Tetrahedron 66 (2010) 9032–9040

Contents lists available at ScienceDirect

Tetrahedron

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

Chiral *N*-phosphino sulfinamide ligands in rhodium(I)-catalyzed [2+2+2] cycloaddition reactions

Sandra Brun [a], Magda Parera [a], Anna Pla-Quintana [a], Anna Roglans [a,*], Thierry León [b], Thierry Achard [b], Jordi Solà [b], Xavier Verdaguer [b,*], Antoni Riera [b,*]

[a] Department of Chemistry, University of Girona, Campus de Montilivi s/n, 17071 Girona, Spain
[b] Institute for Research in Biomedicine (IRB Barcelona) and Department de Química Orgànica, Universitat de Barcelona, C/Baldiri Reixac 10, 08028 Barcelona, Spain

ARTICLE INFO

Article history:
Received 9 July 2010
Received in revised form 30 August 2010
Accepted 3 September 2010
Available online 15 September 2010

This manuscript is dedicated to Professor Carmen Nájera on the occasion of her 60th birthday

Keywords:
[2+2+2] Cycloaddition
Rhodium
Sulfinamide ligands
Alkynes
Enediynes

ABSTRACT

The combination of cationic rhodium(I) complexes with *N*-phosphino *tert*-butylsulfinamides (PNSO) ligands is efficient for catalytic intra- and intermolecular [2+2+2] cycloaddition reactions. PNSO ligands are a new class of chiral bidentate ligands, which have the characteristic of combining the easily accessible sulfur chirality with the coordinating capacity of phosphorous. Cycloaddition of open-chained and macrocyclic *E*-enediynes with these chiral complexes have proved to be highly efficient in terms of yields, giving moderate enantiomeric excesses of the corresponding cyclohexadiene derivatives. In addition Rh(I)/PNSO complexes catalyzed the intermolecular cycloaddition of diynes with monoalkynes in mild reaction conditions and short reaction times.

1. Introduction

Transition-metal-catalyzed-[2+2+2] cycloadditions are valuable strategic reactions in increasing the complexity of target molecules as they enable several bond connections to be made in a single step.[1] This reaction is remarkable in terms of its ability to generate carbocyclic systems by the involvement of various unsaturated substrates, such as alkynes and alkenes. In addition, the enantioselective version of these [2+2+2] cycloadditions is a powerful synthetic method for the construction of chiral cyclic frameworks.[1h,k] Various transition metal catalysts based especially on Ni, Co, Rh, Ru, and Pd have been developed for cyclotrimerization reactions. Given the potential of the process, it is extremely interesting to search for new efficient catalytic systems, which allow us to work, for example, in mild reaction conditions or with air-stable complexes. Some of us have recently described the synthesis of a new class of chiral bidentate ligands: *N*-phosphino *tert*-butylsulfinamides (PNSO, **I**, Fig. 1). These ligands represent an efficient way of combining the easily accessible sulfur chirality with the coordinating capacity of phosphorous. Ligands **I** are modular and can be conveniently assembled from the commercially available enantiopure *tert*-butylsulfinamide, an aldehyde, and a chlorophosphine in two steps. Some of these ligands, such as **1a** have proved to be highly efficient in the intermolecular asymmetric Pauson–Khand reaction acting as bidentate P,S ligands.[2] This study was the first example of a chiral sulfur atom coordinated to a cobalt center.

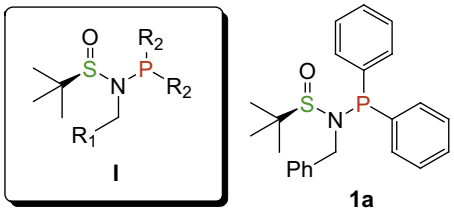


Fig. 1. General structure of the *N*-phosphino *tert*-butylsulfinamides (PNSO) chiral ligands.

We recently reported the first rhodium(I) complexes with PNSO ligands of type **I**. The reaction of $[RhCl(COD)]_2$ with 1 or 2 equiv of **1a** in the presence of 1 equiv of AgOTf, afforded complexes [Rh(**1a**)(COD)]OTf and $[Rh(\mathbf{1a})_2]OTf$ in good yields.[3] We observed that PNSO ligands, depending on the electronic environment around the

* Corresponding authors. E-mail address: anna.roglans@udg.edu (A. Roglans).

0040-4020/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2010.09.009

metal center can work either as P,O or as P,S chelating ligands. Thus, *N*-benzyl-*N*-diphenylphosphino-*tert*-butylsulfinamide (**1a**) provides P,O coordination when olefin ligands (NBD or COD) are attached to the metal center. Alternatively, rhodium complexes with two PNSO ligands provide P,S coordination. The thermodynamically most stable *cis* configuration is preferentially shown in [Rh(PNSO)$_2$] OTf complexes (Fig. 2).

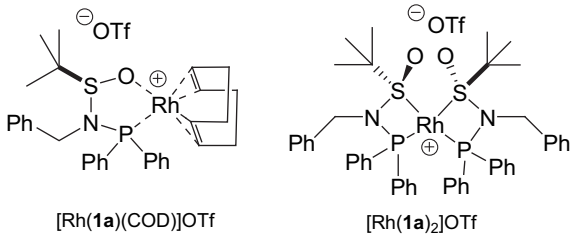
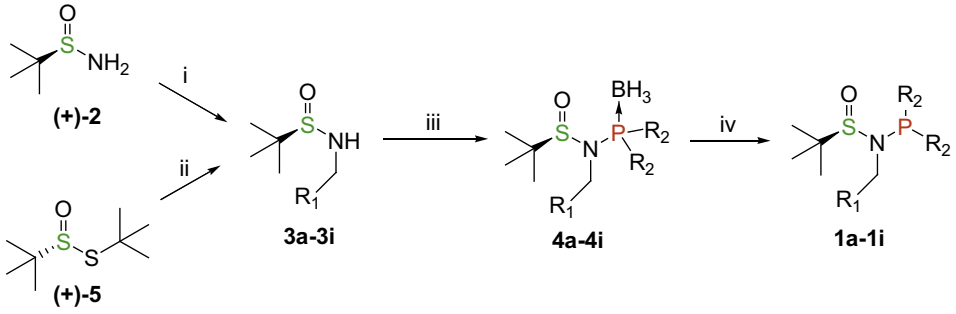


Fig. 2. Structure of previously described cationic rhodium(I) complexes [Rh(**1a**)(COD)] OTf and [Rh(**1a**)$_2$]OTf.

Reductive amination with Ti(OEt)$_4$ in the presence of the corresponding aldehyde produced the intermediate sulfinimines, which were reduced in situ to the corresponding sulfinamides **3a**–**i**. Alternatively, depending on the availability of the required aldehyde, the intermediate sulfinamide **3** could be synthesized from the metalated amine and Ellman's thiosulfinate (+)-**5**. From **3**, anion formation with *n*-BuLi at low temperature followed by the addition of chlorophosphine and the protection of the phosphine moiety with borane resulted in the corresponding borane/protected ligands **4a**–**i**. Protection was necessary to avoid sulfur–phosphorous oxygen migration during the work-up. The borane/free ligand was obtained by deprotection with DABCO to afford PNSO ligands **1a**–**i** in good yields. Once pure, ligands **1a**–**i** were air-stable and could be stored during weeks. In a few cases, the steric hindrance of the PNSO ligand prevented protection with borane. However, in this situation, the ligand was usually resistant to sulfur–phosphorous oxygen transfer (Table 1).

Table 1
Synthesis of the PNSO ligands



i) a) R_1CHO, $Ti(OEt)_4$ and b) $NaBH_4$; ii) $R_1CH_2NH_2$, *n*-BuLi, THF; iii) a) BuLi, R_2PCl, -78 °C and b) BH_3•SMe_2, -10 °C; iv) DABCO, r.t., toluene

Entry	R_1	Yield of **3** (%)	R_2	Yield of **4** (%)	Yield of **1** (%)
1	Ph	**3a**, 91	Ph	**4a**, 93	**1a**, 95
2	Ph		*o*-Tolyl	—[a]	**1b**, 74
3	Ph		*o*-Methoxyphenyl	**4c**, 28	**1c**, 93
4	Ph		*p*-(Trifluoromethyl)phenyl	—[a]	**1d**, 17
5	Ph		3,5-Dimethylphenyl	**4e**, 68	**1e**, 71
6	*p*-Methoxyphenyl	**3f**, 34	Ph	**4f**, 90	**1f**, 69
7	2-Naphthyl	**3g**, 79	Ph	**4g**, 79	**1g**, 82
8	2,4,6-Trimethylphenyl	**3h**, 65	Ph	**4h**, 82	**1h**, 95
9	*p*-Fluorophenyl	**3i**, 60[b]	Ph	**4i**, 88	**1i**, 88

[a] Protection with borane did not take place, so **1b** and **1d** were obtained instead of **4b** and **4d**.
[b] Synthesized from (+)-**5**.

We considered that the rhodium complexes of PNSO ligands might be active in catalytic asymmetric reactions, such as [2+2+2] cycloadditions. The availability and modular nature of these ligands could be extremely valuable in the optimization of the catalyst.

Here we describe the application of rhodium(I) complexes of *N*-phosphino-*tert*-butylsulfinamide [Rh(PNSO)(COD)]X (X=OTf or BF_4) in intra- and intermolecular [2+2+2] cycloaddition reactions. We have applied these chiral complexes to the cycloaddition of open-chained enediynes and macrocyclic enediynes. Furthermore, we have extended their applicability to the cycloaddition between diynes and monoalkynes.

2. Results and discussion

2.1. Synthesis of the ligands

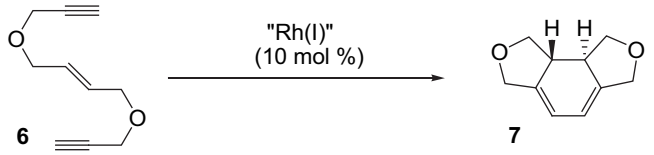
A family of chiral PNSO ligands **1a**–**i** has been synthesized from commercially available *tert*-butylsulfinamide (+)-**2**.

2.2. Cycloaddition reactions

The study was initiated using *O*-tethered (*E*)-enediyne **6** as a substrate (Table 2). To the best of our knowledge, there have only been two significant cases of enantioselective intramolecular [2+2+2] cycloaddition of enediynes reported. Tanaka et al.[4] found that the catalytic system formed by a cationic rhodium(I) complex with BINAP-type ligands catalyzed enantioselective cycloadditions of enediyne **6** and its derivatives, which have different terminal substituents, resulting in good yields and moderate enantiomeric excesses. Shibata et al.,[5] using a similar catalytic system to that used by Tanaka, performed intramolecular cycloaddition of various carbon-, *N*-tosyl-, and oxygen-tethered enediynes, which gave the corresponding cyclohexa-1,3-dienes with high enantioselectivity. However, cycloaddition of enediyne **6** was not reported in this work.

