Reactions of toluquinone–cyclopentadiene Diels–Alder epoxide adducts with nucleophiles under heterogeneous conditions

Andreas A. von Richthofen, José E. P. Cardoso Filho, Liliana Marzorati, Julio Zukerman-Schpector, Edward R.T. Tiekink, and Claudio Di Vitta

Abstract: Toluquinone–cyclopentadiene Diels–Alder epoxide adducts react with sulfur and oxygen nucleophiles under heterogeneous conditions, leading to products resulting from the epoxide ring opening and from skeletal rearrangement, respectively. Pyrolysis of the sulfanyl adducts gave the new 3-sulfanyltoluquinones (**1**).

Key words: toluquinone, phase-transfer catalysis (PTC) conditions, thiolation, epoxide, Diels–Alder.

Résumé : Les époxydes des adduits de Diels–Alder de la toluquinone et du cyclopentadiène réagissent avec des nucléophiles sulfurés et oxygénés, dans des conditions hétérogènes pour conduire respectivement à des produits résultats d'une ouverture de l'époxyde et d'une transposition du squelette. La pyrolyse des adduits sulfanyles conduit aux nouvelles 3-sulfanyltoluquinones (**1**).

Mots-clés : toluquinone, conditions de transfert catalytique de phase (TCP), époxyde, Diels–Alder.

[Traduit par la Rédaction]

Introduction

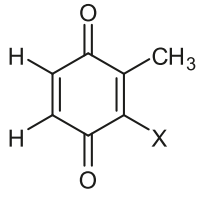
Quinones occur widely in nature as important components of organisms.[1] Natural and synthetic quinone-based compounds are frequently used for therapeutic purposes such as antitumor and anti-infection agents.[2] In particular, benzoquinone thioethers possess a variety of biological and toxicological activities.[3] In the case of 3-sulfanyltoluquinones (**1**) (Fig. 1), it should be mentioned that, although Karrer and Dutta[4] had described the synthesis of the methylsulfanyl derivative **1** (X = SCH_3), by reacting *p*-toluquinone with methanethiol in water, McHale et al.,[5] after trying to reproduce Karrer and Dutta's work, concluded that the product formed under these conditions was 6-methylsulfanyltoluquinone instead of **1** (X = SCH_3).

Therefore, we decided to synthesize **1** (X = SR or SAr) according to the route depicted in Scheme 1, which is based on the pyrolysis of adducts **2**.[6] Such adducts could be prepared by selective cycloaddition at the unsubstituted C=C double bond of **3**, followed by bromine/SR exchange.

However, in view of the described low yields of 3-bromotoluquinone (**3**),[7] we considered an alternative route for adducts **2**, based on the ring opening of epoxides **4** (Scheme 2).

Although the successful ring opening of epoxides **4** (R = R′ = H) was described[8] for 1-phenyl-5-mercaptotetrazole (HPMT) as nucleophile in the presence of catalytic amounts of Et_3N, leading to adduct **2** (R = R′ = H; X = PMT), the use of a stoichiometric mixture of Et_3N and thiols like HPMT, 2-mercaptobenzothiazole (HMBT), and *p*-toluenethiol (HPTT) gave the aromatized substituted adducts **5** in yields ranging from 41% to 50% (Scheme 3) as the result of the action of the base on the α-carbonyl hydrogens of **2** (R = R′ = H; X = SAr). Aromatization was also observed when the epoxide **4** (R = R′ = H) was treated with sodium ethylsulfide in EtOH.[9]

Fig. 1. 2-Alkylsulfanyl- and arylsulfanyl-toluquinones (**1**).



