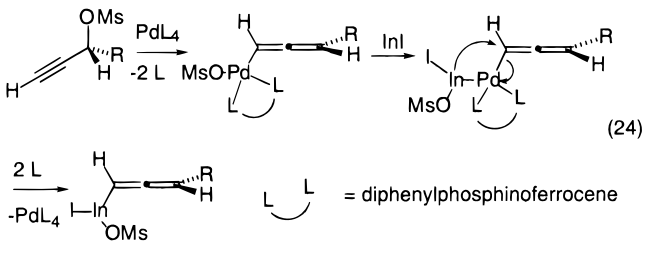
R	solvent	yield, %	*anti*:*syn*	ee, %
c-C_6H_{11}	3:1 THF-HMPA	74	97:3	86
c-C_6H_{11}	3:1 THF-HMPA	79 [a]	95:5	89
c-C_6H_{11}	1:1 THF-DMSO	73	95:5	89
C_6H_{13}	3:1 THF-HMPA	77	84:16	95
C_6H_{13}	1:1 THF-DMSO	83	86:14	96
i-Pr	3:1 THF-HMPA	74	94:6	93
i-Pr	1:1 THF-DMSO	64	96:4	95

[a] InI was prepared from In and I_2.

excellent yield (eq 23).



A possible reaction pathway can be formulated (eq 24) by analogy to that proposed for transmetalations with $SnCl_2$.[29] Accordingly, the allenylpalladium in-



termediate undergoes "nucleophilic" attack by InI to afford an intermediate which is converted to the allenylindium reagent through reductive elimination with regeneration of the catalyst. This net "red−ox" process is typical for organopalladium substitution reactions, although in many π-allyl examples the

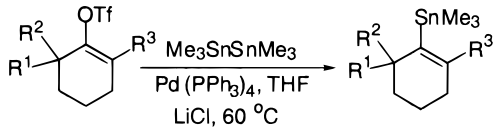
nucleophile attacks a carbon terminus rather than the palladium.

IV. Vinylmetal Reagents

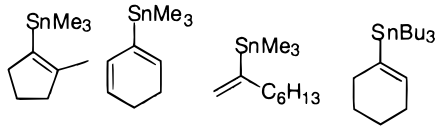
A. Vinylic Stannanes

Wulff and co-workers found that vinylic triflates undergo Pd(0)-catalyzed stannylation with hexamethylditin in THF (Table 33).[30] The use of hexabutylditin led to cyclohexenyltributyltin in only 22% yield after 12 h. Hexamethyldisilane failed to react, while trimethylsilyltrimethyltin afforded the 1-cyclohexenylsilane in 19% yield and the trimethylstannane in 12% yield. Presumably, an intermediate vinylpalladium chloride is converted to trimethyltin chloride and a trimethylstannylpalladium species which undergoes reductive elimination to the vinylstannane (eq 25).[31] Silyl transfer from the Si−Sn reagent leads to the vinylic silane and trimethylstannyl chloride.

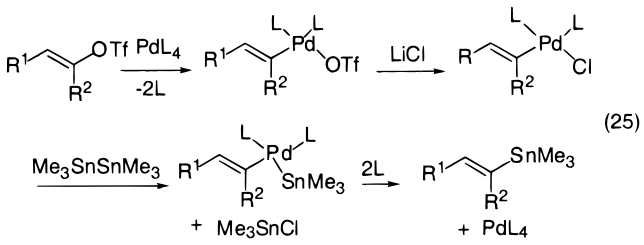
Table 33



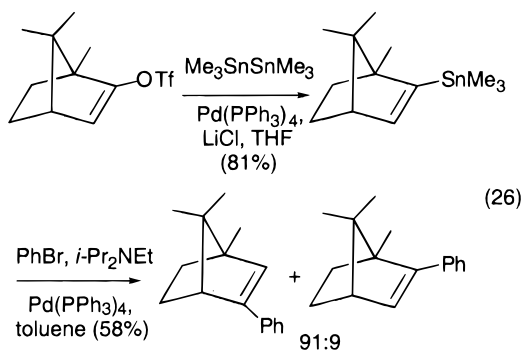
R^1	R^2	R^3	t, h	yield, %
H	H	H	3	81
Me	H	H	9	84
H	H	Me	168	80
Me	H	Me	120	62
Me	Me	Me	240	39



96 h, 80% 4 h, 72% 6 h, 74% 12 h, 22%

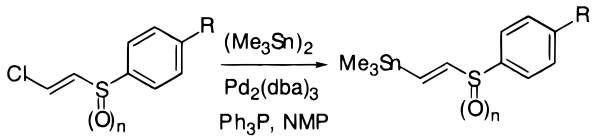


The stannylation reaction was employed by Stork et al. to prepare a bicyclic vinylic stannane from the enol triflate of camphor (eq 26).[32] Interestingly, this stannane afforded the expected Stille coupling product with bromobenzene as the minor constituent of a 91:9 mixture. The isomeric Heck-type insertion product was heavily favored, possibly for steric reasons.

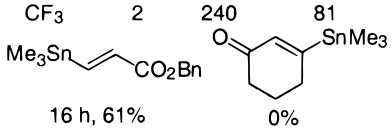


Farina and Hauck employed palladium-catalyzed stannylation to prepare a number of β-stannylated vinylsulfoxides and sulfones from the corresponding chlorides (Table 34).[33] Benzyl β-chloroacrylate could also be stannylated by this procedure, but β-chlorocyclohexenone failed to react. Both hexabutylditin and hexamethyldisilane also failed to give substitution products with the vinylic sulfoxides or sulfones.

Table 34

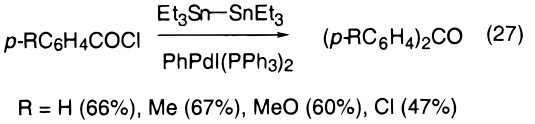


R	n	t, min	yield, %
NO_2	1	40	72
NO_2	2	85	47
H	1	240	78
H	2	90	60
CF_3	1	240	84
CF_3	2	240	81

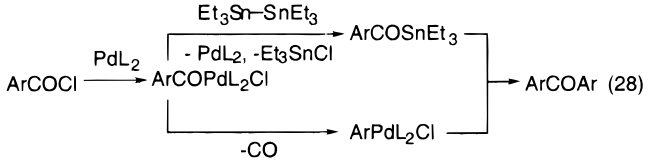


16 h, 61% 0%

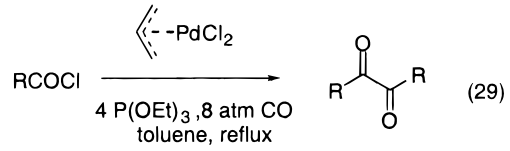
Bumagin and co-workers employed acid chlorides and $Et_3SnSnEt_3$ to prepare symmetrical diaryl ketones (eq 27).[34] The reaction is presumed to involve an initial acylpalladium species which reacts with the distannane to afford an intermediate acylstannane (eq 28). Competitive decarbonylation of the acylpalladium intermediate gives rise to an arylpalladium intermediate which then reacts with the aforementioned acylstannane to yield the ketone product.



R = H (66%), Me (67%), MeO (60%), Cl (47%)



When the reaction is conducted under 8 atm of CO pressure, the decarbonylation process is inhibited and coupling of the acylstannane and acylpalladium intermediates produces symmetrical α-diketones (eq 29). The optimal catalyst precursor for this conversion was found to be π-allylpalladium dichloride with triethyl phosphite as ligand.