The first reaction was run using the known complex [Rh(**1a**)(COD)]OTf in anhydrous dichloromethane at room temperature.

Table 2
Rh(I)/PNSO catalyzed [2+2+2] cycloisomerization reactions of enediyne **6**



Entry	Catalyst[a]	Reaction conditions	Yield (%)	$[\alpha]_D^{23}$	ee (%)
1	[Rh(**1a**)(COD)]OTf	anh. CH_2Cl_2, rt, 5 h	78	+	29
2	[Rh(**1a**)$_2$]OTf	anh. CH_2Cl_2, reflux, 30 h	0	na	0
3[b]	[Rh(COD)$_2$]BF_4/**1a**	anh. CH_2Cl_2, reflux, 22 h	75	+	27
4[b,c]	[Rh(COD)$_2$]BF_4/**1a**	CH_2Cl_2, reflux, 3 h	92	+	32
5[b,c]	[Rh(COD)$_2$]BF_4/**1a**	CH_2Cl_2, rt, 15 min	78	+	30
6[b]	[Rh(COD)$_2$]BF_4	CH_2Cl_2, reflux, 3 h	10[d]	na	–
7[b,c]	[Rh(COD)$_2$]BF_4/**1b**	CH_2Cl_2, reflux, 5 h	20	–	20
8[b,c]	[Rh(COD)$_2$]BF_4/**1c**	CH_2Cl_2, reflux, 5 h	20	–	20
9[b,c]	[Rh(COD)$_2$]BF_4/**1d**	CH_2Cl_2, reflux, 1 h	39	+	24
10[b,c]	[Rh(COD)$_2$]BF_4/**1e**	CH_2Cl_2, reflux, 30 min	42	+	21
11[b,c]	[Rh(COD)$_2$]BF_4/**1f**	CH_2Cl_2, reflux, 5 min	95	+	18
12[b,c]	[Rh(COD)$_2$]BF_4/**1g**	CH_2Cl_2, reflux, 2 h	49	na	0
13[b,c]	[Rh(COD)$_2$]BF_4/**1h**	CH_2Cl_2, reflux, 2 h	87[e]	na	0
14[b,c]	[Rh(COD)$_2$]BF_4/**1i**	CH_2Cl_2, reflux, 3 h	98[e]	–	15

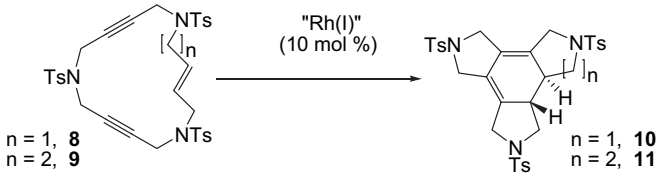
[a] The ratio [Rh(COD)$_2$]BF_4/**1** was 2:1.
[b] Hydrogen gas was introduced to the catalyst solution prior to substrate addition.
[c] Non-dried HPLC grade CH_2Cl_2.
[d] When the reaction was run to completion, only a 20% yield of the product could be isolated after 20 h of heating in refluxing DCM.
[e] Referred to conversion by ^{1}H NMR.

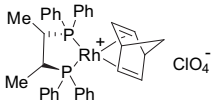
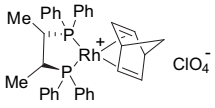
After 5 h, a 78% yield of cyclohexadiene derivative **7** was obtained with a 29% enantiomeric excess (ee) (entry 1, Table 2). In an attempt to improve the ee, other solvents, such as toluene, THF, and EtOH were tested although worse results were obtained. [Rh(**1a**)$_2$]OTf was then tested in dichloromethane at reflux for 30 h but only starting material was recovered (entry 2, Table 2). We concluded that dimers are not active catalysts in these processes.

To facilitate the testing of the family of ligands **1a**–**i**, we studied the generation of the catalyst in situ. Given that the reaction between [Rh(COD)$_2$]BF_4 and **1a** can also give dimeric complex [Rh(**1a**)$_2$]BF_4, ^{31}P NMR studies were performed in order to find the best conditions to have [Rh(**1a**)(COD)]BF_4 as the main compound in the solution. Mixtures containing [Rh(COD)$_2$]BF_4 and **1a** were prepared with a molar ratio ranging from 1:1 to 2:1. After hydrogenation, ^{31}P NMR analysis showed that [Rh(**1a**)(COD)]BF_4 complex was the main compound (93% yield), the other one being dimeric species [Rh(**1a**)$_2$]BF_4 (7%) when the ratio was 2:1. ESI-MS studies confirmed the formation of the two rhodium complexes in solution. A 75% yield of cyclohexadiene derivative **7** was obtained from the in situ formed catalyst at reflux of anhydrous dichloromethane after 22 h of reaction (entry 3, Table 2). The ee was almost the same as using the preformed catalyst (compare entries 1 and 3, Table 2). As we and others have found in previous studies,[6] running the reaction in non-dried solvents without degassing gives better results in some cases. Therefore, the cycloaddition was run in non-dried HPLC grade CH_2Cl_2 and the reaction worked at reflux for 3 h to afford a 92% yield of **7** (entry 4, Table 2). Moreover, running the reaction at room temperature, a remarkable 78% yield of **7** was achieved in just 15 min (entry 5, Table 2). The ee of **7** in the last two experiments was similar to previous experiments (compare entries 4 and 5 with entries 1 and 3). Since some [Rh(COD)$_2$]BF_4 remained in solution, it was necessary to check the catalytic activity of this complex. A blank experiment using [Rh(COD)$_2$]BF_4 without PNSO ligand gave only a 10% yield of final product **7** under the optimized conditions, and the yield was only increased to 20% when the reaction was left to reach completion (entry 6, Table 2). This result demonstrates that the reaction is PNSO-ligand accelerated. In none of the described cases was the formation of double-bond-isomerized compounds detected. Unfortunately the results obtained with ligand **1a** could not be improved with their analogs (entries 7–14, Table 2). Most interestingly, PNSO ligands with *ortho*-substitution in the phosphine moiety (**1b** and **1c**, entries 7 and 8, Table 2) and ligand **1i** (entry 14, Table 2) bearing an *N*-*p*-fluorobenzyl group provided reversed selectivity. However, we still do not have a proper explanation for this fact.

We next decided to study the cycloisomerization of macrocyclic enediynes **8** and **9** (Table 3). Some of us have pioneered the study of [2+2+2] cycloadditions in macrocyclic systems.[7] The cycloaddition of **8** and **9** has previously been reported[7d] using (bicyclo[2.2.1]

Table 3
Rh(I)-catalyzed [2+2+2] cycloisomerization of enediyne macrocycles **8** and **9**



Entry	Starting compound	Catalyst	Reaction conditions	Product, yield (%)	ee (%)
1[a]	**8**		Toluene, 65 °C, 24h	**10**, 95	44
2[a]	**9**		Toluene, 65 °C, 24h	**11**, 46	41
3[b,c]	**8**	[Rh(COD)$_2$]BF_4/**1a**	CH_2Cl_2, rt, 2.5 h	**10**, 91	11
4[c]	**8**	[Rh(**1a**)(COD)]OTf	CH_2Cl_2, rt, 28 h	**10**, 77	48
5	**8**	[Rh(COD)$_2$]BF_4	CH_2Cl_2, rt, 2.5 h	**10**, 84	—
6[c]	**8**	[Rh(**1a**)(COD)]OTf	Toluene, rt, 5.5 h	**10**, 79	50
7[c]	**9**	[Rh(**1a**)(COD)]OTf	Toluene, rt, 5.5 h	**11**, 94	7

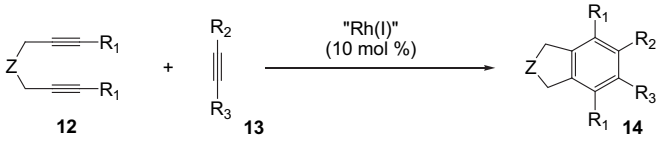
[a] Ref. 7d.
[b] The ratio [Rh(COD)$_2$]BF_4/**1a** was 2:1.
[c] The enantiomer obtained in these cases is the opposite of that obtained in entries 1 and 2.

hepta-2,5-diene)[2*S*,3*S*]-bis(diphenylphosphino)butane rhodium (I) perchlorate as a commercial chiral rhodium complex (entries 1 and 2, Table 3). In order to improve on the previously obtained results, especially the enantiomeric excess, Rh(I)/PNSO, either generated in situ (entry 3, Table 3) or as an isolated complex (entry 4, Table 3) in CH_2Cl_2 at room temperature, was used as the catalyst. In the two cases the reaction worked well but a great difference was observed in terms of ee. The best result was obtained using the isolated complex [Rh(**1a**)(COD)]OTf (compare entries 3 and 4, Table 3). This different behavior of enantioselectivity can be explained with the blank experiment shown in entry 5 demonstrating that the $[Rh(COD)_2]BF_4$ precursor is also active for these macrocyclic systems. With the preformed rhodium complex, we then tested toluene as a solvent and managed to reduce the reaction time considerably (entry 6, Table 3). A 79% yield of **10** with a slightly improved 50% of ee was obtained. The same reaction conditions were applied for macrocycle **9**. In this case an excellent yield of 94% of **11** was obtained although the ee dropped to 7% (entry 7, Table 3). The enantiomer formed with the new PNSO/Rh complex was the opposite to that obtained in entries 1 and 2.

Finally, the new catalytic system was tested in intermolecular [2+2+2] cycloaddition reactions of alkynes[8,9] (Table 4). We first investigated the reaction of non-terminal diynes, which are generally less reactive than their terminal counterparts toward this reaction. *N*-Tosyl-tethered diyne **12a** was reacted with phenylacetylene **13a** in the presence of cationic rhodium(I)/phosphinosulfinamide complex as a catalyst generated in situ. An 84% yield of **14aa** was obtained in short reaction times in DCE at reflux (entry 1, Table 4). The catalytic activity of the excess $[Rh(COD)_2]BF_4$ present in the reaction media was evaluated by running a blank experiment excluding ligand **1a**. In the same reaction conditions only a 5% yield of benzene derivative **14aa** was achieved (entry 2, Table 4) assuming that the process is PNSO-ligand accelerated and that most of the catalytic activity is due to our new complex. We then studied the scope of the reaction by varying the monoyne counterpart. Monosubstituted alkyne **13b** as well as disubstituted alkynes **13c** and **13d** effectively participated in the [2+2+2] cycloaddition reaction (entries 3–5, Table 4). It is worth mentioning that monoyne **13d** gave high quantities of the trimerization product, hexamethyl mellitate **15**, which was responsible for the decreased yield of the partially intramolecular reaction. Therefore, a completely intermolecular cycloaddition was run with alkyne **13d** alone. Hexamethyl mellitate **15** was obtained with a 67% yield after 1.5 h of reaction (entry 6, Table 4). The effect of the tether between the alkynes was also studied by reacting malonate-linked diyne **12b** with phenylacetylene **13a**. The reaction worked effectively at DCE at reflux achieving a 78% yield of the cycloisomerized product **14ba** after 2 h of reaction.