1; X = SR or SAr

Considering the successful use of phase-transfer catalysis (PTC) conditions in suppressing the aromatization reaction, as described by Ferreira et al.,[10] for the substitution of the chlorine atoms of **6** by methylsulfide anion (Scheme 4), we

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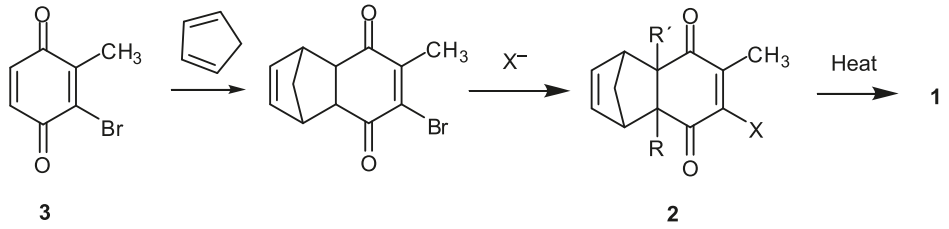
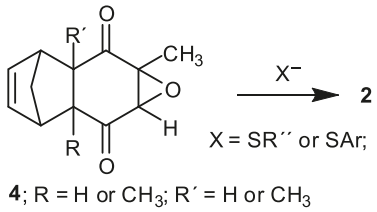
Scheme 1. Proposed synthesis of **1**.



Scheme 2. Proposed alternative synthesis of adducts **2**.



reasoned that we could successfully apply this methodology to the route depicted in Scheme 2 to avoid the aromatization of **2**.

Results and discussion

Accordingly, epoxide **4** (R = R′ = H) was dissolved in benzene and submitted to the reaction with an aqueous solution of methanethiol and sodium hydroxide, using tetrabutylammonium hydrogensulfate (TBAHS) as catalyst.[11] By monitoring the reaction by TLC, and after complete consumption of the starting epoxide **4** (R = R′ = H), three products were formed, two of them had similar retention factors. All these products were easily isolated by chromatography. The minor product (10% yield) was identified by NMR spectroscopy as the desired sulfurated adduct **2** (R = R′ = H; X = SCH_3). The ^1H NMR spectra of the two major products were consistent with the isomeric bis-sulfanylated adducts **7** (30% yield) and **8** (15% yield) (Fig. 2). In the case of the major product, a single crystal was also obtained,[12] allowing for the unequivocal determination of the cis-endo structure **7** for this compound (Fig. 3). Owing to the similarity of the spectroscopic data for compounds **7** and **8**, the same kind of cis-endo structure can be proposed for the latter adduct.

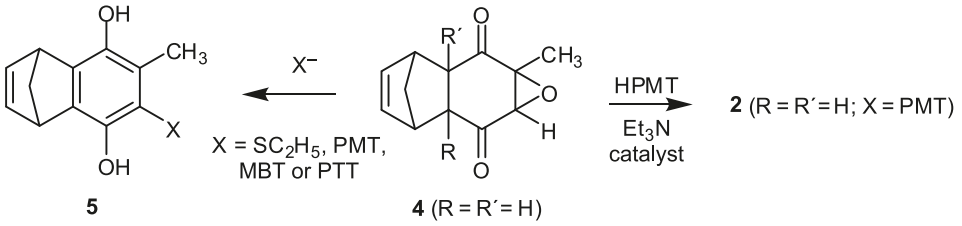
Although under PTC conditions the aromatization side reaction could be completely suppressed, the selective formation of the sulfanylated product **2** could not be achieved. However, by using $HSCH_3$ and a less basic PTC condition (K_2CO_3/benzene/TBAHS), the formation of bis-sulfanylated products was completely avoided and the desired mono-sulfanylated adduct **2** (R = R′ = H; X = SCH_3) was isolated in 21% yield. Unfortunately, a considerable amount of **5** (X = SCH_3; 24% yield) was also obtained.[13] As for other thiols, when benzenethiol was employed as nucleophile in the benzene/NaOH/H_2O system, the mono-sulfanylated adduct **2** (R = R′ = H; X = SC_6H_5) was the sole product and could be isolated in 81% yield. Under such conditions, the $C_6H_5S^-$ nucleophile was also selective in the oxirane ring opening of other similar epoxides **4** (R = H; R′ = CH_3 or R = CH_3; R′ = H), leading exclusively to the mono-sulfanylated adducts **2** (R = H; R′ = CH_3; X = SC_6H_5 in 61% yield, and R = CH_3; R′ = H; X = SC_6H_5 in 40% yield).

