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Influence of Diene Substitution on Diels−Alder Reactions between Vinyl Dihydronaphthalenes and (S*S*)-2-(*p*-Tolylsulfinyl)-1,4-benzoquinone

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The asymmetric Diels−Alder reaction between 2-(*E*-2-acetoxyvinyl)-8-*tert*-butyl-3,4-dihydronaphthalene (**8**) and enantiopure (S*S*)-2-(*p*-tolylsulfinyl)-1,4-benzoquinone (**1**) takes place exclusively on the unsubstituted C_5-C_6 double bond of (S*S*)-**1** with a very high control of the chemo-, regio-, and diastereoselectivity of the process affording tetracyclic sulfinyl derivative **13a** possessing five stereogenic centers. The analogue diene **9**, lacking the *tert*-butyl group, gave a less chemoselective reaction (C_2-C_3/C_5-C_6: 60/40) in favor of reaction through the sulfoxide-substituted double bond C_2-C_3 of **1**. Steric effects of the remote *tert*-butyl group and electronic factors due to the OAc substituent are controlling the process.

Introduction

Asymmetric Diels−Alder reactions with sulfinyl dienophiles[1] and sulfinyl dienes[2] are important transformations in synthesis because they allow for the construction of enantiopure molecules in a highly efficient manner. The ability of the sulfoxide to control the regiochemistry as well as all the stereochemical features of these cycloadditions is the origin of the increasing interest in such reactions. Our previous work devoted to the use of sulfinyl benzo-[3] and naphthoquinones[4] as dienophiles had shown that π-facial diastereoselectivities of their Diels−Alder reactions could be controlled by proper choice of thermal or Lewis acid catalyzed reaction conditions. The excellent results obtained were successfully applied to the enantioselective construction of polycyclic quinones such as natural angucyclinones[5] and [5]helicenequinones.[6]

A study carried out on the chemoselectivity of cycloadditions on 2-(*p*-tolylsulfinyl)-1,4-benzoquinone[3c] and 2-(*p*-tolylsulfinyl)naphthazarin,[4b,7] bearing two different dienophilic double bonds, had revealed an intriguing behavior. Upon reaction with cyclic dienes such as cyclopentadiene or cyclohexadiene, both systems react through the unsubstituted double bond with a high degree of diastereoselectivity despite the long distance between the sulfoxide and the reacting center. When 1-methoxy-1,4-cyclohexadiene was the diene partner, mixtures of adducts resulting from both the unsubstituted and the sulfoxide-bearing double bond resulted.[8] With acyclic dienes such as piperylene, the chemoselective reaction through the sulfinyl-substituted double bond was observed. The cycloadducts resulting from the later underwent spontaneous pyrolysis of the sulfoxide recov-

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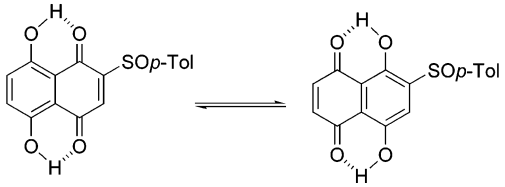

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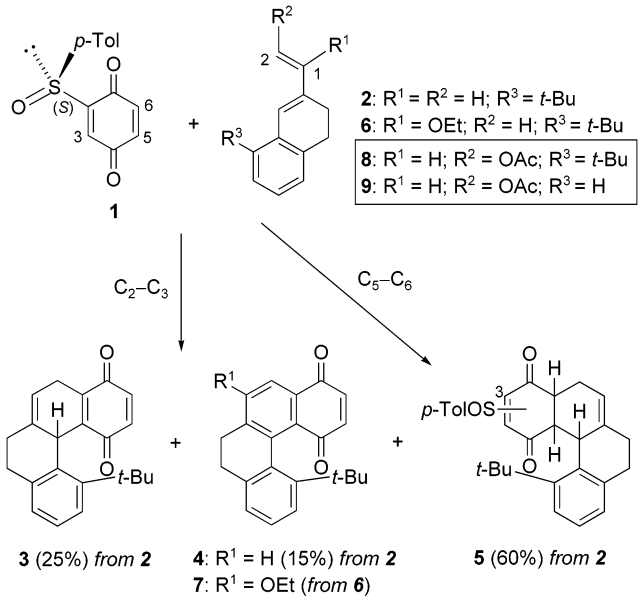
SCHEME 1. Diels−Alder Reactions between Sulfinyl Quinone 1 and *tert*-Butyl Substituted Dienes 2 and 6



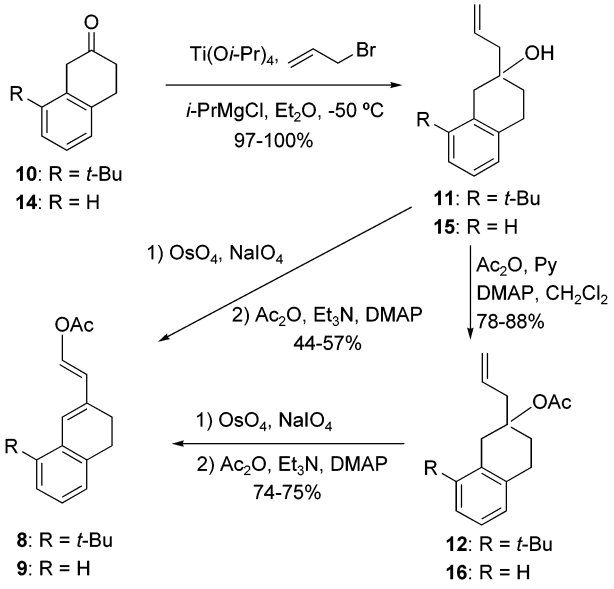
ering the quinone skeleton immediately after the cycloaddition.[3c,4b] Although this domino Diels−Alder reaction/pyrolytic elimination was an extremely useful process in the synthesis of the above-mentioned targets,[5,6] we were interested in the possibility of controlling the chemoselectivity of reactions with such acyclic dienes to direct the cycloaddition through the unsubstituted C_5-C_6 double bond in an efficient manner.