In a second step, diynes featuring two terminal alkynes were submitted to the [2+2+2] cycloaddition reaction. 1,6-Heptadiyne **12c** was reacted with phenylacetylene **13a** in the presence of cationic rhodium(I)/phosphinosulfinamide complex as a catalyst generated in situ. A 60% yield of the biphenyl derivative **14ca** was achieved in just 15 min at room temperature (entry 8, Table 4). The reaction was again shown to be PNSO-ligand accelerated by running a blank experiment that excluded ligand **1a**. In this case (entry 9, Table 4) an 11% yield was obtained in the same reaction conditions, a yield, which was not improved when the reaction was left to run for 45 min. The monoyne counterpart was varied and slightly better yields were achieved with propargyl alcohol **13b** and 2-butyn-1,4-diol **13c** (entries 10 and 11, Table 4). With respect to the tethers, *N*-tosyl-, malonate-, and oxygen-linked diynes could also be used for this reaction (entries 12–19, Table 4). *N*-Tosyl-tethered diyne **12d** gave a moderate 44% yield of **14da** when reacted with phenylacetylene **13a** for 2 h at room temperature, but the yield could be increased up to 78% in just 45 min when switching the reaction media to DCE at reflux. Malonate-tethered diyne **12e** reacted with the three monoynes **13a–c** with yields above 70%

Table 4
Rh(I)/PNSO catalyzed [2+2+2] cycloaddition of 1,6-diynes **12** with monoalkynes **13**



Entry	**12** (Z, R_1)	**13** (R_2, R_3)	Catalyst[a]	Reaction conditions[b]	Product, yield (%)[c]
1	**12a** (NTs, Me)	**13a** (Ph, H)	$[Rh(COD)_2]BF_4$/**1a**	DCE, reflux, 2 h	**14aa**, 84
2	**12a** (NTs, Me)	**13a** (Ph, H)	$[Rh(COD)_2]BF_4$	DCE, reflux, 2 h	**14aa**, 5
3	**12a** (NTs, Me)	**13b** (CH_2OH, H)	$[Rh(COD)_2]BF_4$/**1a**	DCE, reflux, 24 h	**14ab**, 52
4[d]	**12a** (NTs, Me)	**13c** (CH_2OH, CH_2OH)	$[Rh(COD)_2]BF_4$/**1a**	DCE, reflux, 24 h	**14ac**, 63
5	**12a** (NTs, Me)	**13d** (CO_2Me, CO_2Me)	$[Rh(COD)_2]BF_4$/**1a**	DCE, reflux, 5 h	**14ad**, 44
6	—	**13d** (CO_2Me, CO_2Me)	$[Rh(COD)_2]BF_4$/**1a**	CH_2Cl_2, reflux, 1.5 h	**15**, 67
7	**12b** ($C(CO_2Et)_2$, Me)	**13a** (Ph, H)	$[Rh(COD)_2]BF_4$/**1a**	DCE, reflux, 2 h	**14ba**, 78
8	**12c** (CH_2, H)	**13a** (Ph, H)	$[Rh(COD)_2]BF_4$/**1a**	CH_2Cl_2, rt, 15 min	**14ca**, 60
9[e]	**12c** (CH_2, H)	**13a** (Ph, H)	$[Rh(COD)_2]BF_4$	CH_2Cl_2, rt, 15 min	**14ca**, 11
10	**12c** (CH_2, H)	**13b** (CH_2OH, H)	$[Rh(COD)_2]BF_4$/**1a**	DCE, reflux, 1 h	**14 cb**, 73
11[d]	**12c** (CH_2, H)	**13c** (CH_2OH, CH_2OH)	$[Rh(COD)_2]BF_4$/**1a**	DCE, reflux, 2 h	**14cc**, 70
12	**12d** (NTs, H)	**13a** (Ph, H)	$[Rh(COD)_2]BF_4$/**1a**	CH_2Cl_2, rt, 2 h	**14da**, 44
13	**12d** (NTs, H)	**13a** (Ph, H)	$[Rh(COD)_2]BF_4$/**1a**	DCE, reflux, 45 min	**14da**, 78
14	**12e** ($C(CO_2Et)_2$, H)	**13a** (Ph, H)	$[Rh(COD)_2]BF_4$/**1a**	DCE, rt, 6 h	**14ea**, 71
15	**12e** ($C(CO_2Et)_2$, H)	**13b** (CH_2OH, H)	$[Rh(COD)_2]BF_4$/**1a**	DCE, reflux, 2 h	**14eb**, 77
16[d]	**12e** ($C(CO_2Et)_2$, H)	**13c** (CH_2OH, CH_2OH)	$[Rh(COD)_2]BF_4$/**1a**	DCE, reflux, 7 h	**14ec**, 72
17	**12f** (O, H)	**13a** (Ph, H)	$[Rh(COD)_2]BF_4$/**1a**	DCE, rt, 3 h	**14fa**, 60
18	**12f** (O, H)	**13b** (CH_2OH, H)	$[Rh(COD)_2]BF_4$/**1a**	DCE, rt, 5 h	**14fb**, 99
19[d]	**12f** (O, H)	**13c** (CH_2OH, CH_2OH)	$[Rh(COD)_2]BF_4$/**1a**	DCE, rt, 8 h	**14fc**, 48

[a] The ratio $[Rh(COD)_2]BF_4$/**1a** was 2:1.
[b] Hydrogen gas was bubbled into the catalyst solution for 30 min, the hydrogen and solvent were then removed, the solvent was added again, monoyne **13** was introduced and finally diyne **12**.
[c] Isolated yields.
[d] Butyne-1,4-diol **13c** was added to the reaction mixture dissolved in THF (1 mL).
[e] The reaction did not advance further when performed over 45 min.

(entries 14–16, Table 4). Finally, oxygen-linked diyne **12f** was also shown to participate effectively in the [2+2+2] cycloaddition with monoynes **13a–c** in DCE at room temperature (entries 17–19, Table 4).

3. Conclusions

In summary, we have shown that *N*-phosphino *tert*-butylsulfinamide (PNSO) ligands are efficient in rhodium(I)-catalyzed [2+2+2] cycloaddition reactions. The scope of the cycloadditions has been evaluated by effectively reacting completely intramolecular and macrocyclic enediynes as well as the partially intermolecular version of the [2+2+2] cycloaddition of alkynes. This process has been shown to be accelerated by PNSO ligands and in the case of (*E*)-enediynes, moderate enantiomeric excesses have been achieved. The catalytic system presented here is found to be robust and applicable to a broad range of substrates independently of the nature of the linker between unsaturations and the substitution at the termini of the alkynes. We attribute the high activity of these complexes to the hemilabile nature of the PNSO ligands. Hemilabile ligands can provide vacant coordination sites to the substrate, so accelerating the cycloaddition process. The modularity of PNSO ligands allowed a small library of novel ligands to be prepared. These new ligands did not improve the enantioselectivity observed for the parent PNSO ligand **1a**. In the PNSO ligands, the chiral information is located in the hemilabile moiety of the ligand, which can be far away from the metal center in the crucial C–C bond formation step. We think that this fact may hamper the transfer of chiral information from the ligand to the cycloaddition product. Our groups are currently performing further investigations to improve the enantioselectivity in the [2+2+2] cycloaddition process by locating the chiral information closer to the metal center.

4. Experimental section

4.1. General methods

Unless otherwise noted, materials were obtained from commercial suppliers and used without further purification. [Rh(**1a**)(COD)]OTf and [Rh(**1a**)$_2$]OTf were prepared as described by us.[3] Enediyne **6** was prepared following the method described previously in literature.[10] Macrocycles **8**[7b] and **9**,[7d] were previously prepared by us. Cycloisomerized compounds **10**,[7d] **11**,[7d] **14aa**,[6a] and **14ac**,[6a] sulfinamides **3a**[2a] and **3f**,[2a] borane/PNSO ligands **4a**[2a] and **4f**,[2a] and borane/free PNSO ligands **1a**[2a] and **1f**[2a] were previously characterized by us.

^{1}H, ^{13}C NMR, ^{31}P, and ^{19}F spectra were recorded on a 400 or 300 MHz NMR spectrometer. Chemical shifts (δ) for ^{1}H and ^{13}C NMR were referenced to internal solvent resonances and reported relative to SiMe$_4$. ^{31}P NMR spectra were referenced to phosphoric acid. ESI-MS analyses were recorded on an Esquire 6000 Ion Trap Mass Spectrometer (Bruker) equipped with an electrospray ion source.

Optical rotations were recorded on a Perkin–Elmer polarimeter at the sodium D line at room temperature (concentration in g/mL). Melting points were determined using either a Büchi or a Stuart SMP10 melting point apparatus and were not corrected. IR spectra were recorded in an FT-IR apparatus.

4.2. General procedure for the synthesis of sulfinamides (3g,h)

A one-necked round bottomed flask equipped with a magnetic stirring bar was charged with (*R*)-2-methyl-2-propanesulfinamide under a N_2 atmosphere. Ti(OEt)$_4$ in anhydrous THF was added, and the solution was stirred for 10 min at room temperature. The aldehyde was then added and the crude was heated at reflux temperature. The reaction was followed by TLC. A suspension of $NaBH_4$ in anhydrous THF was canulated to the crude previously cooled to 0 °C. The mixture was then allowed to warm to room temperature. After 1 h, methanol was added dropwise and stirred strongly. The resulting crude was poured over icy brine and extracted with dichloromethane. The crude was then filtered through Celite®, washed with dichloromethane, and evaporated under reduced pressure. The resulting oil was purified by column chromatography through silica gel to obtain the desired sulfinamides.

*4.2.1. (R)-N-(Naphthalen-2-ylmethyl)-2-methyl-2-propanesulfinamide, **3g**.* In accordance with the general procedure for sulfinamides, (*R*)-2-methylpropane-2-sulfinamide (1.00 g, 8.25 mmol), Ti(OEt)$_4$ (1.73 mL, 8.25 mmol), 2-naphtaldehyde (1.38 g, 8.66 mmol) in THF (15 mL), and $NaBH_4$ (0.62 g, 16.5 mmol) in THF (2 mL) were used. Column chromatography through silica gel (hexanes/ethyl acetate, 75:25) afforded 1.70 g (79%) of **3g** as a colorless foam. $[\alpha]_D^{23}$ −28.4 (*c* 1.00, $CHCl_3$); IR (film) ν_{max} 3189, 2954, 1470, 1037, 859 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.27 (s, 9H), 3.52 (br s, NH), 4.42 (d, *J*=14 Hz, 1H), 4.52 (d, *J*=14 Hz, 1H), 7.48 (m, 3H), 7.78 (s, 1H), 7.83 (m, 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 22.9, 49.9, 56.3, 126.3, 126.4, 126.5, 127.1, 127.9, 128.0, 128.7, 133.1, 133.5, 136.1 ppm; ESI-MS (*m*/*z*) 262 [M+H]$^+$, 284 [M+Na]$^+$, 545 [2M+Na]$^+$; ESI-HRMS: calcd *m*/*z* for [$C_{15}H_{20}NOS$+H]$^+$ 262.1266, found 262.1252.