Considering that the formation of the bis-sulfanylated adducts **7** and **8**, obtained by using the $HSCH_3$/benzene/NaOH/H_2O system, could arise from the sulfanylation of the two possible enolic forms of adduct **2**[14] (R = R′ = H; X = SCH_3), we performed the same reaction under more controlled conditions, avoiding the presence of oxygen to minimize the oxidation of methanethiol to methyl disulfide, which could act as electrophile in the sulfanylation reaction[15] of **2** (R = R′ = H; X = SCH_3). However, even after careful degassing of the employed solvents and the reaction apparatus, adducts **7** and **8** were still produced in comparable yields. Thus, due to the low concentration of the sulfanylating agent (CH_3SSCH_3, as electrophile) present in the reaction medium,[16] the formation of compounds **7** and **8** via the mechanism depicted in Scheme 5, involving the thiolation process of the intermediate benzoquinone **9**, was suggested. To test this hypothesis, **9** was prepared in 94% yield by oxidation of **5** (X = SCH_3) using Fe^{3+}.[17] Under the heterogeneous conditions used for the thiolation of epoxides **2**, quinone **9** reacted rapidly yielding compounds **7** and **8**, although in a 1:1 ratio, in contrast to the observed 2:1 ratio for the same reaction performed with **2** or **4**.[18]

Having in hands the mono-sulfanylated adducts **2** (R = R′ = H; X = SCH_3 or SC_6H_5), they were heated under vacuum, yielding the corresponding new toluquinones **1** (X = SCH_3 in 80% yield; SC_6H_5 in 25% yield).

In an attempt to explore the use of the heterogeneous condition for the reaction of **4** (R = R′ = H) with other nucleophiles, this compound was submitted to the reaction with methoxide ion in the biphasic system (benzene/H_2O). A colourless solid was obtained in 51% yield for which the presence of a methoxy group incorporated to the structure of the product was evidenced by a singlet at 3.41 ppm in the ^1H NMR spectrum. However, the lack of signals corresponding to the norbornene hydrogens led us to the conclusion that the reaction promoted a structural change also at that moiety of **4** (R = R′ = H). The absence of the characteristic pale yellow colour of toluquinone–cyclopentadiene Diels–Alder adducts indicated the lack of conjugation between the carbonyl groups and the C=C double bond, suggesting that one of the carbonyl groups was no longer present. Accordingly, the ^{13}C NMR spectrum for the product revealed the presence of only one C=O group and two olefinic carbons, thus confirming the absence of the norbornene system. On the other hand, the counting of 13 carbons was consistent with a product resulting from the incorporation of a methoxy group to the epoxide **4** (R = R′ = H). Additionally, the summing of 14 hydrogens by integration of the ^1H NMR spectrum was in agreement with this addition of a methoxide anion, and the same conclusion emerged from the elemental composition of the product for which the minimal formulae

Scheme 3. Reactions of epoxides **4** with nucleophiles under homogeneous conditions.



Scheme 4. Substitution of chlorine atoms of **6** under PTC conditions.

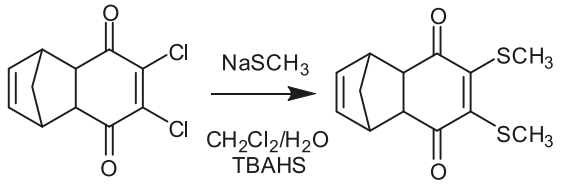


Fig. 2. Bis-sulfanylated products formed by reaction of **4** (R = R′ = H) with $HSCH_3$/benzene/NaOH/H_2O.