In the course of our work directed to the first enantioselective synthesis of dihydro[4]helicenequinones,[9] we had observed that cycloaddition between enantiopure (S*S*)-2-(*p*-tolylsulfinyl)-1,4-benzoquinone (**1**) and 5-*tert*-butyl-3-vinyl-1,2-dihydronaphthalene (**2**) (Scheme 1) gave a 25:15:60 mixture of tetracyclic derivatives **3**, **4,** and **5**. Compounds **3** and **4** resulted from the initial cycloaddition of the diene on the sulfinyl-substituted C_2-C_3 double bond of **1**, followed by the pyrolysis of the sulfoxide. The major component of the reaction mixture was characterized as a mixture of diastereomers and/or regioisomers resulting from the cycloaddition of the diene on the unsubstituted C_5-C_6 double bond of the dienophile. From this mixture, the major component was isolated and later unequivocally characterized as the 3-*p*-tolylsulfinyl derivative **5a** (see Supporting Information).

When cycloaddition was carried out with the more polarized electron-rich diene **6**, bearing an OEt substituent at C-1 of the diene moiety, the exclusive attack on the C_2-C_3 double bond of **1** took place affording dihydro[4]helicenequinone **7** as the sole product.[9]

The different behavior observed for cyclic and acyclic dienes depending upon substitution, as well as the role of the electron-donating susbtituents in the diene partners in controlling the chemoselectivity, was not easy to explain. The products resulting from diastereoselective cycloadditions on the unsubstituted dienophilic double bond such as **5** offer considerable versatility as starting materials for the enantioselective synthesis of more complex structures due to the sulfinyl dienophile moiety present in their skeleton. Accordingly, we decided to study the chemoselectivity of Diels−Alder reactions with acyclic dienes bearing an oxygenated substituent at C-2 of the vinylic moiety, which had not been evaluated in our previous studies. The regiochemistry of their cycloadditions with sulfinylquinone (S*S*)-**1** is a superimposed problem that should be considered.

SCHEME 2. Synthesis of Acetoxy-Substituted Dienes 8 and 9



We report herein the synthesis of 1-acetoxy-substituted dienes **8** (bearing a *tert*-butyl group) and **9** (lacking the *tert*-butyl group), and the results of their cycloadditions with enantiopure (S*S*)-2-(*p*-tolylsulfinyl)-1,4-benzoquinone (**1**), which show the role of remote steric effects and electronic factors due to diene substitution in controlling the chemoselectivity and regioselectivity of the process. Besides the intrinsic fundamental interest, these results have a huge potential synthetic utility as an efficient route to enantiomerically pure tetracyclic sulfoxide-bearing cyclohexene-1,4-diones which could act again as dienophiles opening an easy access to more complex polycyclic structures.

Results and Discussion

The synthesis of diene **8**, depicted in Scheme 2, started with the quantitative addition of an allyltitanium[10] derivative, generated in situ by treatment of an allyl Grignard with $Ti(O^iPr)_4$, to 8-*tert*-butyl-2-tetralone (**10**).[9] Carbinol **11** was thus isolated in excellent yield and acetylated to afford derivative **12** (Ac_2O/Py/DMAP, 78% yield). The oxidation of the terminal double bond of **12** with $OsO_4/NaIO_4$ gave the corresponding aldehyde, which immediately was treated with Ac_2O/Et_3N/DMAP to give the enol acetate **8** (74% overall yield from **12**).[11] Alternatively, oxidation of **11** followed by treatment of the

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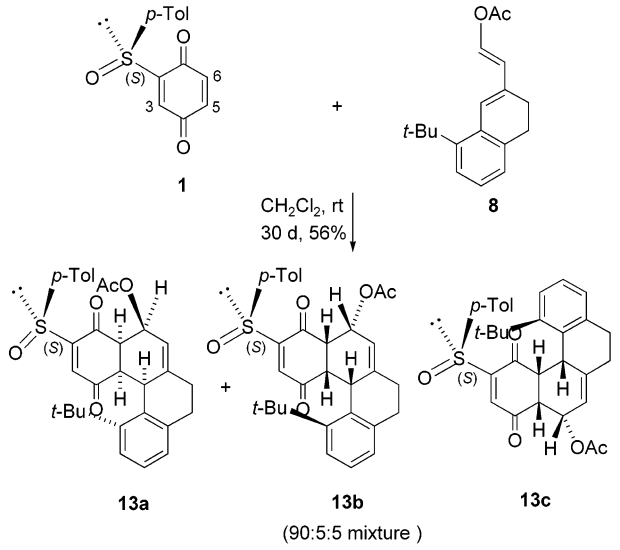
(11) Sodeoka, M.; Iimori, T.; Shibasaki, M. *Chem. Pharm. Bull.* **1991**, *39*, 323−327.

SCHEME 3. Stereoselective Diels–Alder Reaction between Enantiopure Sulfinyl Quinone (S*S*)-1 and Diene 8



resulting aldehyde with Ac_2O/Et_3N/DMAP gave rise to compound **8** resulting from the simultaneous elimination of the hydroxyl group, probably as the corresponding acetate (57% overall yield from carbinol **11**).

With *tert*-butyl substituted diene **8** in hand, we carried out the Diels–Alder reaction with enantiopure (S*S*)-2-(*p*-tolylsulfinyl)-1,4-benzoquinone (**1**).[12] After 30 days at room temperature, the crude reaction mixture showed the formation of a 90:5:5 mixture of compounds **13a**, **13b**, and **13c** proceeding from the exclusive cycloaddition of diene **8** on the unsubstituted C_5-C_6 double bond of (S*S*)-**1** (Scheme 3). To our surprise, no product resulting from the attack on the sulfoxide-substituted C_2-C_3 double bond of (S*S*)-**1** was observed. The major diastereomer **13a** was isolated in 50% yield after flash chromatography and the minor components of the reaction mixture **13b** and **13c** could be obtained in 3% yield, respectively. This result showed that the cycloaddition had occurred with complete chemoselectivity and a high degree of regiochemical and stereochemical control, regardless the long distance existent between the sulfinyl group and the reactive C_5-C_6 double bond of the dienophile.