*4.2.2. (R)-N-(2,4,6-Trimethylbenzyl)-2-methyl-2-propanesulfinamide, **3h**.* In accordance with the general procedure for sulfinamides, (*R*)-2-methylpropane-2-sulfinamide (1.00 g, 8.25 mmol), Ti(OEt)$_4$ (1.73 mL, 8.25 mmol), 2,4,6-trimethylbenzaldehyde (1.35 g, 9.08 mmol) in THF (15 mL), and $NaBH_4$ (0.62 g, 16.5 mmol) in THF (2 mL) were used. Column chromatography through silica gel (hexanes/ethyl acetate, 75:25) afforded 1.35 g (65%) of **3h** as a colorless foam. $[\alpha]_D^{23}$ −8.74 (*c* 1.35, $CHCl_3$); IR (film) ν_{max} 3208, 2952, 1453, 1046, 850 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.19 (s, 9H), 2.26 (s, 3H), 2.36 (s, 6H), 3.08 (d, *J*=8 Hz, NH), 4.16 (dd, *J*=8 and 12 Hz, 1H), 4.37 (dd, *J*=3 and 12 Hz, 1H), 6.86 (s, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 19.8, 21.2, 22.9, 43.1, 55.9, 129.4, 131.5, 137.7, 137.8 ppm; ESI-MS (*m*/*z*) 254 [M+H]$^+$, 507 [2M+H]$^+$; ESI-HRMS: calcd *m*/*z* for [$C_{14}H_{23}NOS$+H]$^+$ 254.1579, found 254.1573. Anal. Calcd for $C_{14}H_{23}NOS$ (253.40): C 66.36, H 9.15, N 5.53, S 12.65. Found: C 66.36, H 9.12, N 5.51, S 12.39.

*4.2.3. (R)-(−)-N-4-Fluorobenzyl-2-methyl-2-propanesulfinamide, **3i**.* A one-necked round bottomed flask equipped with a magnetic stirring bar was charged with 4-fluorobenzylamine (2.9 mL, 25 mmol) in THF (10 mL). The solution was cooled at −78 °C, and *n*-BuLi 2.5 M (8.7 mL, 21.8 mmol) was added carefully. After being stirred for 30 min, a solution of (*R*)-*S*-*tert*-butyl *tert*-butanethiosulfinate (+)-**5** (3.05g, 15.6 mmol) in THF (5 mL) was added. The crude was left to reach room temperature overnight. Brine (10 mL) was then added and the layers were separated. The aqueous layer was extracted with Et_2O (2×10 mL). The organic layer was washed with HCl 0.1 N (2×10 mL), dried over anhydrous $MgSO_4$, filtered, and finally evaporated under reduced pressure. The resulting crude was purified by column chromatography through silica gel (SiO_2, hexanes/ethyl acetate, 50:50) to afford 2.23 g (60%) of **3i** as an oil that slowly crystallized. The desired product was recrystallized with hexane affording colorless crystals. $[\alpha]_D^{23}$ −43.6 (*c* 1.0, $CHCl_3$); IR (film): ν_{max} 3196, 2978, 1510, 1220 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.24 (s, 9H), 3.44 (s, 1H), 4.23 (dd, *J*=7 and 14 Hz, 1H), 4.33 (dd, *J*=5 and 14 Hz, 1H), 7.03 (m, 2H), 7.32 (m, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 22.8, 48.9, 56.1, 115.6 (d, J_F=21 Hz), 129.9 (d, J_F=8 Hz) 134.4 (d, J_F=4 Hz), 162.5 (d, J_F=245 Hz) ppm; ^{19}F NMR (376 MHz, CDCl3) δ −115.1 ppm; MS (CI,

NH_3) *m/z*: 460 ($[2M+2H]^+$, 48%), 247 ($[M+NH_4]^+$, 16%), 230 ($[M+H]^+$, 100%).

4.3. General procedure for the synthesis of borane/PNSO ligands (4c,e,g–i)

An oven-dried one-necked round bottomed flask equipped with a magnetic stirring bar was charged with (*R*)-*N*-benzyl-2-methylpropane-2-sulfinamide under a N_2 atmosphere. Anhydrous THF was added, and the solution was cooled to −78 °C. 2.5 M *n*-BuLi was added dropwise to the solution. After stirring for 15 min, chlorophosphines were added via syringe. The solution was stirred for 1 h, during which time the temperature was raised to −20 °C. BH_3–SMe_2 was immediately added and the resulting mixture was stirred for an additional 20 min. The solution was warmed to 0 °C and H_2O was added carefully. Et_2O was then added. The phases were separated and the aqueous phase was washed with Et_2O. The organic layer was dried over $MgSO_4$, filtered, and finally evaporated under reduced pressure. The resulting crude mixture was purified by column chromatography through silica gel to obtain the desired *N*-phosphino sulfinamides protected with borane.

4.3.1. (R)-N-Benzyl-N-(bis(2-methoxyphenyl)phosphino)-2-methyl-2-propanesulfinamide borane complex, ***4c****.* In accordance with the general procedure for borane/PNSO ligands, **3a** (0.200 g, 0.95 mmol), *n*-BuLi (0.53 mL, 1.05 mmol), chlorobis(2-methoxyphenyl)phosphine (0.33 g, 1.14 mmol) in THF (7 mL), and $BH_3 \cdot SMe_2$ (0.14 mL, 1.43 mmol) were used. Column chromatography through silica gel (hexanes/ethyl acetate, 70:30) afforded 0.124 g (28%) of **4c** as a colorless foam. $[\alpha]_D^{23}$ +91.04 (*c* 0.83, $CHCl_3$); IR (film) ν_{max} 2954, 2916, 2353, 1483, 1451 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 0.96–1.67 (br, BH_3), 0.92 (s, 9H), 3.29 (s, 3H), 3.66 (s, 3H), 4.52 (dd, *J*=13.8 and 17.7 Hz, 1H), 4.97 (dd, *J*=9 and 18 Hz, 1H), 6.64 (dd, *J*=4 and 8 Hz, 1H), 6.88 (dd, *J*=5 and 8 Hz, 1H), 7.05 (m, 7H), 7.44 (dt, *J*=8 and 15 Hz, 2H), 7.66 (dd, *J*=8 and 12 Hz, 1H), 7.98 (dd, *J*=6 and 14 Hz, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 23.5, 43.2, 55.0, 55.4, 60.0 (d, J_P=6 Hz), 111.0 (d, J_P=5 Hz), 111.5 (d, J_P=5 Hz), 118.2, 118.8, 119.4, 121.1 (d, J_P=20 Hz), 121.0 (d, J_P=19 Hz), 126.6, 127.7 (d, J_P=9 Hz), 133.3 (d, J_P=2 Hz), 133.7 (d, J_P=2 Hz), 133.9 (d, J_P=9 Hz), 134.7 (d, J_P=13 Hz), 139.2 (d, J_P=2 Hz), 160.8 (d, J_P=1 Hz), 161.3 (d, J_P=4 Hz) ppm; ^{31}P NMR (121 MHz, $CDCl_3$) δ 75.70 (m); ESI-HRMS: calcd for $[C_{25}H_{33}O_3BNPS-H^-]^+$: 468.19281, found 468.19259.

4.3.2. (R)-N-Benzyl-N-(bis(3,5-dimethylphenyl)phosphino)-2-methy-2-lpropanesulfinamide borane complex, ***4e****.* In accordance with the general procedure for borane/PNSO ligands, **3a** (0.200 g, 0.95 mmol), *n*-BuLi (0.53 mL, 1.05 mmol), chlorobis(3,5-dimethylphenyl)phosphine (0.35 g, 1.14 mmol) in THF (7 mL), and $BH_3 \cdot SMe_2$ (0.14 mL, 1.43 mmol) were used. Column chromatography through silica gel (hexanes/ethyl acetate, 70:30) afforded 0.298 g (68%) of **4e** as a colorless foam. $[\alpha]_D^{23}$ +80.87 (c 0.69, $CHCl_3$); IR (film) ν_{max} 2919, 2381, 2304, 1602 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 0.83–1.74 (br, BH_3), 0.89 (s, 9H), 2.28 (s, 6H), 2.34 (s, 6H), 4.54 (t, *J*=17 Hz, 1H), 4.87 (dd, *J*=9 and 17 Hz, 1H), 7.04–7.20 (m, 5H), 7.28–7.35 (m, 4H), 7.37–7.43 (m, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.4, 21.5, 23.7, 44.2 (d, J_P=3 Hz), 60.5 (d, J_P=5 Hz), 127.1, 127.9, 128.7, 129.1, 129.7, 130.4 (d, J_P=11 Hz), 131.6 (d, J_P=11 Hz), 133.6 (d, J_P=2 Hz), 134.0 (d, J_P=2 Hz), 137.9 (d, J_P=2 Hz), 138.3 (d, J_P=11 Hz), 138.4 (d, J_P=11 Hz) ppm; ^{31}P NMR (121 MHz, $CDCl_3$) δ 78.70 (m); ESI-HRMS: calcd *m/z* for $[C_{27}H_{37}BNOPS-H^-]^+$ 464.23428, found 464.23415.

4.3.3. (R)-N-(Diphenylphosphino)-N-(naphthalen-2-ylmethyl)-2-methyl-2-propanesulfinamide borane complex, ***4g****.* In accordance with the general procedure for borane/PNSO ligands, **3g** (0.500 g, 1.91 mmol), *n*-BuLi (0.84 mL, 2.10 mmol), chlorodiphenylphosphine (0.43 mL, 2.29 mmol) in THF (14 mL) and $BH_3 \cdot SMe_2$ (0.27 mL, 2.87 mmol) were used. Column chromatography through silica gel (hexanes/ethyl acetate, 70:30) afforded 0.696 g (79%) of **4g** as a colorless foam. $[\alpha]_D^{23}$ +82.43 (*c* 0.74, $CHCl_3$); IR (film) ν_{max} 3415, 2381, 2283, 1628 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 0.91–1.78 (br, BH_3), 0.89 (s, 9H), 4.71 (t, *J*=17 Hz, 1H), 5.07 (dd, *J*=9 and 17 Hz, 1H), 7.29–7.58 (m, 9H), 7.61–7.69 (m, 3H), 7.70–7.90 (m, 5H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 23.6, 44.1 (d, J_P=3 Hz), 66.6 (d, J_P=5 Hz), 125.9, 126.0, 126.5, 127.7 (d, J_P=16 Hz), 127.9 (d, J_P=16 Hz), 128.7 (d, J_P=8 Hz), 128.8 (d, J_P=8 Hz), 128.9, 129.3, 129.5, 130.0, 131.8 (d, J_P=2 Hz), 132.3 (d, J_P=2 Hz), 132.6, 132.8 (d, J_P=11 Hz), 132.9, 134.1 (d, J_P=11 Hz), 135.1 (d, J_P=2 Hz) ppm; ^{31}P NMR (121 MHz, $CDCl_3$) δ 78.09 (m); ESI-HRMS: calcd *m/z* for $[C_{27}H_{31}BNOPS-H^-]^+$ 458.1879, found 458.1871.