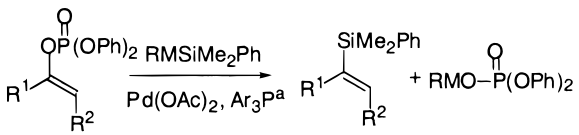
(29)

R = *p*-MeOC$_6$H$_4$ (76%), *p*-MeOC$_6$H$_4$ (73%), C$_6$H$_5$ (70%), *p*-ClC$_6$H$_4$ (63%), 2-furyl (41%), C$_7$H$_{15}$ (78%)

B. Vinylic Silanes

Vinylic silanes were prepared by Oshima and co-workers through Pd(0)-catalyzed coupling of vinylic phosphates with Et_2Al- or $MeMgSiMe_2Ph$ in hexane or THF (Table 35).[35] The substitution proceeds with

Table 35



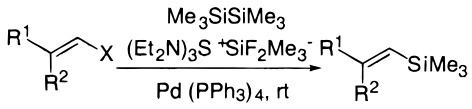
R^1	R^2	RM	solvent	t, h	yield, %
C_6H_{13}	H	Et_2Al	hexane	1.5	55
C_6H_{13}	H	MeMg	THF	1.0	75
$PhCH_2CH_2$	H	MeMg	THF	1.0	56
Me	Et	MeMg	THF	3.0	65
Pr	Bu	Et_2Al	hexane	3.0	74
Pr	Bu	MeMg	THF	1.5	72
Me [b]	Et	MeMg	THF	—	73
Me [c]	Et	MeMg	THF	—	72

[a] Ar = *o*-MeC$_6$H$_4$. [b] (*Z*)-isomer, $PdCl_2(PPh_3)_2$ catalyst. [c] (*E*)-isomer, $PdCl_2(PPh_3)_2$ catalyst.

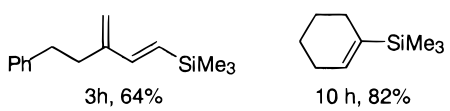
retention of double-bond stereochemistry (Table 35, last two entries). The more nucleophilic silylmetal reagent, $LiSiMe_2Ph$, caused cleavage of the enol phosphate and led to recovered ketone upon workup of the reaction.

Hiyama and Hatanaka found that vinylic halides could be silylated with hexamethyldisilane if the reaction was conducted in the presence of tris-(diethylamino)sulfonium difluoro(trimethyl)silicate (TASF) (Table 36).[36] Aryl halides could also be

Table 36



R^1	R^2	X	t, h	yield, %
Ph	H	I	2	82
Ph	H	Br	10	32
H	Ph	I	15	84
C_6H_{13}	H	I	5	74
$(CH_2)_8CO_2Me$	H	I	3	92
$(CH_2)_9CN$	H	I	4	53

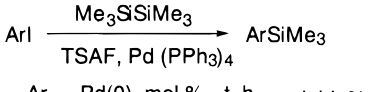


3h, 64%

10 h, 82%

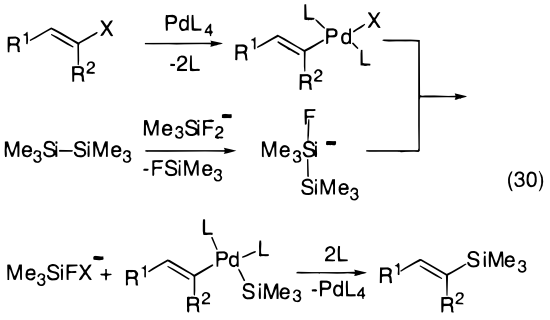
converted to arylsilanes (Table 37). The reaction presumably involves fluoride activation of the disilane, which initiates silyl transfer to the vinylic palladium intermediate (eq 30). Ensuing reductive-

Table 37



Ar	Pd(0), mol %	t, h	yield, %
p-MeC_6H_4	5	15	20
p-MeC_6H_4	20	15	100
1-naphthyl	20	5	100
Ph	5	48	32

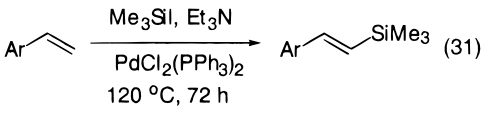
TSAF = $(Et_2N)_3S^+SiF_2Me_3^-$



(30)

elimination affords the vinylic silane and regenerates the Pd(0) catalyst.

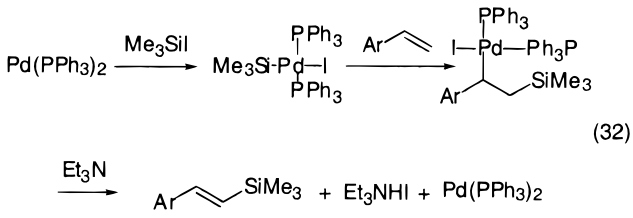
Tanaka and co-workers synthesized β-silylstyrenes through Pd(0)-catalyzed silylation of styrenes with Me_3SiI in the presence of Et_3N (eq 31).[37] They



(31)

Ar = Ph (54%), *p*-ClC$_6$H$_4$ (44%), *p*-MeC$_6$H$_4$ (45%)

proposed a Heck-type pathway in which oxidative addition of the Pd(0) catalyst to Me_3SiI generates an electrophilic silylpalladium intermediate which adds to the styrene double bond (eq 32). Subsequent



(32)

β-hydride elimination leads to the observed product, possibly via a hydridopalladium intermediate.

V. Arylmetal Reagents

A. Arylstannanes

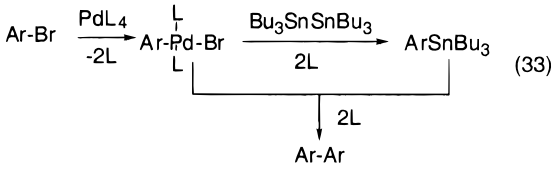
As might be expected by analogy to vinyl halides, the tributylstannylation of aryl halides is relatively difficult. However, by employing elevated temperatures, Kosugi et al. prepared a series of aryltributylstannanes from aryl bromides and $Bu_3SnSnBu_3$ in the presence of 1 mol % $Pd(PPh_3)_4$ (Table 38).[38] Biaryl coupling products were also formed with *m*- and *p*-

Table 38

$$RC_6H_4Br \xrightarrow[\text{toluene, 80 °C}]{Bu_3Sn\,SnBu_3,\ Pd(PPh_3)_4} ArSnBu_3 + Bu_3SnBr + ArAr$$

R	$ArSnBu_3$, %	ArAr, %	$Bu_3SnSnBu_3$, eq
p-NO_2	38	13	1.2
m-NO_2	23	11	1.2
o-NO_2	59	0	1.2
p-CN	22	16	1.2
m-CN	31	18	1.2
o-CN	42	0	1.2
p-MeCO	21	14	1.2
o-MeCO	25	0	1.2
H	58	11	1.1
H	85	4	3.0
H	89	1	8.0

but not *o*-substituted bromides. These byproducts could be minimized through use of a large excess of the distannane in keeping with the proposition that the arylstannane product and the distannane undergo competitive reaction with the intermediate arylpalladium halide (eq 33).



(33)

A more extensive investigation of this stannylation was conducted by Eaborn and co-workers and, independently, by the Bumagin group in Moscow (Table 39).[39] Their studies were conducted at higher tem-

Table 39

$$RC_6H_4X + Bu_3SnSnBu_3 \xrightarrow[\text{toluene}\ 115\ ^oC]{\text{cat}} ArSnBu_3 + Bu_3SnX + ArAr$$

R	X	cat	$ArSnBu_3$, %	ArAr, %
H	I	$PdBr_2(PPh_3)_2$	94	2
H	I	$Pd(PPh_3)_4$	96	3.5
H	Br	$PdBr_2(PPh_3)_2$	75	6
H	Br	$Pd(PPh_3)_4$	79	8
H	Cl	$Pd(PPh_3)_4$	0	0
p-MeO	Br	$Pd(PPh_3)_4$	81	trace
p-Me	Br	$PdBr_2(PPh_3)_2$	81	1.5
o-Me	Br	$Pd(PPh_3)_4$	64	trace
p-CN	Br	$PdBr_2(PPh_3)_2$	57	trace

perature with a 2-fold excess of $Bu_3SnSnBu_3$ and ca. 1 mol % of catalyst. The more easily prepared $PdBr_2(PPh_3)_2$ was found to give comparable results to $Pd(PPh_3)_4$ in these substitution reactions. Both aryl bromides and iodides were suitable substrates but chlorides proved unreactive. Not surprisingly, aryl trimethylstannanes could likewise be prepared (Table 40). Unlike the comparable stannylation of vinylic halides, yields of the aryltrimethylstannanes were not significantly higher than those of the butyl analogues. Subsequently, the Bumagin group con-