The regiochemistry and relative stereochemistry of major tetracyclic derivative **13a** could be established on the basis of its ^{1}H NMR data, in particular, chemical shifts and NOE and NOESY experiments (Figure 1). The structural assignment was confirmed by a comparative analysis of the ^{1}H NMR parameters of **13a–c** and **5a**, whose structure had been unequivocally assigned (see Supporting Information). A noticeable feature is the low chemical shift (δ 0.95 ppm) at which the methyl group of the acetate appeared in **13a** if compared with the same in **13b** (δ 1.95 ppm) and **13c** (δ 1.90 ppm). This would be in accordance with a close proximity of the aromatic *p*-tolyl group of the sulfoxide with respect to the acetate existent in the stereostructure represented for **13a**. Such rigid disposition of the sulfinyl-substituted cyclohexene-1,4-dione moiety corresponds to the most favored *s-cis*

(12) Carreño, M. C.; García Ruano, J. L.; Urbano, A. *Synthesis* **1992**, 651–653.

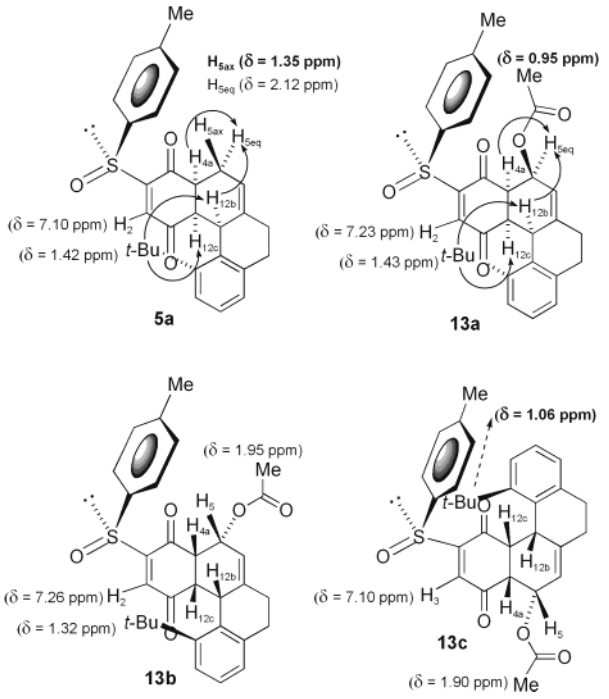


FIGURE 1. Significant ^{1}H NMR parameters and NOESY enhancements of derivatives **5a** and **13a–c** used for configurational assignments.

conformation around the C–S bond of the olefinic sulfoxide moiety,[13] and had been observed in the solid structure of compound **5a** (see Supporting Information). A similar shielding effect had been found in the chemical shift for the axial hydrogen at C-5 of compound **5a** (δ_{H-5ax} 1.35 ppm), which is also under the influence of the aromatic ring, if compared with that of the corresponding equatorial hydrogen (δ_{H-5eq} 2.12 ppm). The anisotropic effect of the *p*-tolyl group on the protons under its influence already has been reported for different sulfoxides.[3c,4a,c,d] The similar chemical shifts of the olefinic hydrogens situated at C-2 in **5a** (δ 7.10 ppm), **13a** (δ 7.23 ppm), and **13b** (δ 7.26 ppm), and that situated at C-3 in **13c** (δ 7.10 ppm) also supports this stereochemical analogy for all derivatives. The NOE enhancements depicted in Figure 1 for the major derivative **13a** evidenced the cis relationship between H-4a and H-5eq as well as that between H-5eq and H-12b. This relative disposition is only possible if the adduct resulted from an endo approach in the Diels–Alder reaction. Moreover, the NOE effects observed between the *tert*-butyl substituent and H-12c and H-12b also indicated the spatial disposition shown in Figure 1 for **13a**. Similar NOE enhancements were found in compound **5a**. The absolute configuration was established on the basis of the known *S* absolute configuration of the starting sulfoxide, which must not be altered during the cycloaddition process.

Following a similar reasoning, we have tentatively assigned the stereostructures of the minor derivatives **13b** and **13c**, as represented in Figure 1. The main differential feature observed for **13c** is the low chemical

(13) (a) Tietze, L. F.; Schuffenhauer, A.; Schreiner, P. R. *J. Am. Chem. Soc.* **1998**, *120*, 7952–7958. (b) Kahn, S. D.; Hehre, W. J. *J. Am. Chem. Soc.* **1987**, *109*, 663–666. (c) Kahn, S. D.; Hehre, W. J. *Tetrahedron Lett.* **1986**, *27*, 6041–6044.

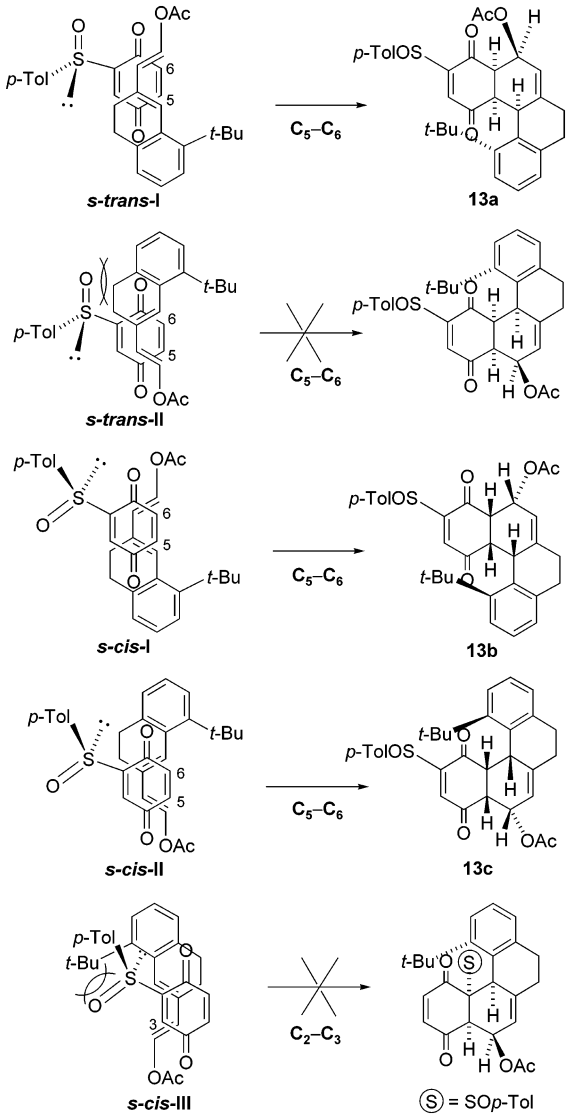


FIGURE 2. Possible endo approaches of diene **8** in Diels–Alder reaction with sulfinyl quinone **1**.

shift (δ 1.06 ppm) at which the *tert*-butyl group appeared if compared with the same in **13a** (δ 1.43 ppm) and **13b** (δ 1.32 ppm). This is again in agreement with the close proximity of the aromatic *p*-tolyl group of the sulfoxide with respect to the *tert*-butyl group existent in the stereostructure represented for **13c**. In the case of derivative **13b**, the relative configuration assigned has been based on mechanistic considerations (see below).