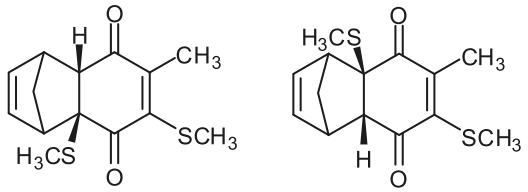
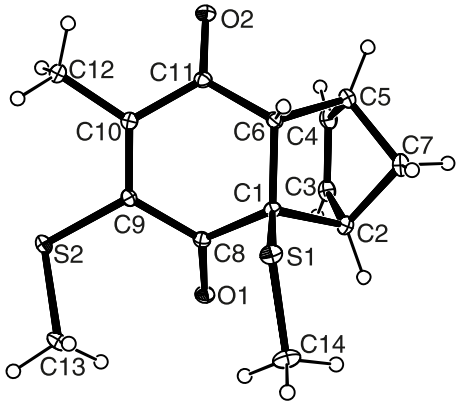


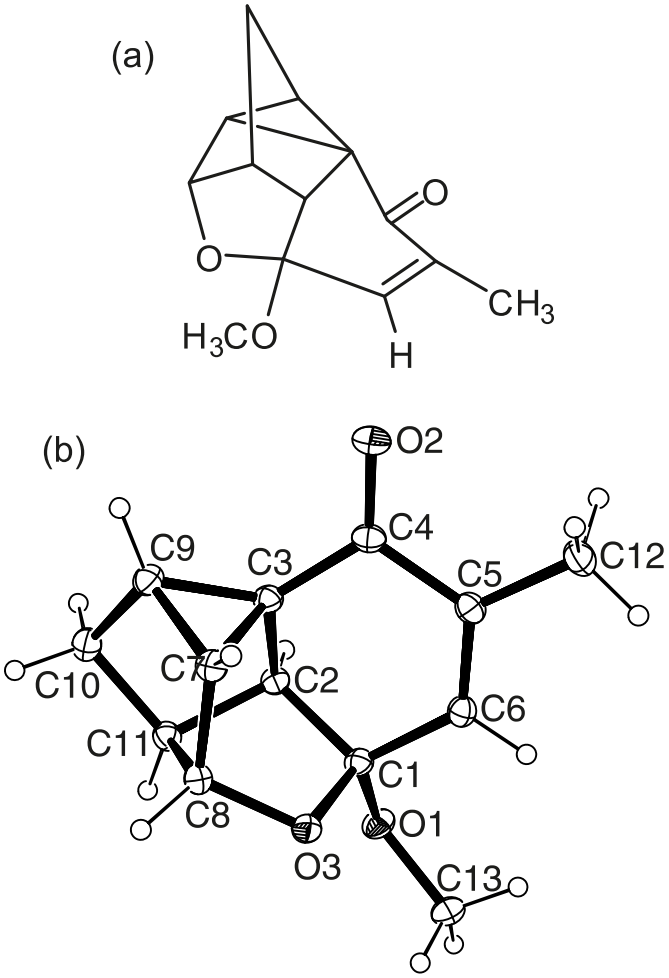
Fig. 3. X-ray crystal structure of compound **7** showing atom labeling and displacement ellipsoids at the 50% probability level (arbitrary spheres for the H atoms).



$C_{13}H_{14}O_3$ could be determined. For this compound, structure **10** (Fig. 4) emerged after a single-crystal X-ray analysis. Crystallographic data are summarized in Table 1.

At this point, it is worth mentioning the remarkable capability of the heterogeneous conditions in changing the reactivity of the methoxide ion in comparison to the homogeneous system. In this sense, in contrast to our result for the reaction between **4** (R = R′ = H) and sodium ethoxide in ethanol, a Favorskii-type ring contraction was described by Herz et al.[19] Our proposal for the formation of **10** is depicted in Scheme 6. The initial step is in accordance

Fig. 4. Molecular structure and X-ray crystal structure of compound **10** showing atom labeling and displacement ellipsoids at the 50% probability level (arbitrary spheres for the H atoms).