Table 40

$$RC_6H_4X + Me_3SnSnMe_3 \xrightarrow[\text{toluene}\ 115\ ^oC]{\text{cat}} ArSnMe_3 + Me_3SnX$$

R	X	cat	yield, %
H	I	$PdBr_2(PPh_3)_2$	96
p-Me	I	$PdBr_2(PPh_3)_2$	86
p-MeO	I	$Pd(PPh_3)_4$	96
p-Cl	I	$Pd(PPh_3)_4$	74
p-Me_2N	Br	$Pd(PPh_3)_4$	0
p-CN	Br	$Pd(PPh_3)_4$	64
p-NO_2	Br	$Pd(PPh_3)_4$	37

ducted couplings catalyzed by a "ligandless" Pd catalyst, $Pd(MeCN)_2Cl_2$, and hexamethylditin (eq 34).[40]

$$p\text{-}RC_6H_4I \xrightarrow[Pd(MeCN)_2Cl_2,\ DMF\ (84\text{-}100\%)]{Me_3Sn\text{—}SnMe_3} p\text{-}RC_6H_4SnMe_3 + Me_3SnI \quad (34)$$

R = MeO, MeO_2C, MeCO, CN, NO_2

Benzylic halides were also found to undergo stannylation by the Eaborn group (Table 41). In this case,

Table 41

$$R^1C_6H_4CH_2X + R_3SnSnR_3 \xrightarrow[\text{toluene},\ 115\ ^oC]{\text{cat}} R^1C_6H_4CH_2SnR_3 + R_3SnX$$

R^1	X	R	cat	yield, %
H	Br	Bu	$Pd(PPh_3)_4$	76
H	Cl	Bu	$Pd(PPh_3)_4$	90
m-MeO	Cl	Bu	$Pd(PPh_3)_4$	87
p-MeO	Cl	Bu	$Pd(PPh_3)_4$	35
m-CN	Br	Bu	$PdBr_2(PPh_3)_2$	56
m-Cl	Br	Bu	$PdBr_2(PPh_3)_2$	51
m-NO_2	Br	Bu	$PdBr_2(PPh_3)_2$	30
m-Cl	Br	Me	$Pd(PPh_3)_4$	65
m-CN	Br	Me	$Pd(PPh_3)_4$	95
p-CN	Br	Me	$Pd(PPh_3)_4$	96

benzylic chlorides proved effective as well as the bromides. A catalytic cycle is depicted in Figure 7.

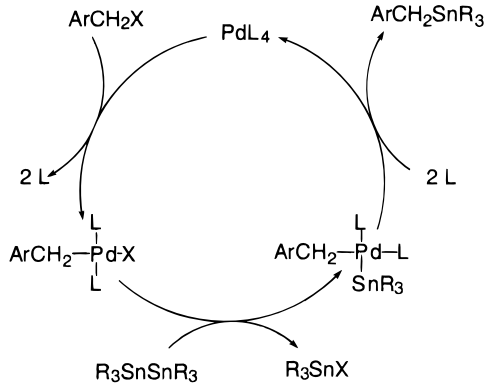


Figure 7. Catalytic cycle for the palladium-catalyzed conversion of benzylic halides to benzylic stannanes by distannanes.

When the mixed reagent $Bu_3SnSiMe_3$ was employed with aryl bromides, the products of silyl

transfer were formed (eq 35). Arylstannanes could not be detected.

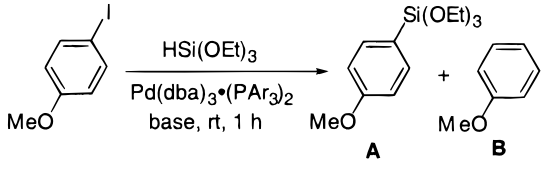
$$RC_6H_4X + Bu_3SnSiMe_3 \xrightarrow[\text{toluene}]{Pd(PPh_3)_4} RC_6H_4SiMe_3 + Bu_3SnBr \quad (35)$$

R=*p*-Me (60%), *p*-Cl (34%), *p*-MeO (50%)

B. Arylsilanes

The possibility of direct silyl transfer to an arylpalladium intermediate was investigated by Masuda and co-workers.[41] The reaction could be achieved with triethoxysilane and $Pd_2(dba)_3$ in the presence of 2 equiv of tris(*o*-tolyl)phosphine as the ligand and a base such as Et_3N or KOAc in a dipolar aprotic solvent (Table 42). Hunig's base, *i*-Pr_2NEt, could also

Table 42

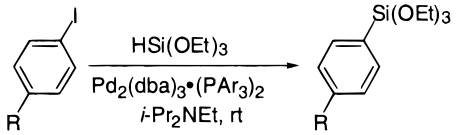


Ar	base	solvent	yield, % **A**	yield, % **B**
o-MeC_6H_4	Et_3N	NMP [a]	88	6
o-MeC_6H_4	*i*-Pr_2NEt	NMP	92	7
o-MeC_6H_4	pyridine	NMP	4	5
o-MeC_6H_4	KOAc	NMP	72	23
o-MeC_6H_4	*i*-Pr_2NEt	DMF	82	17
o-MeC_6H_4	*i*-Pr_2NEt	DMSO	31	19
C_6H_5	*i*-Pr_2NEt	NMP	76	19

[a] *N*-methylpyrrolidone.

be used, but pyridine was not suitable. DMSO was also less effective than NMP (*N*-methylpyrrolidone) or DMF as solvent. Aryl iodides were significantly more reactive than bromides, and the reaction was faster with electron-donating para substituents (Table 43). Electron-withdrawing groups facilitated hydride

Table 43



R	t, h	yield, %
H	1	83
NMe_2	1	81
OAc	1	77
Me	1	82
Cl	4	72
CO_2Et	16	23
CN	16	20

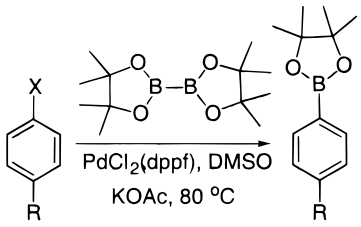
[a] Ar = *o*-MeC_6H_4.

transfer from the silane to produce hydrogenolysis products.

C. Arylboronates

The use of bis(pinacolato)diborane to prepare arylboronates from transient arylpalladium intermediates was the subject of ongoing studies by Miyaura and co-workers.[42] Both bromides and iodides were suitable substrates for reactions employing $PdCl_2$-(dppf) as the catalyst in DMSO with KOAc as an additive at 80 °C (Table 44). The reaction proceeded

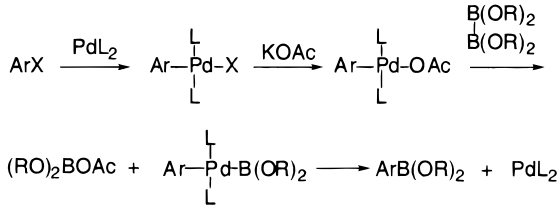
Table 44



X	R	t, h	yield, %
Br	H	2	98
I	NMe_2	6	90
I	OMe	2	82
Br	OMe	24	69
Br	CO_2Me	1	86
Br	CN	1	76
Br	NO_2	2	86
I	Br	1	86

with both electron-donating or electron-withdrawing para substituents. Catalysis by $Pd(PPh_3)_4$ was less effective, and catalysts such as $Ni(PPh_3)_4$, $Pt(PPh_3)_4$, and $RhCl(PPh_3)_3$ gave no product at all.

The KOAc additive was shown to activate the arylpalladium intermediate without promoting cross coupling the boronate product with (eq 36). In

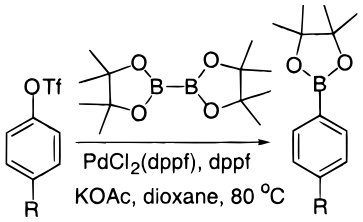


(36)

contrast, significant cross-coupling products were formed with added K_3PO_4 or K_2CO_3. The presence of an arylpalladium acetate intermediate was confirmed through independent synthesis and by ^{31}P and ^{13}C NMR and infrared spectroscopic analysis of the reaction in progress. Aryl iodides were more reactive than bromides, and electron-donating para substituents were found to be rate retarding. The reaction was accelerated by polar solvents such as DMSO and DMF. Dioxane and toluene were not useful as solvents.