On the basis of the stereochemistry assigned to **13a** we tried to rationalize the stereochemical and regiochemical courses of the cycloaddition. Concerning the stereochemical aspects, the endo approach of diene **8** from the less hindered upper face of the unsubstituted double bond of (S*S*)-**1** adopting the s-trans conformation (transition state *s-trans*-**I** in Figure 2) of the sulfoxide would explain the formation of major isomer **13a**. This behavior was not surprising taking into account our previous results[3c,f] which suggested that cycloadditions of cyclopentadiene on the C_5-C_6 unsubstituted double bond of **1** took place preferentially on such s-trans conformation.[3f,14] The regiochemistry shown in the transition state *s-trans*-**I** in Figure 2 also accounts for the structure of the major adduct **13a**. The high degree of regiochemical control achieved is remarkable considering the lack of substitution in the reacting C_5-C_6 dienophilic double bond of the sulfinylquinone as well as the presence of three different substituents on the diene moiety.[15]

Such high regioselectivity is not easy to rationalize. To understand its origin, we must focus on the relative stability of all four possible endo transition states resulting from the two possible regioisomeric approaches on both the s-trans and s-cis conformations of (S*S*)-**1** shown in Figure 2 for the C_5-C_6 cycloaddition. A detailed evaluation of the interactions present in the regioisomeric approach to the s-trans conformation represented as *s-trans*-**II** evidenced a severe steric interaction between the CH_2-CH_2 fragment of the diene and the S=O bond of the sulfoxide, favoring the major reaction through the transition state *s-trans*-**I**. Such interaction does not exist in the approach of the diene with both regiochemistries on the s-cis conformation of (S*S*)-**1** (*s-cis*-**I** and *s-cis*-**II** in Figure 2), and both regioisomers **13b** and **13c** corresponding to these evolutions were obtained in equal amounts although in low ratio (5% each one).

The chemoselection of the process was also surprising taking into account that the sulfinyl-substituted double bond of (S*S*)-**1** had been shown to be more reactive than the unsubstituted one except for reactions with cyclic dienes such as cylopentadiene or cyclohexadiene.[3c] An evaluation of the relative stabilities of the transition states arising from the cycloaddition on C_2-C_3 could help to rationalize the results. According to previous studies,[1,3,4] the most favored endo approach of a diene to the C_2-C_3 sulfinyl-substituted double bond of **1** occurred from the face of the quinone containing the less sterically demanding lone electron pair at sulfur in the s-cis conformation (Figure 2). In accordance with the Hammett substituent constants of the OAc group ($\sigma_m = 0.39$, $\sigma_p = 0.31$) and aryl groups ($\sigma_m = \sigma_p = 0.05$),[16] we can assume that the regiochemistry of cycloadditions on the substituted C_2-C_3 double bond of **1** is mainly controlled by the aryl substituent. The endo transition state that emerges, shown in Figure 2 as *s-cis*-**III**, is strongly destabilized by the interaction existent between the *tert*-butyl group and the S=O bond. Thus, as mentioned above, the most favored situation corresponds to the transition state shown in Figure 2 as *s-trans*-**I,** which explains the major formation of **13a** in the reaction on the unsubstituted C_5-C_6 double bond of **1**.

To check the important role of the *tert*-butyl group in the control of the regio- and chemoselectivity of the cycloaddition on C_5-C_6, we decided to perform the cycloaddition of quinone **1** with diene **9**, lacking the bulky *tert*-butyl group, which was prepared from 2-tetralone (**14**) in a synthetic sequence similar to that followed for diene **8**, as shown in Scheme 2.

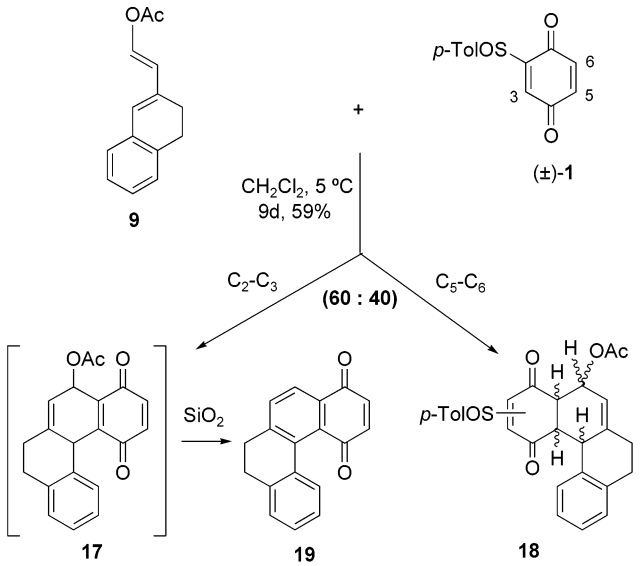
Thus, starting from **14**, the addition of the allyltitanium reagent afforded in quantitative yield carbinol

(14) García Ruano, J. L.; Carreño, M. C.; Carretero, J. C.; Martín Cabrejas, L. M.; Urbano, A. *Pure Appl. Chem.* **1996**, *68*, 925–930.

(15) Two or more substituents in the diene partner make a regiochemical prediction on the basis of FMO theory difficult: Kahn, S. D.; Hehre, W. J. *J. Am. Chem. Soc.* **1986**, *108*, 7381–7396.

(16) Hansch, C.; Leo, A.; Taft, R. W. *Chem. Rev.* **1991**, *91*, 165–195.