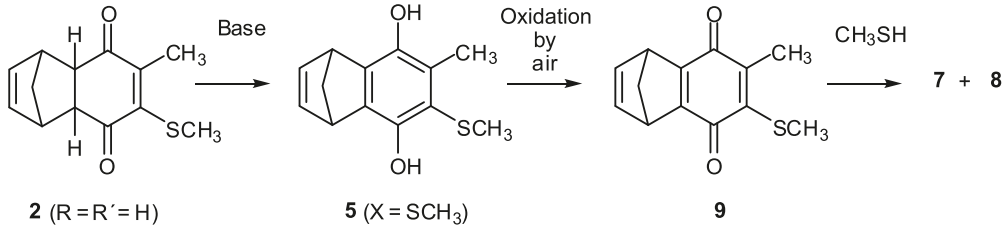
with the Loftfield mechanism for the Favorskii rearrangement,[20] giving an intermediate resulting from displacement of an oxirane bond by the enolate of C8a. However, in the second step under heterogeneous conditions, attack of methoxide ion occurs on C4 of the protonated intermediate, leading to compound **10** instead of the cyclopropanone ring opening by attack at C1.

It should be mentioned that no reaction was observed employing nitrogen nucleophiles like H_2NCH_3, $HN(CH_3)_2$, or aniline under the same heterogeneous conditions.

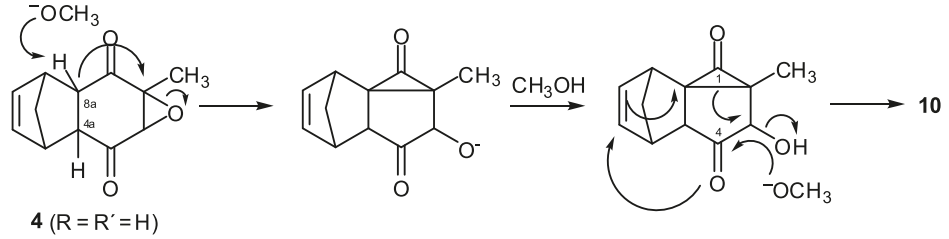
Conclusion

For the reactions of **4** with $^-SCH_3$, the two-phase system

Scheme 5. Proposed mechanism for the formation of **7** and **8** under heterogeneous condition.



Scheme 6. Proposed mechanism for the formation of **10** under heterogeneous condition.



can suppress the aromatization process. The use of sodium methoxide as nucleophile under similar conditions led to the product with the conspicuous strained structure **10**, with complete suppression of the Favorskii-type ring contraction reaction.

The present work reports also the first unequivocal synthesis of 3-sulfanyltoluquinones (**1**; X = SCH_3 or SC_6H_5).

Experimental

Methods and materials

Melting points were determined on a Koffler micro hot stage and are uncorrected. NMR spectra were recorded with a Bruker AC 200 or a Varian INOVA 300 spectrometers against Me_4Si (for ^1H NMR) or the central line of the solvent signal ($CDCl_3$ triplet at 77.0 ppm, for ^{13}C NMR). TLC and dry-flash chromatography were carried out on Merck silica gel. All reagents and solvents were used as received from commercial suppliers. Epoxides **4** (R = R′ = H or R = H; R′ = CH_3 or R = CH_3; R′ = H) were prepared according to literature procedures.[21]

X-ray crystallography for compound 10

A single crystal suitable for X-ray crystallographic analysis was obtained from a slow evaporation of a methanol solution (see Supplementary data section). Intensity data were measured at 153 K on a Rigaku AFC12κ/SATURN724 diffractometer fitted with Mo Kα radiation (λ = 0.71073 Å). Data processing and absorption corrections were accomplished with CrystalClear and ABSCOR,[22] respectively. Details of cell data, X-ray data collection, and structure refinement are given in Table 1. The structures were solved by direct-methods.[23] Full-matrix least-squares refinement on F^2 with anisotropic thermal parameters for all non-hydrogen atoms was performed.[24] H atoms were placed on stereochemical grounds and refined with fixed geometry, each riding on a carrier atom with an isotropic displacement parameter amounting to 1.2 times (1.5 for methyl-H) the value of the equivalent isotropic displacement parameter of the respective carrier atom. A weighing scheme of the form $w = 1/[\sigma^2(F_o^2) + (0.0429P)^2 + 0.534P]$ where $P = (F_o^2 + 2F_c^2)/3$) was introduced in each case.[24]