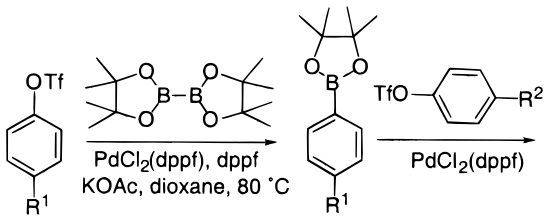
The Miyaura group also found that the boronate transmetalation could be carried out on aryl triflates (Table 45).[43] However, reaction conditions identical to those previously optimized for the halides afforded relatively low yields of product. In these cases, dioxane was the best solvent and an additional equivalent of the dppf ligand was required. Even so, the reaction was slower than the comparable substitution on the corresponding aryl bromides or iodides. It was possible to cross-couple two different aryl triflates by adding a second triflate and fresh catalyst after completion of the initial boronate transfer (eq

Table 45



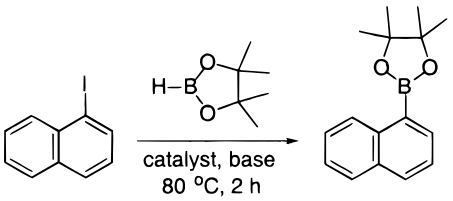
R	t, h	yield, %
NO_2	6	86
CN	15	75
CHO	6	92
CO_2Me	21	80
OMe	13	93
SMe	24	81

37). In this way, unsymmetrical biphenyls could be prepared in high yield.



Masuda and co-workers discovered that pinacol areneboronates could also be obtained by transmetalation of arylpalladium intermediates with pinacol boron hydride, thus obviating the need for the related, but less readily available, pinacolato diborane.[44] The conditions were optimized with 1-iodonaphthalene as the aryl component (Table 46).

Table 46



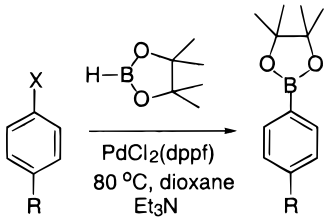
catalyst	base	solvent	yield, % [a]
$PdCl_2(dppf)$	Et_3N	dioxane	89
$PdCl_2(dppf)$	*i*-Pr_2NEt	dioxane	64
$PdCl_2(dppf)$	pyridine	dioxane	12
$PdCl_2(PPh_3)_2$	Et_3N	dioxane	75
$Pd(PPh_3)_4$	Et_3N	dioxane	10
$PdCl_2(dppf)$	Et_3N	toluene	79
$PdCl_2(dppf)$	Et_3N	$ClCH_2CH_2Cl$	81
$PdCl_2(dppf)$	Et_3N	CH_3CN	83

[a] In each case varying amounts of naphthalene were formed as a byproduct.

Both $PdCl_2(dppf)$ and $PdCl_2(PPh_3)_2$ were suitable catalyst precursors and were markedly superior to $Pd(PPh_3)_4$. Elevated temperatures were required, but the reaction was relatively insensitive to solvent.

The borylation was tolerant of a variety of aryl substituents; both electron-donating and electron-withdrawing groups were accommodated (Table 47).

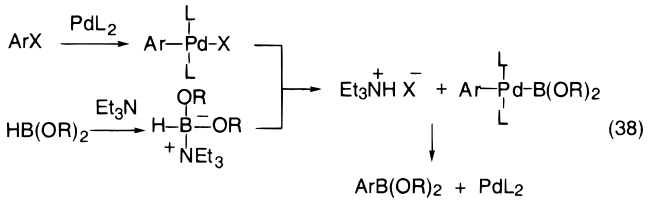
Table 47



X	R	t, h	yield, %
I	OMe	1	77
Br	OMe	3	77
OTf	OMe	4	81
I	Me	1	79
I	H	2	84
Br	H	6	67
OTf	H	4	93
I	Cl	3	83
I	CO_2Et	2	79
I	CN	4	73
I	NO_2	4	84

While iodides were most reactive, bromides and triflates could be used with extended reaction times.

The proposed reaction pathway initiates by oxidative addition of the Pd(0) catalyst to the aryl derivative ArX and subsequent ligand exchange with a complex of the tertiary amine and the dialkoxyborane (eq 38). Reductive elimination of the resulting pal-



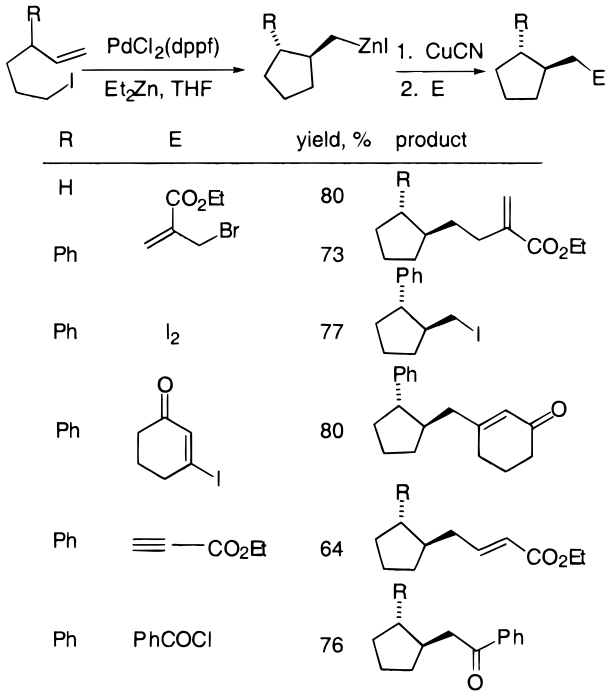
ladium complex leads to the product with regeneration of the catalyst. The alternative pathway involving oxidative addition of the Pd(0) catalyst to the B−H bond of the boronpinacolate was excluded by the failure to detect a signal for a $H-Pd-B(OR)_2$ species in the ^1H NMR spectrum of a mixture of $Pd(PPh_3)_4$ and the pinacolato boron hydride. Presumably the bulky amine, *i*-Pr_2NEt, is less effective than Et_3N for steric reasons while pyridine is not sufficiently basic to generate a highly nucleophilic boronate intermediate.

VI. Alkylzinc Intermediates

A. Alkylzinc Halides

Knochel et al. employed Et_2Zn to capture a carbopalladation intermediate originating from 6-iodo-1-hexene or the 3-phenyl derivative (Table 48).[45] The organozinc iodide intermediate was transmetalated with CuCN to afford a cyanocuprate, which under-

Table 48



went reaction with various electrophiles to yield the final product. This multistep transformation proceeds with high overall efficiency and is tolerant of various functional groups in the electrophile and the organozinc intermediate. A possible catalytic cycle is depicted in Figure 8.

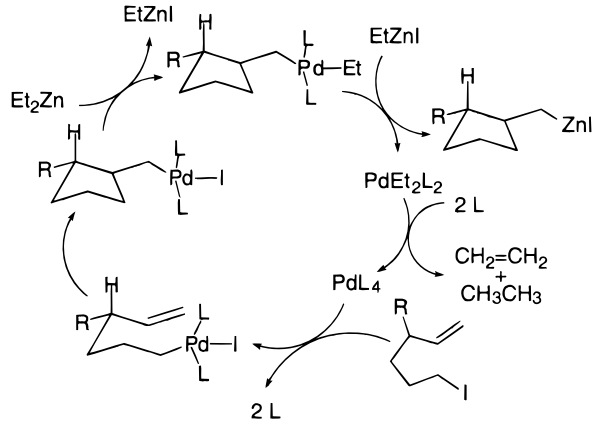
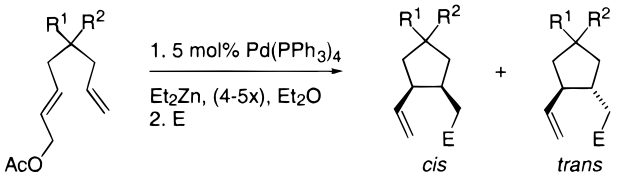


Figure 8. Catalytic cycle for the formation of alkylzinc iodides from 6-haloalkenes via alkylpalladium intermediates.