SCHEME 4. Diels–Alder Reaction between Racemic Sulfinyl Quinone 1 and Diene 9

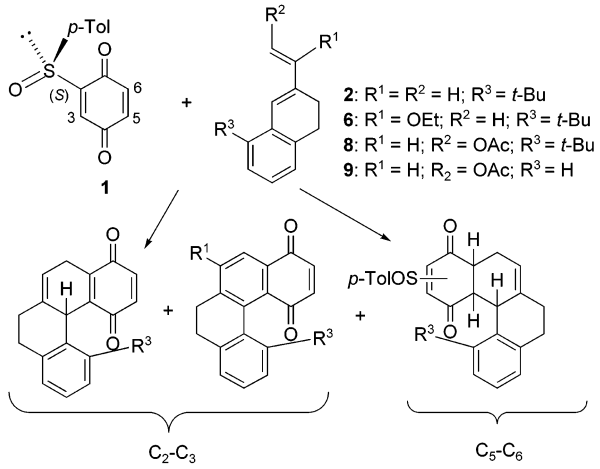


15,[10,17] whose reaction with $OsO_4/NaIO_4$ followed by treatment with Ac_2O/Et_3N/DMAP yielded 44% of the corresponding acetoxy-substituted diene **9**. Alternatively, carbinol **15** was acetylated to **16** (88% yield) and further transformed, under the same conditions as above, into diene **9** in 66% overall yield from **15**.

The Diels–Alder reaction between diene **9** and racemic sulfinyl quinone (±)-**1**[12] at 5 °C in CH_2Cl_2 for 9 days (Scheme 4) afforded a 60:40 mixture of two compounds **17** and **18**. Quinone **17** proceeded from the cycloaddition of the diene on the sulfinyl-substituted C_2-C_3 double bond of **1** and further elimination of the sulfoxide in the initially formed cycloadduct. Tetracyclic derivative **18** resulted from the attack of the diene on the C_5-C_6 unsubstituted double bond of **1**. After flash chromatography, we isolated 35% yield of quinone **19** proceeding from the partial aromatization of derivative **17** and 24% of derivative **18** as a mixture of regio- and/or diastereoisomers which could not be separated.

The results obtained in the reaction between sulfinylquinone **1** and dienes **2**, **6**, **8**, and **9** are summarized in Table 1. The regio- and chemoselective reaction of the OEt-substituted diene **6** (Table 1, entry 1) through C_2-C_3 is in full agreement with the frontier orbital theory[18] due to the effect of the electron-donating substituent ($\sigma_m = 0.10$, $\sigma_p = -0.24$)[17] of the diene and the electron-withdrawing character of the sulfoxide group ($\sigma_m = 0.50$, $\sigma_p = 0.44$ for the SOPh group)[16] in the dienophile, in the energy and coefficients of the frontier orbitals. Steric interactions due to the presence of the *tert*-butyl group of diene **6** in controlling the chemoselectivity are negligible in this cycloaddition due to the overwhelming activating effect of the OEt group of **6**. With diene **2**, bearing a 8-*tert*-butyl-substituted dihydronaphthalene moiety and lacking the ethoxy group, the chemoselectivity is slightly inverted (Table 1, entry 2) and 60% yield of the product resulting from the cycloaddition through

TABLE 1. Reactivity and Chemoselectivity in Diels–Alder Reactions between Sulfinyl Quinone 1 and Dienes 2, 6, 8, and 9



entry	diene	time (d)	*T* (°C)	C_2-C_3 (%)	C_5-C_6 (%)
1	**6**	1	−20	100	0
2	**2**	7	20	40	60
3	**8**	30	20	0	100
4	**9**	9	5	60	40

C_5-C_6 was formed. This result evidenced the ability of the *tert*-butyl group in controlling the chemoselectivity of the process, probably through the steric effects above-mentioned which force the reaction through transition state *s-trans*-**I**. When the reacting diene is **8**, which bears both an acetoxy substituent at C-1 of the diene system and a *tert*-butyl group at C-8 of the dihydronaphthalene moiety, the process occurs in a highly chemoselective way giving rise to the exclusive formation of the products resulting from the C_5-C_6 cycloaddition (Table 1, entry 3). Thus, the reaction of diene **8** gave compound **13a** as the major regiosiomer. A balance between steric and electronic factors, in favor of the former, is controlling both the chemo- and the regioselectivity of the process. These results suggested that, in the absence of strong electron-donating effects, steric interactions become important and the cycloaddition mainly occurs through the unsubstituted double bond of **1**. The fact that in the reaction of diene **9**, lacking the bulky *tert*-butyl group but with an OAc substituent, the chemoselectivity was inverted with respect to the analogue AcO and *t*-Bu-substituted diene **8**, confirmed the importance of steric effects (Table 1, entry 4) and the poor ability of the OAc to activate the diene system.

The different reaction times required to complete the cycloadditions of dienes **2**, **6**, **8**, and **9** also revealed the influence of diene substitution on the results. The high reactivity observed for the ethoxy-substituted derivative **6** (Table 1, entry 1) is in full agreement with the FMO theory.[18] Diene **2**, lacking the OEt group, reacted more slowly (entry 2) but at a comparable rate than derivative **9** bearing the 1-OAc substitutent at the diene moiety and lacking the bulky *tert*-butyl group (entry 4). These results showed that the acetoxy substituent is not activating the diene partner for the cycloaddition process. Finally, although the simultaneous presence of the OAc and *tert*-butyl substituents in diene **8** is significantly decreasing the reaction rate (entry 3), this combination allowed the

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regioselective synthesis of the tetracyclic sulfinyl-substituted dione **13a** in an efficient way. This slow reaction also confirmed the importance of steric and electronic effects in the process. Although the influence of both steric and electronic effects of diene substitution on the reactivity was known,[19] their influence on the chemoselectivity of cycloadditions with an ambident dienophile such as **1** has been evidenced for the first time.

Conclusions

We have disclosed an easy way to control the chemoselectivity of Diels−Alder reactions on 2-(*p*-tolylsulfinyl)-1,4-benzoquinone, based on the use of appropriately substituted vinyl dihydronaphthalenes as diene partners. The synthesis of tetracyclic compounds bearing a 2-(*p*-tolylsulfinyl)-1,4-dione moiety is thus efficiently achieved. A balance between steric effects of a remote substituent and electronic factors in the diene partner is the origin of the observed chemo- and regioselectivities of the cycloadditions that occur from the C_5-C_6 unsubstituted double bond of the dienophile.