Reaction of 4 with nucleophiles

Using thiols in a liquid–liquid system — General procedure

A mixture of epoxide **4** (1.0 mmol), benzene (14 mL), aqueous sodium hydroxide (0.35 mol/L; 14 mL), and thiol (10 mmol) was vigorously stirred at room temperature until complete consumption of the epoxide, as indicated by TLC. For CH_3SH, the reaction flask was equipped with a dry-ice cold finger, and the mixture was saturated with the thiol. The organic layer was separated and the aqueous layer was extracted with CH_2Cl_2. The combined organic extracts were washed twice with water, dried over anhydrous $MgSO_4$, and concentrated under vacuum. The crude product was submitted to dry-flash chromatography using a gradient of *n*-hexane/ethyl acetate as eluant.

Adduct 2 (R = R′ = H; X = SCH_3) was isolated as a yellow solid. Mp 75–76 °C. δ_H (200 MHz, $CDCl_3$, Me_4Si): 1.42 (d, 1H, *J* = 8.8 Hz), 1.54 (d, 1H, *J* = 8.8 Hz), 2.02 (s, 3H), 2.46 (s, 3H), 3.27 (m, 2H), 3.50 (m, 2H), 6.05 (m, 2H). δ_C (75 MHz, $CDCl_3$, Me_4Si): 13.59, 16.03, 36.77, 42.77, 40.85, 59.74, 77.45, 96.40, 82.99, 87.02, 91.00, 110.21, 112.77. Elemental analysis (%) ($C_{13}H_{14}SO_2$) calcd.: C 66.6, H 6.0; found: C 66.4, H 6.1.

Adduct 2 (R = R′ = H; X = SC_6H_5) was isolated as a yellow solid. Mp 82–83 °C. δ_H (200 MHz, $CDCl_3$, Me_4Si): 1.42 (d, 1H; *J* = 6.5 Hz), 1.52 (d, 1H; *J* = 6.5 Hz), 2.05 (s, 3H), 3.23 (dd, 1H, J_1 = 9.0 Hz; J_2 = 3.6 Hz), 3.30 (dd, 1H, J_1 = 9.0 Hz; J_2 = 3.6 Hz), 3.45 (m, 1H), 3.53 (m, 1H), 6.06 (m, 2H), 7.30 (m, 5H). δ_C (75 MHz, $CDCl_3$, Me_4Si): 15.69, 48.00, 48.16, 48.54, 48.77, 49.48, 127.72, 129.09, 131.32, 133.03, 135.38, 135.99, 150.47, 150.76, 193.73, 196.30. Elemental analysis (%) ($C_{18}H_{16}SO_2$) calcd.: C 72.9, H 5.4; found: C 72.8, H 5.3.

Adduct 2 (R = H; R′ = CH_3; X = SC_6H_5) was isolated as a yellow solid. Mp 61–62 °C. δ_H (200 MHz, $CDCl_3$, Me_4Si): 1.36 (s, 3H), 1.51 (dt, 1H, J_1 = 10 Hz, J_2 = 1.6 Hz), 1.63 (br

Table 1. Crystallographic data and refinement details for compound **10**.

Empirical formula	$C_{13}H_{14}O_3$
Formula mass	218.24
Colour, habit	Colourless, plate
Crystal dimensions (mm)	0.25 × 0.25 × 0.05
Crystal system	Monclinic
Space group	$P2_1/c$
a (Å)	6.0728(10)
b (Å)	16.256(3)
c (Å)	10.474(2)
β (°)	102.119(6)
V (Å^3)	1010.9(3)
$D_{calcd.}$ (Mg m^{-3})	1.434
Z	4
Absortion coeff. (μ) (mm^{-1})	0.101
$F(000)$	464
θ range for data collection (°)	3.43–26.50
Collected/Independent/observed refls. [$I > 2\sigma(I)$]	5506 (R_{sigma} = 0.0286)/2085/1941 (R_{int} = 0.0296)
Data/restraint/parameters	2085/0/146
Goodnes-of-fit on F^2	1.088
Final R indices [$I > 2\sigma(I)$]	R = 0.0480, wR = 0.1090
R indices (all data)	R = 0.0515, wR = 0.1116
Largest diff. peak and hole (e Å^{-3})	0.220, −0.195