B. Zinc–Ene Reaction

A related synthesis of alkylzinc compounds was reported by Oppolzer and co-workers.[46] In this case, a π-allylpalladium intermediate gives rise to an allylzinc species which then effects an intramolecular zinc−ene reaction to afford a *cis*-1-vinyl-2-(methylenozinc)cyclopentane intermediate as the predominant cyclization product (Table 49). Subsequent protonolysis, iodination, or cyanation led to the respective substitution products. Vinylpyrrolidenes could also be prepared by this methodology (Table 50). A further application employing silylalkynes as the ene partner was also examined (Table 51).

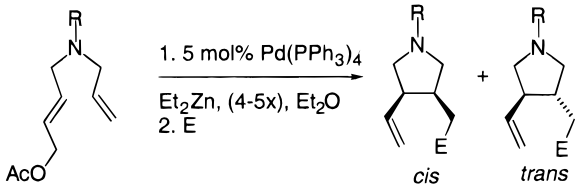
Table 49



R^1	R^2	E	yield, %[a]	cis:trans
SO_2Ph	SO_2Ph	H[b]	79	86:14
o-$(SO_2)_2C_6H_4$		H[b]	45	92:8
CO_2Et	CO_2Et	H[b]	83	----
SO_2Ph	SO_2Ph	I[c]	62	83:17
o-$(SO_2)_2C_6H_4$		I[c]	87	> 98:2
SO_2Ph	SO_2Ph	CN[d]	58	83:17

[a] Percent yield of the cis product after purification. [b] The reaction was quenched with aq. NH_4Cl. [c] The reaction was quenched with I_2. [d] $Li_2Cu(CN)Cl_2$ was added to the reaction mixture followed by TsCN.

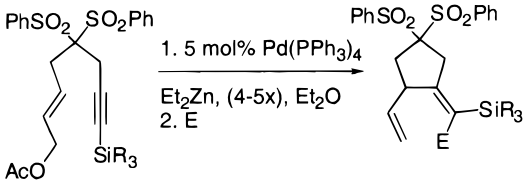
Table 50



R	E	yield, %[a]	cis:trans
CPh_3	H[b]	79	98:2
Ts	H[b]	44	96:4
Ts	I[c]	51	96:4

[a] Percent yield of the cis product after purification. [b] The reaction was quenched with aq. NH_4Cl. [c] The reaction was quenched with I_2.

Table 51



R	E	yield, %[a]
Me	H[a]	87
Et	H[a]	88
Me	I[b]	55
i-Pr	I[b]	81

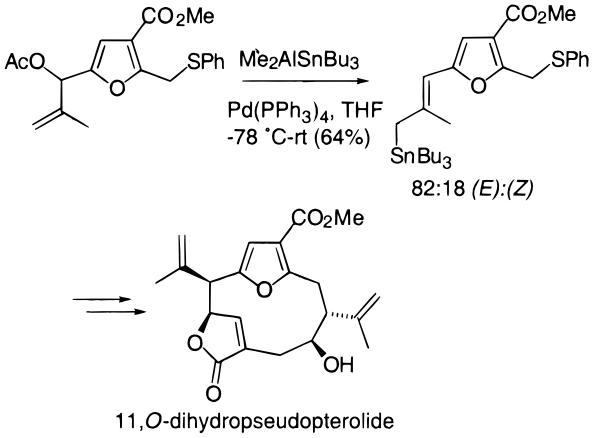
[a] The reaction was quenched with aq. NH_4Cl. [b] The reaction was quenched with I_2.

VII. Miscellaneous Applications

A. Allylstannane Couplings

Paquette and co-workers utilized the Trost protocol to prepare a furanyl allylic stannane in their synthesis of a derivative of the marine natural product pseudopterolide (Scheme 1).[47] This methodology was particularly applicable because of the presence of an ester grouping in the starting material which would render conventional approaches to this intermediate through use of organolithium reagents problematic.

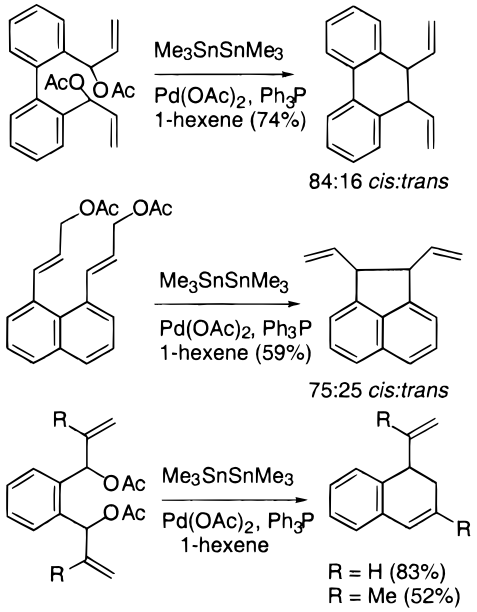
Scheme 1



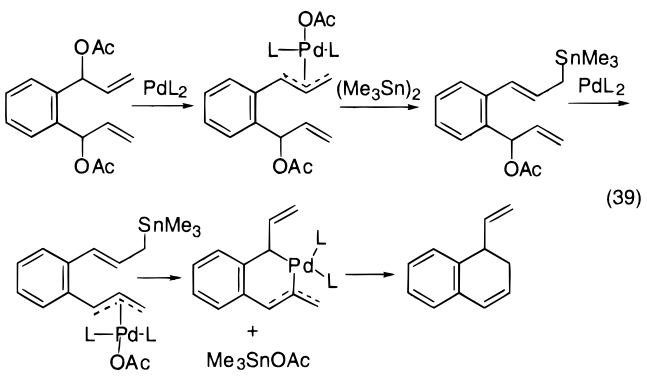
In addition, the instability of furan-substituted alkyl halides would have further complicated this transformation.

Trost and Pietrusiewicz employed allylic palladium stannylation methodology to prepare a number of fused-ring compounds through cyclization of bis-allylic acetates (Scheme 2).[48] They recognized that

Scheme 2



an initially formed allylic stannane would expectedly couple with a proximate π-allylpalladium intermediate to form a five- or six-membered ring (eq 39). By



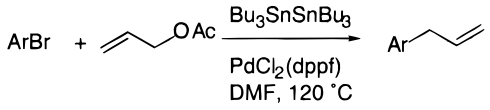
(39)

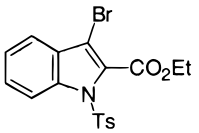
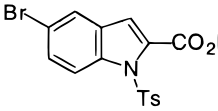
this sequence, one of the allylic acetates is transformed to the nucleophile, an allylic stannane, and the second becomes the more typical π-allylpalladium electrophile.

B. Arylstannane Couplings

The Pd(0)-catalyzed coupling of aryl bromides and allyl acetate was studied by Murakami and co-workers (Scheme 3).[49] The reaction was most

Scheme 3



ArBr	t, h	yield, %
	1.0	88
	0.5	49
p-$BrC_6H_4CONH_2$	0.5	86
p-BrC_6H_4COPh	0.5	86
p-BrC_6H_4NHAc	0.5	69

efficient when the bidentate catalyst precursor $PdCl_2$(dppf) was employed with a 50% excess of $Bu_3SnSnBu_3$ and allyl acetate. Two pathways are possible. The first entails formation of the allylic stannane which then couples to an arylpalladium intermediate with regeneration of the catalyst. Alternatively, an initially formed arylstannane could couple with a π-allylpalladium acetate, also with regeneration of the catalyst. Both processes were shown to be feasible by sequential addition of the reacting partners to the catalyst. Thus, addition of aryl halide to the catalyst followed by the allylic stannane or addition of allyl acetate to the catalyst followed by the arylstannane afforded the same coupling product. However, the yield of this product was higher when the coupling was performed on the allylic acetate and aryl bromide, as depicted in Scheme 3.