Experimental Section

Melting points were obtained in open capillary tubes and are uncorrected. ^{1}H and ^{13}C NMR spectra were recorded in $CDCl_3$ at 300 and 75 MHz, respectively. All reactions were monitored by thin-layer chromatography that was performed on precoated sheets of silica gel 60, and flash column chromatography was done with silica gel 60 (230−400 mesh). Eluting solvents are indicated in the text. The apparatus for inert atmosphere experiments was dried by flaming in a stream of dry argon. CH_2Cl_2 was dried over P_2O_5. Dry THF was distilled from sodium/benzophenone ketyl. All other reagent-quality solvents were used without purification.

2-Allyl-8-*tert*-butyl-1,2,3,4-tetrahydronaphthalen-2-ol (11). To a solution of $Ti(O^iPr)_4$ (128 μL, 0.43 mmol) and allyl bromide (37 μL, 0.43 mmol) in dry ethyl ether (3 mL) was added 2 M ^{i}PrMgBr in ethyl ether (0.43 mL, 0.86 mmol) dropwise at −50 °C. After being stirred for 2 h between −50 and −40 °C, the initial yellow solution turned brown. 8-*tert*-Butyl-2-tetralone (**10**) (60 mg, 0.30 mmol, in 1 mL of ether) was then added at −45 °C and the mixture was allowed to warm to 0 °C over 30 min. After addition of aqueous 1 N HCl (2.5 mL) at this temperature, the mixture was warmed to room temperature. The organic layer was separated and the aqueous layer was extracted with ether. The combined organic extracts were washed with saturated aqueous $NaHCO_3$, dried over $MgSO_4$, and concentrated under reduced pressure to give **11**, which was used without further purification, in 97% yield: mp 77−78 °C; ^{1}H NMR δ 1.49 (s, 9H), 1.88 (m, 3H), 2.42 (d, 2H, J = 7.7 Hz), 2.86 (dt, 1H, J = 16.6 and 7.3 Hz), 3.03 (d, 1H, J = 15.5 Hz), 3.03 (dt, 1H, J = 16.6 and 7.3 Hz), 3.17 (d, 1H, J = 15.5 Hz), 5.23 (m, 1H), 5.26 (m, 1H), 6.05 (ddt, 1H, J = 17.0, 10.1, and 7.7 Hz), 7.06 (dd, 1H, J = 7.7 and 1.2 Hz), 7.15 (t, 1H, J = 7.7 Hz), 7.32 (dd, 1H, J = 8.1 and 1.2 Hz); ^{13}C NMR δ 27.9, 31.3 (3C), 34.2, 35.8, 41.6, 45.5, 71.6, 119.0, 123.8, 125.6, 126.8, 133.5 (2C), 137.3, 148.4; MS (EI) *m*/*z* (%) 57 (100), 226 ($M^+ - H_2O$, 7), 244 (M^+, 1.4). HMRS calcd for $C_{17}H_{24}O$ 244.18272, found 244.18230.

2-Acetoxy-2-allyl-8-*tert*-butyl-1,2,3,4-tetrahydronaphthalene (12). Pyridine (245 μL, 3.05 mmol), acetic anhydride (288 μL, 3.05 mmol), and a catalytic amount of DMAP were added to a stirred solution of alcohol **11** (150 mg, 0.61 mmol) in CH_2Cl_2 (4 mL), and the mixture was stirred for 10 days at room temperature. After evaporation of the solvent and the excess of reagents, the residue was purified by column chromatography (eluent hexane/EtOAc 16:1) to give compound **12** as colorless oil, in 78% yield: ^{1}H NMR δ 1.47 (s, 9H), 1.96 (s, 3H), 2.02 (ddd, 1H, J = 6.0, 8.5, and 14.0 Hz), 2.30 (m, 1H), 2.73−3.02 (m, 4H), 3.10 (d, 1H, J = 16.2 Hz), 3.62 (d, 1H, J = 16.2 Hz), 5.16 (ddt, 1H, J = 1.2, 2.2, and 5.3 Hz), 5.20 (t, 1H, J = 1.2 Hz), 5.89 (m, 1H), 7.03 (dd, 1H, J = 1.2 and 7.7 Hz), 7.13 (t, 1H, J = 7.7 Hz), 7.30 (dd, 1H, J = 1.2 and 7.7 Hz); ^{13}C NMR δ 22.1, 27.7, 31.3 (3C), 32.0, 35.7, 38.3, 41.4, 83.0, 118.6, 123.8, 125.6, 126.4, 132.8, 133.0, 137.5, 148.2, 170.5; MS (FAB) *m*/*z* (%) 57 (100), 227 (M^+ − OAc, 75).

2-(*E*-2-Acetoxyvinyl)-8-*tert*-butyl-3,4-dihydronaphthalene (8). From 11: To a solution of alcohol **11** (73 mg, 0.30 mmol) in Et_2O (2.5 mL) was added OsO_4 4% in water (184 μL, 0.030 mmol). To this solution was slowly added $NaIO_4$ (193 mg, 0.90 mmol) in H_2O (3 mL) and the mixture was stirred overnight at room temperature. After adding solid Na_2SO_3, the mixture was stirred for 20 min and the organic layer was separated and filtered through a pad of $Na_2SO_4-SiO_2$. After evaporation of the solvent, toluene (3 mL), Et_3N (334 μL, 2.40 mmol), acetic anhydride (142 μL, 1.50 mmol), and a catalytic amount of DMAP were added, and the mixture was stirred at 80 °C for 2.5 h. After the solution was cooled to room temperature, the reaction was quenched by the addition of brine and extracted with ether. The combined extracts were washed with brine, dried over $MgSO_4$, and concentrated. The residue was purified by flash chromatography (eluent hexane/EtOAc 20:1) to afford compound **8** as colorless oil, in 57% yield: ^{1}H NMR δ 1.47 (s, 9H), 2.20 (s, 3H), 2.39 (dd, 2H, J = 6.7 and 8.4 Hz), 2.85 (dd, 2H, J = 7.7 and 8.1 Hz), 6.37 (d, 1H, J = 12.5 Hz), 7.07 (m, 3H), 7.27 (dd, 1H, J = 1.6 and 7.7 Hz), 7.59 (d, 1H, J = 12.5 Hz); ^{13}C NMR δ 20.6, 22.6, 29.2, 31.6 (3C), 35.4, 118.5, 124.2, 125.7, 126.2, 127.1, 132.2, 132.7, 135.8, 137.1, 145.4, 167.9; MS (EI) *m*/*z* (%) 228 (100), 270 (M^+, 18). HMRS calcd for $C_{18}H_{22}O_2$ 270.16198, found 270.16116.