4.3.4. (R)-N-(Diphenylphosphino)-N-(2,4,6-trimethylbenzyl)-2-methyl-2-propanesulfinamide borane complex, ***4h****.* In accordance with the general procedure for borane/PNSO ligands, **3h** (0.500 g, 1.97 mmol), *n*-BuLi (0.87 mL, 2.17 mmol), chlorodiphenylphosphine (0.45 mL, 2.36 mmol) in THF (14 mL), and $BH_3 \cdot SMe_2$ (0.28 mL, 2.96 mmol) were used. Column chromatography through silica gel (hexanes/ethyl acetate, 70:30) afforded 0.729 g (82%) of **4h** as a colorless foam. $[\alpha]_D^{23}$ +72.36 (*c* 1.40, $CHCl_3$); IR (film) ν_{max} 2959, 2391, 1435, 755 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 0.48 (s, 9H), 0.77–1.81 (br, BH_3), 2.21 (s, 3H), 2.52 (s, 6H), 4.69 (dd, *J*=2 and 16 Hz, 1H), 4.93 (dd, *J*=8 and 16 Hz, 1H), 6.75 (s, 2H), 7.47 (m, 2H), 7.53 (m, 4H), 7.87 (m, 4H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.0, 21.2, 23.6, 43.3 (br), 61.3 (d, J_P=4 Hz), 128.6 (d, J_P=11 Hz), 128.9 (d, J_P=10 Hz), 129.6, 130.3, 130.8, 130.9, 131.5 (d, J_P=2 Hz), 132.3 (d, J_P=2 Hz), 132.7 (d, J_P=10 Hz), 134.2 (d, J_P=11 Hz), 138.1, 139.6 ppm; ^{31}P NMR (121 MHz, $CDCl_3$) δ 80.74 (m); ESI-HRMS: calcd for $[C_{26}H_{35}BNOPS-H^-]^+$ 450.2192, found 450.2192.

4.3.5. (R)-(+)-N-Diphenylphosphino-N-4-fluorobenzyl-2-methyl-2-propansulfinamide borane complex, ***4i****.* In accordance with the general procedure for borane/PNSO ligands, **3i** (1.15 g, 5 mmol), *n*-BuLi (2.2 mL, 5.5 mmol), chlorodiphenylphosphine (0.98 mL, 0.55 mmol) in THF (20 mL) and $BH_3 \cdot SMe_2$ (0.58 mL, 6 mmol) were used. Column chromatography through silica gel (80:20 hexanes/ethyl acetate) afforded 1.88 g (88%) of **4i** as a colorless foam. $[\alpha]_D^{23}$ +99.0 (*c* 1.0, $CHCl_3$); IR (film) ν_{max} 3058, 2963, 2389, 1510, 1437, 1086 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 0.88 (s, 9H), 1.00–1.80 (br, BH_3), 4.60 (t, *J*=17 Hz, 1H), 4.82 (dd, *J*=8 and 17 Hz, 1H), 6.84 (m, 2H), 7.35 (m, 2H), 7.38–7.56 (m, 6H), 7.70–7.82 (m, 4H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 23.8, 43.9 (d, J_P=4 Hz), 60.8 (d, J_P=5 Hz), 114.8 (d, J_F=21 Hz), 128.6 (d, *J*=11 Hz), 128.8 (d, *J*=11 Hz), 129.4 (d, J_P=19 Hz), 129.9, 131.0 (d, *J*=8 Hz), 131.8 (d, *J*=3 Hz), 132.4 (d, *J*=2 Hz), 132.6 (d, *J*=11 Hz), 133.1 (m), 134.3 (d, *J*=10 Hz), 162.0 (d, J_F=244 Hz) ppm; ^{31}P NMR (121 MHz, $CDCl_3$) δ 76.9 ppm; ^{19}F NMR (376 MHz, $CDCl_3$) δ −115.8 ppm; ESI-HRMS: calcd for $[C_{23}H_{28}BFNOPS-H^-]^+$: 426.1628, found 426.1623.

4.3.6. (R)-(+)-N-Benzyl-N-di-o-tolylphosphino-2-methyl-2-propanesulfinamide, ***1b****.* In accordance with the general procedure for the borane/PNSO ligands, **3a** (0.415 g, 1.96 mmol), *n*-BuLi (0.86 mL, 2.15 mmol), chlorodiphenylphosphine (0.535 mL, 2.15 mmol) in THF (12 mL) were used. In this case, the ligand is unreactive toward borane and so P-protection is not necessary. Column chromatography through silica gel (80:20 hexanes/ethyl acetate) afforded 0.615 g (74%) of **1b** as a colorless solid. $[\alpha]_D^{23}$ +26.6 (*c* 1.0, $CHCl_3$); IR (film) ν_{max} 3056, 2960, 1471, 1453, 1361 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 0.95 (s, 9H), 2.07 (d, *J*=2 Hz, 3H), 2.51 (s, 3H), 4.50 (t, *J*=15 Hz, 1H), 4.61 (dd, *J*=10 and 15 Hz, 1H), 7.02–7.30 (m, 12H), 7.71 (m, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.0 (d, J_P=21 Hz), 21.7 (d, J_P=23 Hz), 23.5 (d, J_P=2 Hz), 48.7 (d, J_P=15 Hz), 59.6, 125.7, 126.6, 127.2, 128.1, 129.07, 129.12 (d, J_P=2 Hz), 130.1, 130.5 (d, J_P=5 Hz), 130.6 (d, J_P=4 Hz), 131.7 (d, J_P=3 Hz), 134.5, 135.2 (d, J_P=11 Hz),

135.3 (d, J_P=21 Hz), 138.1(d, J_P=3 Hz), 140.6 (d, J_P=27 Hz), 142.6 (d, J_P=31 Hz) ppm; ^{31}P NMR (121 MHz, $CDCl_3$) δ 43.4 ppm; ESI-HRMS: calcd for $[C_{25}H_{30}NOPS+H]^+$ 424.1864, found 424.1858.

4.3.7. (R)-N-Benzy-N-(bis(4-(trifluoromethyl)phenyl)phosphino)-2-methyl-2-propanesulfinamide, ***1d****.* In accordance with the general procedure for borane/PNSO ligands, **3a** (0.200 g, 0.95 mmol), *n*-BuLi (0.53 mL, 1.05 mmol), chlorobis(4-(trifluoromethyl)phenyl)phosphine (0.42 g, 1.14 mmol) in THF (6 mL) were used. In this case, the ligand is unreactive toward borane and so P-protection is not necessary. Column chromatography through silica gel (hexanes/ethyl acetate, 90:10) afforded 0.088 g (17%) of **1d** as a colorless foam. $[\alpha]_D^{23}$ +56.75 (*c* 0.615, $CHCl_3$); IR (film) ν_{max} 2958, 2917, 1459, 1323, 1065 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.95 (s, 9H), 4.62 (t, *J*=17 Hz, 1H), 4.90 (dd, *J*=9 and 17 Hz, 1H), 7.09–7.18 (m, 3H), 7.27 (m, 2H), 7.63 (m, 2H), 7.74 (m, 2H), 7.84 (m, 2H), 7.92 (m, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 23.7, 44.8 (d, J_P=4 Hz), 61.3 (d, J_P=5 Hz), 123.46 (q, J_F=273 Hz), 123.50 (q, J_F=273), 125.5–125.9 (m), 127.6, 128.2, 128.8, 133.1 (d, J_P=15 Hz), 133.2 (d, J_P=11 Hz), 133.5 (d, J_P=15 Hz), 133.95 (dq, J_F=2 Hz and J_P=33 Hz), 134.4 (dq, J_F=2 Hz and J_P=33 Hz), 134.5 (d, J_P=11 Hz), 136.5 (d, J_P=2 Hz) ppm; ^{31}P NMR (121 MHz, $CDCl_3$) δ 76.32 (s); ESI-HRMS: calcd *m*/*z* for $[C_{25}H_{24}F_6NOPS+H]^+$ 532.12932, found 532.12919.

4.4. General procedure for the synthesis of borane/free PNSO ligands (1c,e,g–i)

An oven-dried one-necked round bottomed flask equipped with a magnetic stirring bar was charged with the corresponding *N*-phosphino sulfinamide borane complex and DABCO under a N_2 atmosphere. After adding anhydrous toluene, the reaction took place at 40 °C. After stirring for 1 h, the crude was evaporated under reduced pressure. The resulting crude mixture was purified by column chromatography through silica gel to obtain the desired *N*-phosphino sulfinamides.

4.4.1. (R)-N-Benzyl-N-(bis(2-methoxyphenyl)phosphino)-2-methyl-2-propanesulfinamide, ***1c****.* In accordance with the general procedure for borane/free PNSO ligands, **4c** (0.084 g, 0.18 mmol), DABCO (0.030 g, 0.27 mmol) in toluene (1.5 mL) were used. Column chromatography through silica gel (hexanes/ethyl acetate, 70:30) afforded 0.076 g (93%) of **1c** as a colorless foam. $[\alpha]_D^{23}$ −61.20 (*c* 0.50, $CHCl_3$); IR (film) ν_{max} 2959, 2360, 1472, 1251, 1069 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.88 (s, 9H), 3.57 (s, 3H), 3.92 (s, 3H), 4.29 (t, *J*=16 Hz, 1H), 4.74 (t, *J*=16 Hz, 1H), 6.76–6.89 (m, 3H), 7.02–7.45 (m, 9H), 7.88 (m, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 23.2, 47.0 (d, J_P=16 Hz), 55.40, 55.44, 59.2 (d, J_P=2 Hz), 110.1 (d, J_P=2 Hz), 110.3, 120.5, 121.5, 124.3 (d, J_P=10 Hz), 124.6 (d, J_P=26 Hz), 126.9, 128.1, 128.6 (d, J_P=2 Hz), 130.5, 131.7, 132.8 (d, J_P=4 Hz), 134.7, 139.0 (d, J_P=2 Hz), 160.3 (d, J_P=17 Hz), 161.2 (d, J_P=20 Hz) ppm; ^{31}P NMR (121 MHz, $CDCl_3$) δ 46.90 (s); ESI-HRMS: calcd *m*/*z* for $[C_{25}H_{30}NO_3PS+H]^+$ 456.17568, found 456.17577.