Trost and Walchli formulated an intramolecular application of this coupling reaction to prepare a number of fused-ring carbocyclic and heterocyclic compounds (Scheme 4).[50] They utilized $Et_2AlSnBu_3$ as the in situ precursor of the stannane and $Pd_2(dba)_3 \cdot CHCl_3$ as the catalyst precursor. Both aryl and vinyl bromides underwent these cyclization reactions.

An interesting intramolecular application of the stannylation/aryl halide coupling reaction to yield dihydrophenanthrenes was reported by Kelly et al. (Table 52).[51] These reactions could be carried out with aryl triflates as well as bromides or iodides. It is

Scheme 4

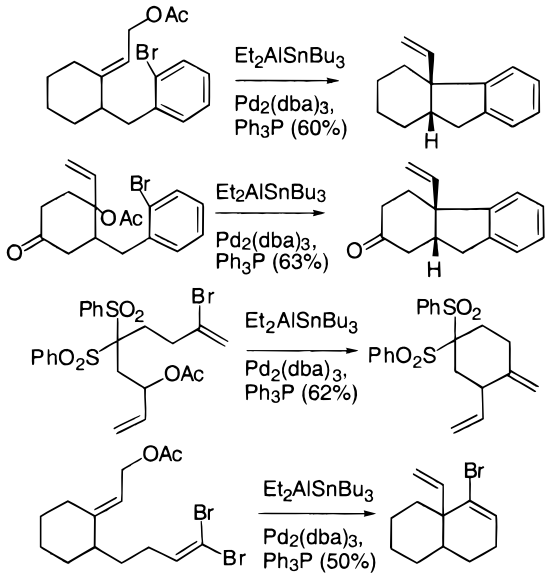
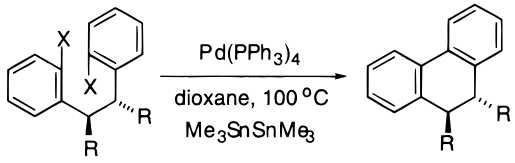


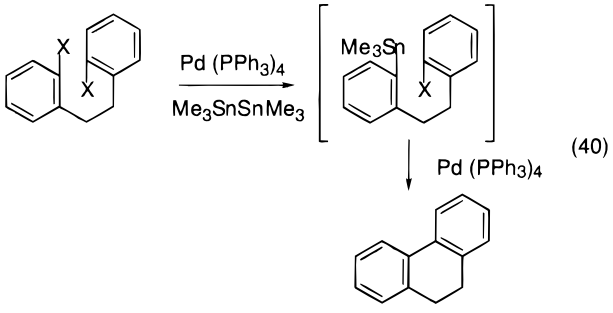
Table 52



X	R	t, h	yield, %
Br	OH	24	80
Br	OH	24	59 [a]
I	OH	24	87
OTf	OH	24	88 [b]
Br	H	53	82
OTf	H	24	95 [b]

[a] Toluene as solvent at 110 °C. [b] 5 equiv of LiCl was present.

proposed that the initial arylpalladium intermediate reacts with the distannane to afford the expected substitution product (eq 40). Subsequent oxidative

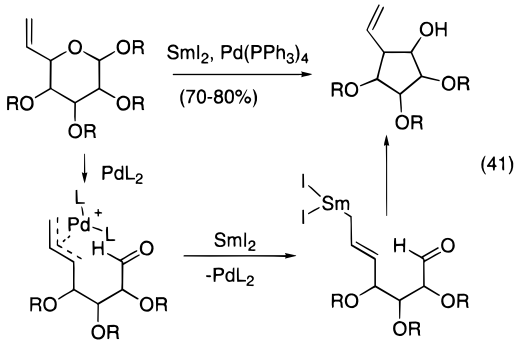


(40)

addition by the Pd(0) catalyst generates a second arylpalladium species, which undergoes aryl transfer by the Stille mechanism to afford the product and regenerate the Pd(0) catalyst.

C. Allylsamarium Couplings

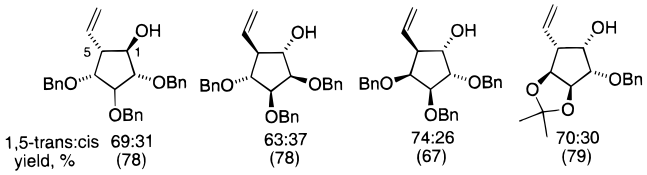
Auurecoechea and López prepared a number of vinyl-substituted C-glycosides as precursors to 5-vinylcyclopentanols (eq 41).[52] The conversion is



(41)

thought to occur by initial formation of a ring-opened π-allylpalladium intermediate followed by transmetalation with SmI_2. The resulting allylsamarium intermediate undergoes cyclization to the observed products. Yields are generally high, but mixtures of diastereomers are obtained (Table 53).

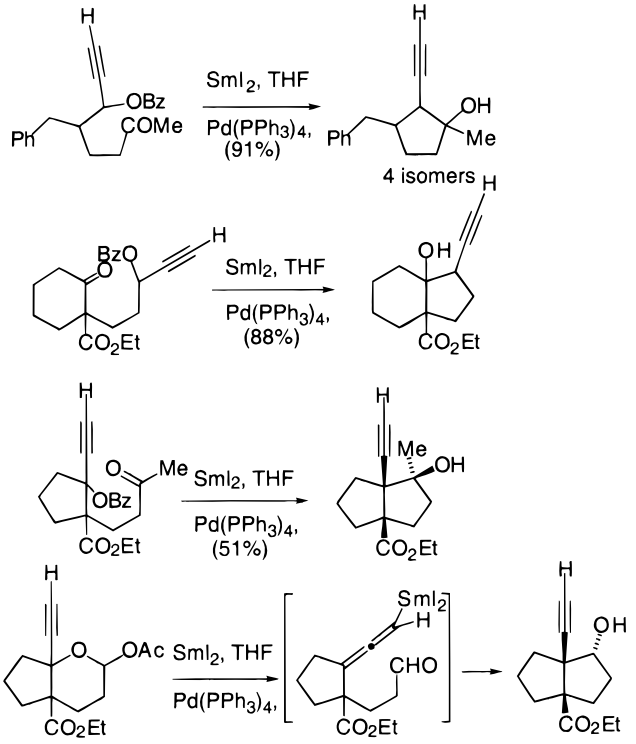
Table 53



D. Allenylsamarium Couplings

An intramolecular application of the allenylsamarium addition reaction was employed by Aurrecoechea and Antón to prepare a series of alkynylcyclopentanols (Scheme 5).[53] Aldehyde substrates gave inferior results because of competing reduction. How-

Scheme 5

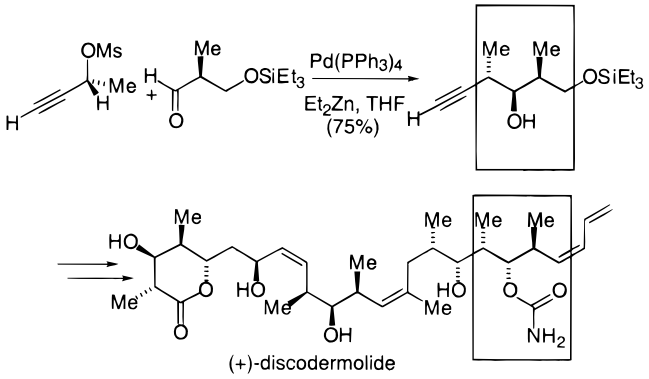


ever, this problem could be solved by masking the aldehyde as a cyclic hemiacylal (Scheme 5, last example). In this way, the aldehyde is liberated in concert with generation of the allenylpalladium intermediate. Evidently transmetalation of this species and subsequent intramolecular addition of the allenylsamarium intermediate is faster than reduction of the aldehyde by external SmI_2.