From 12: To a solution of compound **12** (135 mg, 0.47 mmol) in Et_2O (3 mL) was added a solution of OsO_4 4% in H_2O (288 μL, 0.047 mmol). To this solution was slowly added $NaIO_4$ (302 mg, 1.41 mmol) in H_2O (4 mL) and the mixture was stirred overnight at room temperature. After solid Na_2SO_3 was added, the mixture was stirred for 20 min and the organic layer was separated and filtered through a pad of $Na_2SO_4-SiO_2$. After evaporation of the solvent, toluene (3 mL), Et_3N (523 μL, 3.76 mmol), acetic anhydride (222 μL, 2.35 mmol), and a catalytic amount of DMAP were added, and the mixture was stirred at 80 °C for 1.5 h. After the solution was cooled to room temperature, the reaction was quenched by the addition of brine and extracted with ether. The extracts were washed with brine, dried over $MgSO_4$, and concentrated. The residue was purified by column chromatography (eluent hexane/EtOAc 20:1) to afford compound **8** as a colorless oil, in 74% yield.

12-*tert*-Butyl-2-(*p*-tolylsulfinyl)-4a,5,7,8,12b,12c-hexahydrobenzo[*c*]phenanthrene-1,4-dione (13a). To a solution of (*SS*)-2-(*p*-tolylsulfinyl)-1,4-benzoquinone (**1**)[13] (42 mg, 0.17 mmol) in CH_2Cl_2 (1.5 mL) under argon was added diene **8** (46 mg, 0.17 mmol) in CH_2Cl_2 (1.5 mL) at room temperature. After the mixture was stirred for 30 days, the solvent was evaporated and the crude reaction mixture was purified by flash chromatography (eluent hexane/EtOAc 4:1) to give major isomer **13a** as a yellow solid, in 50% yield, together with a mixture of **13b** and **13c**. After preparative thin-layer chromatography (eluent CH_2Cl_2/EtOAc 15:1), both minor isomers **13b** and **13c** could be separated, in 3% yield each one.

13a: Mp 127−129 °C (hexane); $[\alpha]^{20}_D$ +451 ($CHCl_3$, *c* 0.075); ^{1}H NMR δ 0.95 (s, 3H), 1.43 (s, 9H), 2.29 (m, 1H), 2.36 (s, 3H), 2.43 (dt, 1H, J = 12.1 and 3.4 Hz), 2.84 (ddd, 1H, J = 2.8, 4.0, and 15.7 Hz), 3.25 (dt, 1H, J = 4.0 and 14.1 Hz), 3.70 (t, 1H, J = 5.9 Hz), 3.77 (dd, 1H, J = 4.0 and 5.7 Hz), 4.25 (m, 1H), 5.40 (m, 2H), 6.99 (bd, 1H, J = 7.3 Hz), 7.11 (t, 1H, J = 7.7 Hz), 7.23 (s, 1H), 7.27 (d, 2H, J = 8.3 Hz), 7.34 (bd, 1H, J = 7.7 Hz), 7.67 (d, 2H, J = 8.3 Hz); ^{13}C NMR δ 19.5, 21.3, 32.4, 32.8, 33.9 (3C), 37.5, 37.6, 53.2 (2C), 66.5, 114.9, 125.0, 125.9,

(19) Robiette, R.; Marchand-Brynaert, J.; Peeters, D. *J. Org. Chem.* **2002**, *67*, 6823−6826 and references therein.

126.3, 127.8, 130.1, 132.9, 138.3, 139.5, 142.2, 142.3, 145.5, 147.1, 157.7, 169.2, 193.7, 194.0; MS (FAB) *m/z* (%) 154 (100), 457 (M^+ − OAc, 8). HMRS calcd for $C_{29}H_{29}O_3S$ (M^+ − OAc) 457.18374, found 457.18475.

13b: $[\alpha]^{20}_D$ +56 ($CHCl_3$, *c* 0.05); ^{1}H NMR δ 1.32 (s, 9H), 1.95 (s, 3H), 2.34 (m, 1H), 2.40 (s, 3H), 2.50 (m, 1H), 2.87 (m, 1H), 3.31 (m, 1H), 3.51 (m, 2H), 4.16 (m, 1H), 5.51 (m, 1H), 5.61 (m, 1H), 7.01 (dd, 1H, J = 7.5 and 1.0 Hz), 7.11 (t, 1H, J = 7.5 Hz), 7.26 (s, 1H), 7.28 (d, 2H, J = 8.1 Hz), 7.32 (dd, 1H, J = 7.5 and 1.0 Hz), 7.59 (d, 2H, J = 8.1 Hz).

13c: $[\alpha]^{20}_D$ +325 ($CHCl_3$, *c* 0.06); ^{1}H NMR δ 1.06 (s, 9H), 1.90 (s, 3H), 2.35 (m, 1H), 2.37 (s, 3H), 2.48 (m, 1H), 2.88 (m, 1H), 3.26 (m, 2H), 3.55 (m, 1H), 4.12 (m, 1H), 5.55 (m, 2H), 6.91−7.18 (m, 8H).

2-Allyl-1,2,3,4-tetrahydronaphthalen-2-ol (15). Compound **15** was prepared as previously described,[11] in quantitative yield: ^{1}H NMR δ 1.70 (br s, 1H), 1.71−1.96 (m, 2H), 2.35 (m, 2H), 2.73−3.11 (m, 4H), 5.17 (m, 1H), 5.23 (m, 1H), 5.99 (m, 1H), 7.03−7.14 (m, 4H); ^{13}C NMR δ 25.9, 33.4, 41.4, 45.4, 70.1, 118.6, 125.5, 125.6, 128.4, 129.3, 133.3, 134.2, 135.2.