4.4.2. (R)-N-Benzyl-N-(bis(3,5-dimethylphenyl)phosphino)-2-methyl-2-propanesulfinamide, ***1e****.* In accordance with the general procedure for borane/free PNSO ligands, **4e** (0.245 g, 0.53 mmol), DABCO (0.090 g, 0.79 mmol) in toluene (1.5 mL) were used. Column chromatography through silica gel (hexanes/ethyl acetate, 70:30) afforded 0.170 g (71%) of **1e** as a colorless foam. $[\alpha]_D^{23}$ +57.68 (*c* 0.69, $CHCl_3$); IR (film) ν_{max} 2914, 1958, 1451, 1075, 762 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.96 (s, 9H), 2.27 (s, 6H), 2.31 (s, 6H), 4.42 (dd, *J*=12 and 16 Hz, 1H), 4.57 (t, *J*=9 and 16 Hz, 1H), 6.94 (s, 1H), 7.03 (s, 1H), 7.09–7.23 (m, 9H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.4, 21.5, 23.7 (d, J_P=2 Hz), 49.6 (d, J_P=11 Hz), 59.5 (d, J_P=2 Hz), 127.1, 128.1, 129.1, 129.9 (d, J_P=20 Hz), 130.6, 131.6, 131.9 (d, J_P=23 Hz), 136.6 (d, J_P=18 Hz), 137.0 (d, J_P=14 Hz), 137.9 (d, J_P=6 Hz), 138.0 (d, J_P=7 Hz), 138.5 (d, J_P=1 Hz) ppm; ^{31}P NMR (121 MHz, $CDCl_3$) δ 60.25 (s); ESI-HRMS: calcd *m*/*z* for $[C_{27}H_{34}NOPS+H]^+$ 452.2173, found 452.2177.

4.4.3. (R)-N-(Diphenylphosphino)-N-(naphthalen-2-ylmethyl)-2-methyl-2-propanesulfinamide, ***1g****.* In accordance with the general procedure for borane/free PNSO ligands, **4g** (0.200 g, 0.44 mmol), DABCO (0.074 g, 0.66 mmol) in toluene (1.5 mL) were used. Column chromatography through silica gel (hexanes/ethyl acetate, 70:30) afforded 0.160 g (82%) of **1g** as a colorless foam. $[\alpha]_D^{23}$ +32.70 (*c* 1.00, $CHCl_3$); IR (film) ν_{max} 3053, 2959, 2917, 2231, 1428, 1075, 814 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.95 (s, 9H), 4.61 (dd, *J*=12 and 16 Hz, 1H), 4.78 (dd, *J*=9 and 16 Hz, 1H), 7.23–7.27 (m, 1H), 7.30–7.37 (m, 3H), 7.30–7.43 (m, 5H), 7.52 (s, 1H), 7.55–7.70 (m, 6H), 7.74 (m, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 23.7 (d, J_P=2 Hz), 49.3 (d, J_P=11 Hz), 59.6 (d, J_P=3 Hz), 125.9, 126.0, 126.8 (d, J_P=1 Hz), 127.7, 127.89 (d, J_P=1 Hz), 127.94, 128.5, 128.6, 128.7, 129.1, 130.1, 132.2 (d, J_P=20 Hz), 132.6, 133.2, 134.4 (d, J_P=22 Hz), 135.8 (d, J_P=2 Hz), 136.9 (d, J_P=18 Hz), 137.4 (d, J_P=15 Hz) ppm; ^{31}P NMR (121 MHz, $CDCl_3$) δ 59.77 (s); ESI-HRMS: calcd *m*/*z* for $[C_{27}H_{28}NOPS+H]^+$ 446.1708, found 446.1707.

4.4.4. (R)-N-(Diphenylphosphino)-N-(2,4,6-trimethylbenzyl)-2-methyl-2-propanesulfinamide, ***1h****.* In accordance with the general procedure for borane/free PNSO ligands, **4h** (0.150 g, 0.33 mmol), DABCO (0.056 g, 0.50 mmol) in toluene (1.5 mL) were used. Column chromatography through silica gel (hexanes/ethyl acetate, 90:10) afforded 0.138 g (95%) of **1h** as a colorless foam. $[\alpha]_D^{23}$ −32.80 (*c* 0.25, $CHCl_3$); IR (film) ν_{max} 2910, 1431, 1077, 739 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.99 (s, 9H), 2.24 (s, 3H), 2.35 (br s, 6H), 4.10 (dd, *J*=3 and 12 Hz, 1H), 4.85 (m, 1H), 6.80 (s, 2H), 7.28–7.40 (m, 6H), 7.51–7.61 (m, 4H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.4, 21.2, 24.7 (d, J_P=2 Hz), 42.3 (br), 59.6, 127.8 (d, J_P=13 Hz), 128.2 (d, J_P=11 Hz), 128.30 (d, J_P=13 Hz), 128.31, 129.1, 129.7 (d, J_P=7 Hz), 130.2, 131.4 (br, J_P=20 Hz), 133.1 (d, J_P=9 Hz), 135.6 (d, J_P=25 Hz), 137.9, 138.9 (d, J_P=1 Hz) ppm; ^{31}P NMR (121 MHz, $CDCl_3$) δ 49.01 (s); ESI-HRMS: calcd *m*/*z* for $[C_{26}H_{32}NOPS+H]^+$ 438.2021, found 438.2028.

4.4.5. (R)-(+)-N-Diphenylphosphino-N-4-fluorobenzyl-2-methyl-2-propanesulfinamide, ***1i****.* In accordance with the general procedure for borane/free PNSO ligands, **4i** (1.75 g, 4.1 mmol), DABCO (0.690 g, 6.2 mmol) in toluene (30 mL) were used. Column chromatography through silica gel (90:10 hexanes/ethyl acetate) afforded 1.49 g (88%) of **1i** as a colorless foam. $[\alpha]_D^{23}$ +47.5 (*c* 1.0, $CHCl_3$); IR (film) ν_{max} 3054, 2960, 1603, 1509, 1075 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 0.95 (s, 9H), 4.50 (d, *J*=10 Hz, 2H), 6.86 (m, 2H), 7.11 (m, 2H), 7.30–7.42 (m, 6H), 7.48–7.60 (m, 4H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 23.8 (d, J_P=2 Hz), 48.7 (d, J_P=12 Hz), 59.7 (d, J_P=2 Hz), 115.1 (d, J_F=21 Hz), 128.56 (d, *J*=5 Hz), 128.63 (d, *J*=5 Hz), 129.1, 130.1, 130.9 (dd, *J*=2 and 8 Hz), 132.0 (d, *J*=20 Hz), 134.0 (m), 134.5 (d, *J*=23 Hz), 136.8 (d, J_P=18 Hz), 137.3 (d, J_P=14 Hz), 162.1 (d, J_F=244 Hz) ppm; ^{31}P NMR (121 MHz, $CDCl_3$) δ 58.4 ppm; ^{19}F NMR (376 MHz, $CDCl_3$) δ −115.7 ppm. Anal. Calcd for $C_{23}H_{25}FNOPS$ C 66.81, H 6.09, N 3.39, S 7.75. Found C 66.40, H 6.17, N 3.39, S 7.72.

4.5. General procedure for intramolecular [2+2+2] cycloaddition reactions catalyzed by Rh(I)/PNSO formed in situ (Tables 2 and 3)

In a 25 mL flask, a mixture of $[Rh(COD)_2]BF_4$ (0.2 equiv) and ligand **1a** (0.1 equiv) was dissolved in the appropriate solvent (3 mL) (see Tables 2 and 3). Hydrogen gas was introduced to the catalyst solution and stirred for 30 min. The resulting mixture was then concentrated to dryness. Solvent (8 mL) was added and the solution was stirred under a N_2 atmosphere. Enediyne (**6**, **8**, **9**) (1 equiv) in solvent (2 mL) was then added to the previous solution and the reaction mixture was stirred under N_2 until completion

(for temperatures and reaction times see Tables 2 and 3). The solvent was evaporated and the residue was purified by column chromatography through silica gel.

4.5.1. Cyclohexadiene derivative ***7***[4]. Column chromatography: hexanes/ethyl acetate (8:2); colorless solid; mp 187–189 °C; IR (ATR) ν_{max} 2846, 1366, 1152, 1046 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 2.71–2.76 (m, 2H), 3.43–3.49 (m, 2H), 4.24–4.30 (m, 2H), 4.35 (d, J=13 Hz, 2H), 4.55 (d, J=13 Hz, 2H), 5.86 (s, 2H) ppm; ^{13}C NMR (75 MHz, $CDCl_3$) δ 43.5, 69.1, 74.0, 114.3, 141.1 ppm. The ee was determined with HPLC analysis using a chiral column (Kromasil 100 TBB column, 4.6×250 mm, 5 μm, rt); eluent: 99% heptane/1% THF, flow rate: λ=254 nm; t_R=8.4 min (major isomer), t_R=8.1 min (minor isomer).

4.6. General procedure for intermolecular [2+2+2] cycloaddition reactions catalyzed by Rh(I)/PNSO formed in situ (Table 4)

In a 25 mL flask, a mixture of $[Rh(COD)_2]BF_4$ (0.2 equiv) and ligand **1a** (0.1 equiv) was dissolved in the appropriate solvent (3 mL) (see Table 4). Hydrogen gas was introduced to the catalyst solution and stirred for 30 min. The resulting mixture was then concentrated to dryness. Solvent (2 mL) was added and the solution was stirred under a N_2 atmosphere. A solution of alkyne **13** (5 equiv) in the appropriate solvent (3 mL) was then added at room temperature followed by the diyne **12** (1 equiv) solution (3 mL) over a 10-min period. The reaction mixture was then stirred until completion (for temperatures and reaction times see Table 4). The solvent was evaporated and the residue was purified by column chromatography through silica gel.

4.6.1. Compound ***14ab*** *(entry 3, Table 4).* Column chromatography: hexanes/ethyl acetate (7:3); colorless solid; mp 175–177 °C (dec); IR (ATR) ν_{max} 3493, 2921, 1332, 1158 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.56 (br abs, 1H), 2.15 (s, 3H), 2.16 (s, 3H), 2.41 (s, 3H), 4.56 (s, 2H), 4.57 (s, 2H), 4.63 (ap d, J=4 Hz, 2H), 7.05 (s, 1H), 7.32 (AA′ part, AA′BB′ system, J=8 Hz, 2H), 7.78 (BB′ part, AA′BB′ system, J=8 Hz, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.7, 18.3, 21.6, 53.5, 53.7, 63.2, 127.6, 128.1, 128.9, 129.9, 133.9, 134.6, 135.9, 138.6, 143.8 ppm; ESI-MS (m/z) 332.1 $[M+H]^+$, 354.1 $[M+Na]^+$. Anal. Calcd for $C_{18}H_{21}NO_2S$: C, 65.23; H, 6.39; N, 4.23. Found: C, 65.46; H, 6.78; N, 4.26.