E. Allenylzinc Additions

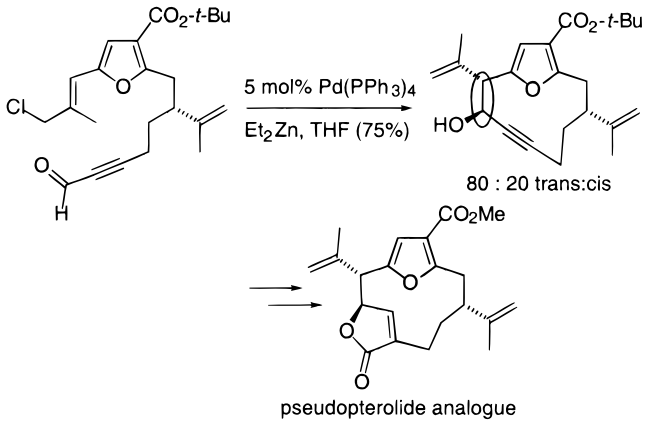
The allenylzinc methodology is well suited to the preparation of stereotriad subunits that are commonly found in polyketide natural products. For example, Marshall and Johns employed this chemistry in their total synthesis of the important marine natural product, discodermolide (Scheme 6).[54]

Scheme 6



An intramolecular application of the allylic zinc methodology was used by Marshall, McNulty, and Zou to prepare a 2,5-bridged furanocyclic alcohol from an allylic chloride precursor (Scheme 7).[55] This

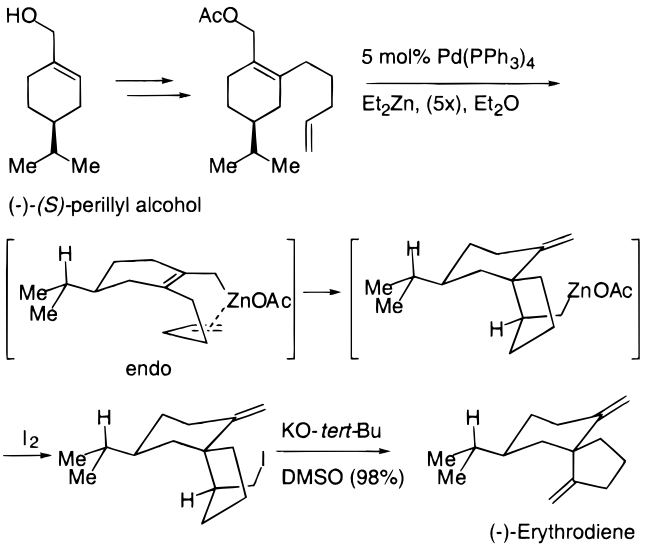
Scheme 7



intermediate was further transformed to an analogue of the marine natural product pseudopterolide.

Oppolzer and Flachsmann applied the zinc−ene methodology to a synthesis of the spirovetivane sesquiterpene (−)-erythrodiene from (−)-(*S*)-perillyl alcohol (Scheme 8).[56] The key ene cyclization step proceeded with complete endo diastereoselectivity to afford an organozinc intermediate which was trapped with I_2. Subsequent elimination of HI yielded the final product in high yield.

Scheme 8



VIII. Conclusions

The transmetalation of organopalladium intermediates represents an exceptionally mild route to certain highly useful organometallic compounds. As reagents, these intermediates can react in situ with various electrophiles both inter- and intramolecularly. The ability to access such intermediates from allylic, propargylic, and vinylic esters, as well as the more conventional halide starting materials, is particularly advantageous. Furthermore, the finding that allenylmetal reagents can be prepared both regio- and stereoselectively, and that their ensuing addition to aldehydes is highly stereoselective, should find numerous applications in the synthesis of complex natural products of significant medicinal potential.

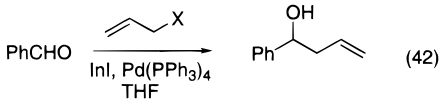
IX. Acknowledgments

The experimental contributions to the work from our laboratory cited in this review came from coworkers Nick Adams, Charsetta Grant, Brian Johns, LuAnne McNulty, Eli Wallace, Mark Wolf, and Dong Zou. We thank them for their experimental expertise, diligence, and intellectual input. Support was provided by NSF Grant CHE9220166 and NIH Grants AI31422 and GM29475.

X. Addendum (Added in Proof)

A. Allylindium Additions

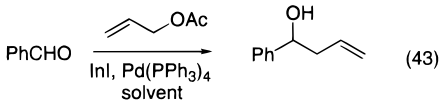
In a conceptual extension of the work of Marshall and Grant, Araki and co-workers examined additions of allylic indium salts derived from allylic halides or esters via transmetallation of transient π-allylpalladium intermediates with In(I) halides (eq 42).[57] Allyl



X = OAc (86%), Cl (100%), OPh (89%), OCO_2Et (76%), OH (76%), SMe (43%)

acetate, carbonate, chloride, and alcohol gave the adduct to benzaldehyde in satisfactory yield. The methyl sulfide proved less satisfactory, and the alcohol was appreciably slower than the esters, chloride, or phenyl ether.

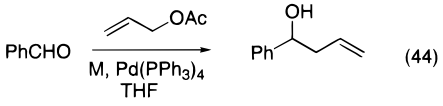
Nonpolar solvents such as benzene or hexane could not be used for the addition, but THF, THF-H_2O, H_2O, or EtOH were most suitable (eq 43). Of these, 1:1 THF−H_2O and EtOH gave the highest yield of adduct, but the addition was appreciably faster in the former solvent pair.



(43)

THF (86-91%), THF-H_2O (100%), H_2O (96%), EtOH (100%), hexane (8%), benzene (8%)

Both InI and InBr could be employed as the indium source with comparable results; InCl was less effective (eq 44). Indium metal powder could also be used,



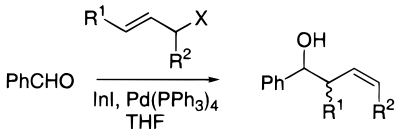
(44)

M = InI (86%), InBr (84%), InCl (51%), In (48%), $InCl_3•H_2O$, Al (82%)

but the addition was quite slow requiring nearly 1 week for ca. 50% addition. An economically attractive combination of a mixture of hydrated $InCl_3$ and aluminum powder to produce InCl, or possibly activated In, in situ was also effective.

A survey of various allylic precursors employing $Pd(PPh_3)_4$ as the catalyst with InI in THF and benzaldehyde is summarized in Table 54. In general, anti

Table 54



R^1	R^2	X	yield,%	*syn:anti*
H	Me	Cl	92	58:42[a]
Me	H	Cl[b]	96	37:63
Me	H	OAc[b]	98	32:68
Ph	H	OAc	100	14:86
Ph	Me	OAc	79	11:89
H	OEt	OEt	91	64:36[c]

[a] R^1 = Me in the product
[b] (*E*):(*Z*) = 85:15
[c] R^1 = OEt in the product

adducts are favored over syn with a few exceptions (entries 1 and 6). In the latter case, chelation may favor the formation of a (*Z*)-3-ethoxyallylindium halide intermediate which reacts via the usual cyclic transition state to afford the *syn* adduct.