2-Acetoxy-2-allyl-1,2,3,4-tetrahydronaphthalene (16). A mixture of pyridine (213 μL, 2.65 mmol), acetic anhydride (250 μL, 2.65 mmol), and a catalytic amount of DMAP was added to a stirred solution of alcohol **15** (100 mg, 0.53 mmol) in CH_2Cl_2 (2 mL). After the solution was stirred for 24 h at room temperature and the solvent and the excess of reagents were evaporated, the residue was purified by flash chromatography (eluent hexane/CH_2Cl_2 1:1) to give compound **16** as a colorless oil, in 88% yield: ^{1}H NMR δ 1.88 (ddd, 1H, J = 6.1, 9.7, and 13.3 Hz), 1.97 (s, 3H), 2.52 (ddt, 1H, J = 2.0, 13.3, and 5.3 Hz), 2.84 (m, 4H), 2.99 (d, 1H, J = 17.0 Hz), 3.32 (d, 1H, J = 17.0 Hz), 5.16 (m, 1H), 5.20 (br s, 1H), 5.89 (m, 1H), 7.13 (m, 4H); ^{13}C NMR δ 22.0, 25.7, 31.0, 38.8, 40.8, 81.8, 118.5, 125.8 (2C), 128.3, 129.2, 132.6, 133.8, 135.2, 170.5; MS (FAB) *m/z* (%) 154 (100), 171 (M^+ − OAc, 80).

2-(*E*-2-Acetoxyvinyl)-3,4-dihydronaphathalene (9). From 15: To a solution of alcohol **15** (100 mg, 0.53 mmol) in Et_2O (3 mL) was added OsO_4 4% in H_2O (324 μL, 0.053 mmol). To this solution was slowly added $NaIO_4$ (340 mg, 1.59 mmol) in H_2O (4 mL) and the mixture was stirred overnight at room temperature. After solid Na_2SO_3 was added and stirring was continued for an additional 20 min, the organic layer was separated and filtered through a pad of Na_2SO_4−SiO_2. After evaporation of the solvent, toluene (3 mL), Et_3N (590 μL, 4.24 mmol), acetic anhydride (250 μL, 2.65 mmol), and a catalytic amount of DMAP were added, and the mixture was stirred at 80 °C for 1.5 h. After the mixture was cooled to room temperature, the reaction was quenched by the addition of brine and extracted with ethyl ether. The combined ether extracts were washed with brine, dried over $MgSO_4$, and concentrated. The residue was purified by flash chromatography (eluent hexane/EtOAc 12:1) to afford compound **9** as a colorless oil, in 44% yield: ^{1}H NMR δ 2.19 (s, 3H), 2.46 (t, 2H, J = 8.1 Hz), 2.87 (t, 2H, J = 8.1 Hz), 6.26 (d, 1H, J = 12.5 Hz), 6.41 (s, 1H), 7.02−7.21 (m, 4H), 7.56 (dd, 1H, J = 0.8 and 12.5 Hz); ^{13}C NMR δ 20.7, 23.3, 27.5, 117.6, 126.1, 126.5, 126.9, 127.2, 127.4, 133.8, 134.3, 135.1, 136.0, 167.9; MS (EI) *m/z* (%) 172 (100), 214 (M^+, 20). HMRS calcd for $C_{14}H_{14}O_2$ 214.09938, found 214.09906.

From 16: To a solution of compound **16** (80 mg, 0.348 mmol) in Et_2O (2.5 mL) was added OsO_4 4% in H_2O (214 μL, 0.035 mmol). To this solution was slowly added $NaIO_4$ (225 mg, 1.05 mmol) in H_2O (3.5 mL) and the mixture was stirred for 2 days at room temperature. After solid Na_2SO_3 was added and the mixture was stirred for 20 min, the ethereal layer was separated and filtered through a pad of Na_2SO_4−SiO_2. After evaporation of the solvent, toluene (3 mL), Et_3N (387 μL, 2.78 mmol), acetic anhydride (164 μL, 1.74 mmol), and a catalytic amount of DMAP were added, and the mixture was stirred at 80 °C for 2.5 h. After the mixture was cooled to room temperature, the reaction was quenched by the addition of brine and extracted with ether. The combined extracts were washed with brine, dried over $MgSO_4$, and concentrated. The residue was purified by flash chromatography (eluent hexane/EtOAc 12:1) to afford compound **9** as a colorless oil, in 75% yield.

7,8-Dihydrobenzo[*c*]phenanthrene-1,4-dione (19). To a solution of racemic 2-(*p*-tolylsulfinyl)-1,4-benzoquinone (**1**)[13] (48 mg, 0.196 mmol) in CH_2Cl_2 (1.5 mL) under argon was added diene **9** (42 mg, 0.196 mmol) in CH_2Cl_2 (1.5 mL) at 5 °C. After the solution was stirred for 9 days at the same temperature and the solvent was evaporated, the crude was purified by flash chromatography (eluent hexane/EtOAc 2:1) to afford compound **18** as a mixture of isomers that could not be separated, in 24% yield, and compound **19** as an orange solid, in 35% yield: Mp 158−160 °C; ^{1}H NMR δ 2.83 (m, 4H), 6.91 and 6.97 (AB system, 2H, J = 10.1 Hz), 7.19 (m, 1H), 7.28 (m, 2H), 7.39 (dt, 1H, J = 7.7 and 1.2 Hz), 7.55 (d, 1H, J = 7.7 Hz), 7.98 (d, 1H, J = 7.7 Hz); ^{13}C NMR δ 28.8, 30.1, 125.6, 125.7, 127.5, 128.7, 129.7, 130.5, 132.0, 132.3, 133.1, 136.6, 137.2, 138.8, 140.5, 147.5, 184.9, 186.9; MS (EI) *m/z* (%) 259 (100), 260 (M^+, 62). HMRS (FAB) calcd for $C_{18}H_{12}O_2$ 260.08373, found 260.08293.

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Supporting Information Available: ^{1}H and ^{13}C NMR spectra for all compounds and crystallographic data for **5a**. This material is available free of charge via the Internet at http://pubs.acs.org.

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