4.6.2. Compound ***14ad*** *(entry 5, Table 4).* Column chromatography: hexanes/ethyl acetate (7:3); colorless solid; mp 193–195 °C; IR (ATR) ν_{max} 2920, 2850, 1722, 1344, 1319, 1216, 1158 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 2.20 (s, 6H), 2.42 (s, 3H), 3.84 (s, 6H), 4.61 (s, 4H), 7.33 (d, J=8 Hz, 2H) 7.77 (d, J=8 Hz, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 16.7, 21.9, 52.9, 54.3, 127.9, 129.5, 130.4, 132.6, 134.0, 138.5, 144.5, 168.6 ppm; ESI-MS (m/z) 418 $[M+H]^+$; ESI-HRMS: calcd m/z for $[C_{21}H_{23}NSO_6+H]^+$ 418.1319, found 418.1316.

4.6.3. Hexamethyl ester benzene derivative, ***15***[11] *(entry 6, Table 4).* Column chromatography hexanes/ethyl acetate (7:3); colorless solid; mp 181–183 °C (lit.[11] mp 186 °C); IR (ATR) ν_{max} 2921, 1726, 1442, 1225 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 3.88 (s, 18H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 53.5, 133.9, 165.1 ppm; ESI-MS (m/z) 427 $[M+H]^+$, 444 $[M+NH_4]^+$, 449 $[M+Na]^+$.

4.6.4. Compound ***14ba*** *(entry 7, Table 4).* Column chromatography: methylene chloride/hexanes (6:4); orange pale oil; IR (ATR) ν_{max} 2924, 1730, 1243 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.28 (t, J=7 Hz, 6H), 2.13 (s, 3H), 2.25 (s, 3H), 3.58 (s, 2H), 3.59 (s, 2H), 4.23 (q, J=7 Hz, 4H), 6.90 (s, 1H), 7.25–7.33 (m, 3H), 7.36–7.41 (m, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.2, 16.8, 18.7, 39.7, 40.3, 59.7, 61.9, 126.7, 128.1, 128.4, 129.5, 130.0, 130.6, 137.8, 139.5, 141.1, 142.0, 172.1 ppm; ESI-HRMS: calcd m/z for $[C_{23}H_{26}O_4+Na]^+$ 389.1723, found 389.1719.

4.6.5. Compound ***14ca*** *(entries 8 and 9, Table 4).* Column chromatography: hexanes/ethyl acetate (24:0.2); colorless solid; mp 74–76 °C (lit.[8w] mp 75–76 °C); IR (ATR) ν_{max} 2921, 2850, 1478 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 2.11 (ap quint, J=8 Hz, 2H), 2.95 (ap q, J=8 Hz, 4H), 7.25–7.48 (m, 6H), 7.54–7.60 (m, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 25.6, 32.7, 33.0, 123.3, 124.7, 125.3, 126.9, 127.2, 128.7, 139.5, 141.8, 143.5, 145.0 ppm.

4.6.6. Compound ***14cb*** *(entry 10, Table 4).* Column chromatography: hexanes/ethyl acetate (16:2); colorless solid; mp 70–72 °C (lit.[8w] mp 71–72 °C); IR (ATR): 3322, 2921, 1345, 1027 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.64 (br abs, 1H), 2.08 (quint, J=8 Hz, 2H), 2.90 (dt, J=3 and 8 Hz, 4H), 4.64 (s, 2H), 7.10–7.24 (m, 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 25.6, 32.7, 32.9, 65.7, 123.4, 124.5, 125.3, 138.9, 143.9, 144.8 ppm.

4.6.7. Compound ***14cc*** *(entry 11, Table 4).* Column chromatography: hexanes/ethyl acetate (1:1); colorless solid; mp 93–95 °C (lit.[12] mp 90–92 °C); IR (ATR) ν_{max} 3211, 2928, 994 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 2.07 (quint, J=7 Hz, 2H), 2.89 (t, J=7 Hz, 4H), 3.35 (br abs, 2H), 4.64 (s, 4H), 7.19 (s, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 25.5, 32.7, 64.4, 126.0, 137.5, 144.8 ppm.

4.6.8. Compound ***14da***[13] *(entries 12 and 13, Table 4).* Column chromatography: hexanes/dichloromethane (1:1); colorless solid; mp 170–173 °C; IR (ATR) ν_{max} 2919, 2850, 1465, 1343, 1160 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 2.38 (s, 3H), 4.64 (br abs, 4H), 7.20 (d, J=8 Hz, 1H), 7.26–7.36 (m, 4H), 7.37–7.44 (m, 3H), 7.45–7.52 (m, 2H), 7.77 (d, J=8 Hz, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 21.7, 53.8, 53.9, 121.5, 123.1, 127.1, 127.3, 127.7, 127.8, 129.0, 130.0, 133.9, 135.3, 137.0, 140.7, 141.5, 143.9 ppm; ESI-MS (m/z) 372 $[M+Na]^+$, 388 $[M+K]^+$.

4.6.9. Compound ***14ea*** *(entry 14, Table 4).* Column chromatography: methylene chloride/hexanes (20:5); yellow oil;[14] IR (ATR) ν_{max} 2979, 2930, 1730 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.27 (t, J=7.2 Hz, 6H), 3.63 (s, 2H), 3.65 (s, 2H), 4.22 (q, J=7 Hz, 4H), 7.24–7.26 (m, 1H), 7.29–7.34 (m, 1H), 7.38–7.43 (m, 4H), 7.53–7.57 (m, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.1, 40.3, 40.6, 60.6, 61.9, 123.1, 124.6, 126.2, 127.1, 127.2, 128.8, 139.3, 140.4, 140.8, 141.4, 171.8 ppm.

4.6.10. Compound ***14eb*** *(entry 15, Table 4).* Column chromatography: hexanes/ethyl acetate (from 9:1 to 8:2); yellow oil;[8w] IR (ATR) ν_{max} 3452, 2981, 1726, 1249 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.25 (t, J=7 Hz, 6H), 1.72 (br abs, 1H), 3.57 (br s, 4H), 4.20 (q, J=7 Hz, 4H), 4.63 (s, 2H), 7.13–7.21 (m, 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.1, 40.3, 40.5, 60.6, 61.8, 65.5, 123.1, 124.4, 126.1, 139.7, 139.9, 140.6, 171.7 ppm.

4.6.11. Compound ***14ec*** *(Entry 16, Table 4).* Column chromatography: methylene chloride/hexanes/ethyl acetate (8:5:7); colorless solid; mp 84–86 °C (lit.[9d] oil); IR (ATR) ν_{max} 3272, 2919, 1725, 1267, 1194, 1065 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 1.25 (t, J=7 Hz, 6H), 3.21 (br abs, 2H), 3.56 (s, 4H), 4.19 (t, J=7 Hz, 4H), 4.65 (s, 4H), 7.17 (s, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 14.1, 40.3, 60.6, 61.9, 64.3, 125.7, 138.5, 140.5, 171.7 ppm.

4.6.12. Compound ***14fa*** *(entry 17, Table 4).* Column chromatography: methylene chloride/hexanes (1:1); colorless solid; mp 80–82 °C (lit.[15] yellow oil); IR (ATR) ν_{max} 2855, 1479, 1037 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 5.16 (s, 2H), 5.17 (s, 2H), 7.30 (d, J=8 Hz, 1H), 7.32–7.38 (m, 1H), 7.41–7.51 (m, 4H), 7.55–7.59 (m, 2H) ppm;

^{13}C NMR (100 MHz, $CDCl_3$) δ 73.5, 73.6, 119.8, 121.3, 126.6, 127.3, 127.4, 128.9, 138.3, 140.0, 140.9, 141.1 ppm.

4.6.13. Compound ***14fb*** *(entry 18, Table 4).* Column chromatography: methylene chloride/hexanes/ethyl acetate (from 20:16:2 to 20:12:2); colorless solid; mp 69–71 °C (lit.[8w] mp 70–71 °C); IR (ATR) ν_{max} 3318, 2919, 1367, 1034 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.16 (br abs, 1H), 4.68 (s, 2H), 5.06 (s, 2H), 5.07 (s, 2H), 7.18–7.26 (m, 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 65.2, 73.4, 119.7, 121.1, 126.3, 138.5, 139.6, 140.4 ppm.

4.6.14. Compound ***14fc*** *(entry 19, Table 4).* Column chromatography: methylene chloride/hexanes/ethyl acetate (5:1:4); colorless solid; mp 108–110 °C (lit.[16] thick gum); IR (ATR) ν_{max} 3244, 2853, 1068, 995 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.12 (br abs, 2H), 4.73 (s, 4H), 5.07 (s, 4H), 7.22 (s, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$) δ 64.3, 73.5, 122.4, 138.9, 139.5 ppm.

Acknowledgements

We would like to thank the Spanish MICINN (projects CTQ2008-05409 and CTQ2008-00763), IRB Barcelona, and the Generalitat de Catalunya (projects 2009SGR637 and 2009SGR00901) for their financial support. S.B. thanks University of Girona (UdG) and T.L. thanks AGAUR for a predoctoral fellowship. We also acknowledge the Research Technical Services of the UdG for spectral data.

Supplementary data

NMR spectra of PNSO ligands **1b**–**i**, cyclohexadiene derivative **7**, and benzene derivatives **14** and **15**. Supplementary data associated with this article can be found in online version at doi:10.1016/j.tet.2010.09.009.