XI. References

(1) Trost, B. M.; Herndon, J. W. *J. Am. Chem. Soc.* **1984**, *106*, 6835.
(2) Matsubara, S.; Wakamatsu, K.; Morizawa, Y.; Tsuboniwa, N.; Oshima, K.; Noyaki, H. *Bull. Chem. Soc. Jpn.* **1985**, *58*, 1196.
(3) Bumagin, N. A.; Kasatakin, A. N.; Beletkaya, I. P. *Izv. Akad. Nauk. SSSR, Ser. Khim.* **1984**, 636. Bumagina, I. G.; Bumagin, N. A.; Bakunin, V. N.; Beletskaya, I. P. *Izv. Akad. Nauk. SSSR, Ser. Khim.* **1980**, 2185.
(4) Tabuchi, T.; Inanaga, J.; Yamaguchi, M. *Tetrahedron Lett.* **1987**, *28*, 215.
(5) Masuyama, Y.; Hayashi, R.; Otake, K.; Kurusu, Y. *J. Chem. Soc., Chem. Commun.* **1988**, 44.
(6) Masuyama, Y.; Otake, K.; Kurusu, Y. *Tetrahedron Lett.* **1988**, *29*, 3563.
(7) Masuyama, Y.; Takahara, Y.; Kurusu, Y. *Tetrahedron Lett.* **1988**, *29*, 3437.
(8) Masuyama, Y.; Tsunoda, T.; Kurusu, Y. *Chem. Lett.* **1989**, 1647.
(9) Masuyama, Y.; Nimura, Y.; Kurusu, Y. *Tetrahedron Lett.* **1991**, *32*, 225.
(10) Masuyama, Y.; Hayakawam, A.; Kurusu, Y. *J. Chem. Soc., Chem Commun.* **1992**, 1102.
(11) Takahara, J. P.; Masuyama, Y.; Kurusu, Y. *J. Am. Chem. Soc.* **1992**, *114*, 2577.
(12) Tsuji, Y.; Kajita, S.; Isobe, S.; Funato, M. *J. Org. Chem.* **1993**, *58*, 3607.
(13) Matsumoto, Y.; Ohno, A.; Hayashi, T. *Organometallics* **1993**, *12*, 4051.
(14) Tabuchi, T.; Inanaga, J.; Yamaguchi, M. *Tetrahedron Lett.* **1986**, *21*, 1195.
(15) Masuyama, Y.; Kinugawa, N.; Kurusu, Y. *J. Org. Chem.* **1987**, *52*, 3702.
(16) Qui, W.; Wang, Z. *J. Chem. Soc., Chem. Commun.* **1989**, 356.
(17) Yasui, K.; Goto, Y.; Yajima, T.; Taniseki, Y.; Fugami, K.; Tanaka, A.; Tamaru, Y. *Tetrahedron Lett.* **1993**, *34*, 7619.
(18) Shimizu, M.; Kimuro, M.; Tanaka, S.; Tamaru, Y. *Tetrahedron Lett.* **1998**, *39*, 609.
(19) Tamaru, Y.; Tanaka, A.; Yasui, K.; Goto, S.; Tanaka, S. *Angew. Chem., Int. Ed.* **1995**, *34*, 787.
(20) Kimura, M.; Ogawa, Y.; Schimizu, M.; Tanaka, S.; Tamaru, Y. *Tetrahedron Lett.* **1998**, *39*, 6903.
(21) Sakamoto, T.; Takahashi, K.; Yamazaki, T.; Kitazume, T. *J. Org. Chem.* **1999**, *64*, 9467.
(22) Kimura, M.; Kiyama, I.; Tomizawa, T.; Horino, Y.; Tanaka, S.; Tamaru, Y. *Tetrahedron Lett.* **1999**, *40*, 6795. Tamaru, Y.; Goto, S.; Tanaka, A.; Shimizu, M.; Kimura, M. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 878.
(23) Ishiyama, T.; Ahiko, T.; Miyaura, N. *Tetrahedron Lett.* **1996**, *37*, 6889.
(24) Tamaru, Y.; Goto, S.; Tanaka, A.; Shimizu, M.; Kimura, M. *Angew. Chem., Int. Ed.* **1996**, *35*, 878.
(25) Marshall, J. A.; Adams, N. D. *J. Org. Chem.* **1998**, *63*, 3813.
(26) Marshall, J. A.; Wolf, M. A.; Wallace, E. M. *J. Org. Chem.* **1997**, *62*, 367; Elsevier, C. J.; Kleijn, H.; Boersma, J.; Vermeer, P. *Organometallics* **1986**, *5*, 716. For recent studies on the structure of allenyl/propargyl palladium compounds, see Tsutsumi, K.; Ogoshi, S.; Nishiguchi, S.; Kurosawa, H. *J. Am. Chem. Soc.* **1998**, *120*, 1938.
(27) Marshall, J. A.; Adams, N. D. *J. Org. Chem.* **1999**, *64*, 5201.
(28) Marshall, J. A.; Grant, C. M. *J. Org. Chem.* **1999**, *64*, 696.
(29) Marshall, J. A.; Grant, C. M. *J. Org. Chem.* **1999**, *64*, 8214.
(30) Wulff, W. D.; Peterson, G. A.; Bauta, W. E.; Chan, K. S.; Faron, K. L.; Gilbertson, S. R.; Kaesler, R. W.; Yang, D. C.; Murray, C. K. *J. Org. Chem.* **1986**, *51*, 277.
(31) Scott, W. J.; Stille, J. K. *J. Am. Chem. Soc.* **1986**, *108*, 3033.
(32) Stork, G.; Isaacs, R. C. A. *J. Am. Chem. Soc.* **1990**, *112*, 7399.
(33) Farina, V.; Hauck, S. I. *J. Org. Chem.* **1991**, *56*, 4317.
(34) Bumagin, N. A.; Gulevich, Y. V.; Beletskaya, I. P. *J. Organomet. Chem.* **1985**, *282*, 421.
(35) Okuda, Y.; Sato, M.; Oshima, K.; Nozaki, H. *Tetrahedron Lett.* **1983**, *24*, 2015.
(36) Hatanaka, Y.; Hiyama, T. *Tetrahedron Lett.* **1987**, *28*, 4715.
(37) Yamashita, H.; Kobayashi, T.; Hayashi, T.; Tanaka, M. *Chem. Lett.* **1991**, 761.
(38) Kosugi, M.; Shimuzu, K.; Ohtani, A.; Migita, T. *Chem. Lett.* **1981**, 829.
(39) Azizian, H.; Eaborn, C.; Pidcock, A. *J. Organomet. Chem.* **1981**, *215*, 49. Kashin, A. N.; Bumagina, I. G.; Bumagin, N. A.; Bakunin, I. P. *Zh. Org. Khim.* **1981**, *17*, 905.
(40) Bumagin, N. A.; Bumagina, I. G.; Beletskaya, I. P. *Dokl. Akadf. Nauk. SSSR* **1984**, 274.
(41) Murata, M.; Suzuki, K.; Watanabe, S.; Masuda, Y. *J. Org. Chem.* **1997**, *62*, 8569.
(42) Ishiyama, T.; Murata, M.; Miyaura, N. *J. Org. Chem.* **1995**, *60*, 7508.
(43) Ishiyama, T.; Itoh, Y.; Kitano, T.; Miyaura, N. *Tetrahedron Lett.* **1997**, *38*, 3447.
(44) Murata, M.; Oyama, T.; Watanabe, S.; Masuda, Y. *J. Org. Chem.* **2000**, *65*, 164.
(45) Stadtmüller, H.; Lentz, R.; Tucker, C. E.; Stüdemann, T.; Dörner, W.; Knochel, P. *J. Am. Chem. Soc.* **1993**, *115*, 7027.

(46) Oppolzer, W.; Scröder, F. *Tetrahedron. Lett.* **1994**, *35*, 7939.
(47) Paquette, L. A.; Rayner, C. M.; Doherty, A. M. *J. Am. Chem. Soc.* **1990**, *112*, 4078.
(48) Trost, B. M.; Pietrusiewicz, K. M. *Tetrahedron Lett.* **1985**, *26*, 4039.
(49) Yokoyama, Y.; Ito, S.; Takahashi, Y.; Murakami, Y. *Tetrahedron Lett.* **1985**, *26*, 6457.
(50) Trost, B. M.; Walchli, R. *J. Am. Chem. Soc.* **1987**, *109*, 3487.
(51) Kelly, T. R.; Li, Q.; Bhushan, V. *Tetrahedron Lett.* **1990**, *31*, 161.
(52) Aurrecoechea, J. M.; López, B. *Tetrahedron Lett.* **1998**, *39*, 2857.
(53) Aurrecoechea, J. M.; Antón, R. F.-S. *J. Org. Chem.* **1994**, *59*, 702.
(54) Marshall, J. A.; Johns, B. A. *J. Org. Chem.* **1998**, *63*, 7885.
(55) Marshall, J. A.; McNulty, L. M.; Zou, D. *J. Org. Chem.* **1999**, *64*, 5193.
(56) Oppolzer, W.; Flachsmann, F. *Tetrahedron Lett.* **1998**, *39*, 5019.
(57) Araki, S.; Kamei, T.; Hirashita, T.; Yamamura, H.; Kawai, M. *Org. Lett.* **2000**, *2*, 847.

CR000003U