References and notes

1. For recent reviews, see: (a) Saito, S.; Yamamoto, Y. *Chem. Rev.* **2000**, *100*, 2901–2915; (b) Varela, J. A.; Saá, C. *Chem. Rev.* **2003**, *103*, 3787–3801; (c) Yamamoto, Y. *Curr. Org. Chem.* **2005**, *9*, 503–519; (d) Kotha, S.; Brahmachary, E.; Lahiri, K. *Eur. J. Org. Chem.* **2005**, 4741–4767; (e) Chopade, P. R.; Louie, J. *Adv. Synth. Catal.* **2006**, *348*, 2307–2327; (f) Gandon, V.; Aubert, C.; Malacria, M. *Chem. Commun.* **2006**, 2209–2217; (g) Heller, B.; Hapke, M. *Chem. Soc. Rev.* **2007**, *36*, 1085–1094; (h) Tanaka, K. *Synlett* **2007**, 1977–1993; (i) Agenet, N.; Buisine, O.; Slowinski, F.; Gandon, V.; Aubert, C.; Malacria, M. *Org. React.* **2007**, *68*, 1–302; (j) Varela, J. A.; Saá, C. *Synlett* **2008**, 2571–2578; (k) Shibata, T.; Tsuchikama, K. *Org. Biomol. Chem.* **2008**, *6*, 1317–1323; (l) Galan, B. R.; Rovis, T. *Angew. Chem., Int. Ed.* **2009**, *48*, 2830–2834; (m) Tanaka, K. *Chem.—Asian J.* **2009**, *4*, 508–518.
2. (a) Solà, J.; Revés, M.; Riera, A.; Verdaguer, X. *Angew. Chem., Int. Ed.* **2007**, *46*, 5020–5023; (b) Ji, Y.; Riera, A.; Verdaguer, X. *Org. Lett.* **2009**, *11*, 4346–4349; (c) Revés, M.; Riera, A.; Verdaguer, X. *Eur. J. Inorg. Chem.* **2009**, 4446–4453.
3. Achard, T.; Benet-Buchholz, J.; Riera, A.; Verdaguer, X. *Organometallics* **2009**, *28*, 480–487.
4. Tanaka, K.; Nishida, G.; Sagae, H.; Hirano, M. *Synlett* **2007**, 1426–1430.
5. Shibata, T.; Kurokawa, H.; Kanda, K. *J. Org. Chem.* **2007**, *72*, 6521–6525.
6. (a) González, I.; Pla-Quintana, A.; Roglans, A. *Synlett* **2009**, 2844–2848. For examples of air-tolerant Ru- and Co-catalyzed [2+2+2] cycloadditions, respectively, see: (b) Adriaenssens, L.; Severa, L.; Šálová, T.; Císařová, I.; Pohl, R.; Šaman, D.; Rocha, S. V.; Finney, N. S.; Pospíšil, L.; Slavíček, P.; Teplý, F. *Chem.—Eur. J.* **2009**, *15*, 1072–1076; (c) Geny, A.; Agenet, N.; Iannazzo, L.; Malacria, M.; Aubert, C.; Gandon, V. *Angew. Chem., Int. Ed.* **2009**, *48*, 1810–1813.
7. (a) Pla-Quintana, A.; Roglans, A.; Torrent, A.; Moreno-Mañas, M.; Benet-Buchholz, J. *Organometallics* **2004**, *23*, 2762–2767; (b) Torrent, A.; González, I.; Pla-Quintana, A.; Roglans, A.; Moreno-Mañas, M.; Parella, T.; Benet-Buchholz, J. *J. Org. Chem.* **2005**, *70*, 2033–2041; (c) González, I.; Bouquillon, S.; Roglans, A.; Muzart, J. *Tetrahedron Lett.* **2007**, *48*, 6425–6428; (d) Brun, S.; Garcia, L.; González, I.; Torrent, A.; Dachs, A.; Pla-Quintana, A.; Parella, T.; Roglans, A. *Chem. Commun.* **2008**, 4339–4341; (e) Ref. 6a; (f) Dachs, A.; Torrent, A.; Roglans, A.; Parella, T.; Osuna, S.; Solà, M. *Chem.—Eur. J.* **2009**, *15*, 5289–5300.
8. For selected examples of [2+2+2] cycloadditions of diynes with monoynes using rhodium catalysts, see: (a) Sedlák, D.; Novák, P.; Kotora, M.; Bartunek, P. *J. Med. Chem.* **2010**, *53*, 4290–4294; (b) Wu, W.; Zhang, X. Y.; Kang, S. X. *Chin. Chem. Lett.* **2010**, *21*, 18–22; (c) Tanaka, K.; Sawada, Y.; Aida, Y.; Thammathevo, M.; Tanaka, R.; Sagae, H.; Otake, Y. *Tetrahedron* **2010**, *66*, 1563–1569; (d) Garcia, L.; Pla-Quintana, A.; Roglans, A. *Org. Biomol. Chem.* **2009**, *7*, 5020–5027; (e) Kotha, S.; Khedkhar, P. *Eur. J. Org. Chem.* **2009**, 730–738; (f) Komine, Y.; Kamisawa, A.; Tanaka, K. *Org. Lett.* **2009**, *11*, 2361–2364; (g) Suda, T.; Noguchi, K.; Hirano, M.; Tanaka, K. *Chem.—Eur. J.* **2008**, *14*, 6593–6596; (h) Novák, P.; Cíhalová, S.; Otmar, M.; Hocek, M.; Kotora, M. *Tetrahedron* **2008**, *64*, 5200–5207; (i) Nishida, G.; Noguchi, K.; Hirano, M.; Tanaka, K. *Angew. Chem., Int. Ed.* **2007**, *46*, 3951–3954; (j) Oppenheimer, J.; Hsung, R. P.; Figueroa, R.; Johnson, W. L. *Org. Lett.* **2007**, *9*, 3969–3972; (k) Clayden, J.; Moran, W. J. *Org. Biomol. Chem.* **2007**, *5*, 1028–1030; (l) Taylor, M. S.; Swager, T. M. *Org. Lett.* **2007**, *9*, 3695–3697; (m) Young, D. D.; Senaiar, R. S.; Deiters, A. *Chem.—Eur. J.* **2006**, *12*, 5563–5568; (n) Wu, Y.-T.; Hayama, T.; Baldridge, K. K.; Linden, A.; Siegel, J. S. *J. Am. Chem. Soc.* **2006**, *128*, 6870–6884; (o) Tanaka, K.; Sagae, H.; Toyoda, K.; Noguchi, K. *Eur. J. Org. Chem.* **2006**, 3575–3581; (p) Dufková, L.; Císařová, I.; Štepnička, P.; Kotora, M. *Eur. J. Org. Chem.* **2003**, 2882–2887; (q) Witulski, B.; Zimmermann, A. *Synlett* **2002**, 1855–1859; (r) Kotha, S.; Brahmachary, E. *Bioorg. Med. Chem.* **2002**, *10*, 2291–2295; (s) Kotha, S.; Sreenivasachary, N. *Eur. J. Org. Chem.* **2001**, 3375–3383; (t) Grigg, R.; Savic, V.; Tambyrajah, V. *Tetrahedron Lett.* **2000**, *41*, 3003–3006; (u) Witulski, B.; Stengel, T. *Angew. Chem., Int. Ed.* **1999**, *38*, 2426–2430; (v) McDonald, F. E.; Zhu, H. Y. H.; Holmquist, C. R. *J. Am. Chem. Soc.* **1995**, *117*, 6605–6606; (w) Grigg, R.; Scott, R.; Stevenson, P. *J. Chem. Soc., Perkin Trans. 1* **1988**, 1357–1364.
9. For selected examples of [2+2+2] cycloadditions of diynes with monoynes using other metals, see: Cobalt: (a) Saino, N.; Kawaji, T.; Ito, T.; Matsushita, Y.; Okamoto, S. *Tetrahedron Lett.* **2010**, *51*, 1313–1316; (b) Young, D. D.; Teske, J. A.; Deiters, A. *Synthesis* **2009**, 3785–3790; (c) Doszczak, L.; Tacke, R. *Organometallics* **2007**, *26*, 5722–5723; (d) Saino, N.; Amemiya, F.; Tanabe, E.; Kase, K.; Okamoto, S. *Org. Lett.* **2006**, *8*, 1439–1442; (e) Gandon, V.; Leca, D.; Aechtner, T.; Vollhardt, K. P. C.; Malacria, M.; Aubert, C. *Org. Lett.* **2004**, *6*, 3405–3407; (f) Kotha, S.; Brahmachary, E. *J. Organomet. Chem.* **2004**, *689*, 158–163. Palladium; (g) Sato, Y.; Tamura, T.; Kinbara, A.; Mori, M. *Adv. Synth. Catal.* **2007**, *349*, 647–661; (h) Peña, D.; Pérez, D.; Guitián, E.; Castedo, L. *Eur. J. Org. Chem.* **2003**, 1238–1243; (i) Yamamoto, Y.; Nagata, A.; Nagata, H.; Ando, Y.; Arikawa, Y.; Tatsumi, K.; Itoh, K. *Chem.—Eur. J.* **2003**, *9*, 2469–2483. Ruthenium; (j) Shchetnikov, G. T.; Osipov, S. N.; Bruneau, C.; Dixneuf, P. H. *Synlett* **2008**, 578–582; (k) Yamamoto, Y.; Hattori, K. *Tetrahedron* **2008**, *64*, 847–855; (l) Senaiar, R. S.; Teske, J. A.; Young, D. D.; Deiters, A. *J. Org. Chem.* **2007**, *72*, 7801–7804; (m) Young, D. D.; Sripada, L.; Deiters, A. *J. Comb. Chem.* **2007**, *9*, 735–738; (n) Yamamoto, Y.; Arakawa, T.; Ogawa, R.; Itoh, K. *J. Am. Chem. Soc.* **2003**, *125*, 12143–12160. Iridium; (o) Shibata, T.; Yoshida, S.; Arai, Y.; Otsuka, M.; Endo, K. *Tetrahedron* **2008**, *64*, 821–830; (p) Matsuda, T.; Kadowaki, S.; Goya, T.; Murakami, M. *Org. Lett.* **2007**, *9*, 133–136; (q) Kezuka, S.; Tanaka, S.; Ohe, T.; Nakaya, Y.; Takeuchi, R. *J. Org. Chem.* **2006**, *71*, 543–552; (r) Shibata, T.; Fujimoto, T.; Yokota, K.; Takagi, K. *J. Am. Chem. Soc.* **2004**, *126*, 8382–8383; (s) Takeuchi, R.; Tanaka, S.; Nakaya, Y. *Tetrahedron Lett.* **2001**, *42*, 2991–2994. Nickel; (t) Zou, Y.; Young, D. D.; Cruz-Montanez, A.; Deiters, A. *Org. Lett.* **2008**, *10*, 4661–4664; (u) Teske, J. A.; Deiters, A. *J. Org. Chem.* **2008**, *73*, 342–345; (v) Turek, P.; Kotora, M.; Tislerová, I.; Hocek, M.; Votruba, I.; Císarová, I. *J. Org. Chem.* **2004**, *69*, 9224–9233; (w) Jeevanandam, A.; Korivi, R. P.; Huang, I.; Cheng, C.-H. *Org. Lett.* **2002**, *4*, 807–810; (x) Sato, Y.; Ohashi, K.; Mori, M. *Tetrahedron Lett.* **1999**, *40*, 5231–5234; (y) Sato, Y.; Nishimata, T.; Mori, M. *J. Org. Chem.* **1994**, *59*, 6133–6135.
10. Grigg, R.; Scott, R.; Stevenson, P. *J. Chem. Soc., Perkin Trans. 1* **1988**, 1365–1369.
11. Desroy, N.; Robert-Peillard, F.; Toueg, J.; Hénaut, C.; Duboc, R.; Rager, M. N.; Savignac, M.; Genêt, J. P. *Synthesis* **2004**, 2665–2672.
12. Kotha, S. K.; Khedkar, P. *J. Org. Chem.* **2009**, *74*, 5667–5670.
13. Son, S. U.; Choi, D. S.; Chung, Y. K. *Org. Lett.* **2000**, *2*, 2097–2100.
14. Yoshida, K.; Morimoto, I.; Mitsudo, K.; Tanaka, H. *Tetrahedron* **2008**, *64*, 5800–5807.
15. García, D.; Foubelo, F.; Yus, M. *Tetrahedron* **2008**, *64*, 4275–4286.
16. Grigg, R.; Kilner, C.; Senthilnanthanan, M.; Seabourne, C. R.; Sridharan, V.; Murrer, B. A. *Arkivoc* **2007**, *xi*, 145–160.