d, 1H, J = 10 Hz), 2.08 (s, 3H), 2.84 (d, 1H, J = 4 Hz), 2.98 (br s, 1H), 3.44 (br s, 1H), 5.99 (dd, 1H, J_1 = 4.0 Hz; J_2 = 2.0 Hz), 6.11 (dd, 1H, J_1 = 4.0 Hz; J_2 = 2.0 Hz), 7.20–7.42 (m, 5H). δ_C (75 MHz, $CDCl_3$, Me_4Si): 15.3, 26.3, 45.7, 47.9, 52.2, 53.8, 57.2, 127.9, 129.0, 131.8, 132.7, 134.8, 139.2, 149.0, 151.0, 196.1, 196.8. Elemental analysis (%) ($C_{19}H_{18}SO_2$) calcd.: C 73.5, H 5.8; found: C 73.4, H 6.1.

Adduct 2 (R = CH_3; R′ = H; X = SC_6H_5) was isolated as a yellow solid. Mp 76–77 °C. δ_H (200 MHz, $CDCl_3$, Me_4Si): 1.50 (s, 3H), 1.52 (m, 1H), 1.62 (br d, 1H, J = 9.6 Hz), 2.07 (s, 3H), 2.82 (d, 1H, J = 4.0 Hz), 3.08 (br s, 1H), 3.37 (br s, 1H), 6.00 (dd, 1H, J_1 = 6.5 Hz, J_2 = 3.3 Hz), 6.15 (dd, 1H, J_1 = 6.5 Hz, J_2 = 3.3 Hz), 7.20–7.35 (m, 5H). δ_C (75 MHz, $CDCl_3$, Me_4Si): 15.9, 27.3, 46.1, 48.1, 53.0, 58.1, 127.7, 129.1, 131.1, 133.1, 135.3, 138.3, 149.8, 149.9, 193.9, 200.1. Elemental analysis (%) ($C_{19}H_{18}SO_2$) calcd.: C 73.5, H 5.8; found: C 73.8, H 6.2.

Adduct 7 was isolated as a yellow solid. Mp 69–72 °C. δ_H (300 MHz, $CDCl_3$, Me_4Si): 1.62 (dt, 1H, J_1 = 8.9 Hz; J_2 = 1.7 Hz), 1.97 (s, 3H), 2.01–2.06 (m, 1H), 2.11 (s, 3H), 2.46 (s, 3H), 2.86 (d, 1H, J = 3.9 Hz), 3.37 (br s, 1H), 3.51 (br s, 1H), 6.08–6.17 (m, 2H). δ_C (75 MHz, $CDCl_3$, Me_4Si): 12.8, 14.0, 14.9, 15.2, 45.0, 45.8, 46.0, 46.2, 57.7, 59.6, 134.4, 137.5 (2C), 142.9, 154.2, 184.8, 193.0. Elemental analysis (%) ($C_{14}H_{16}S_2O_2$) calcd.: C 60.0, H 5.7; found: C 60.7; H 6.0.

Adduct 8 was isolated as a yellow solid. Mp 75–76 °C. δ_H (300 MHz, $CDCl_3$, Me_4Si): 1.63 (dt, 1H, J_1 = 9.0 Hz; J_2 = 1.9 Hz), 2.04 (br d, 1H, J = 9.1 Hz), 2.07 (s, 3H), 2.11 (s, 3H), 2.43 (s, 3H), 2.89 (d, 1H, J = 3.9 Hz), 3.35 (br s, 1H), 3.50 (br s, 1H), 6.05 (dd, 1H, J_1 = 6.0 Hz; J_2 = 3.0 Hz), 6.15 (dd, 1H, J_1 = 6.0 Hz; J_2 = 3.0 Hz).

Using CH_3SH in a solid–liquid system

A mixture of epoxide **4** (R = R′ = H; 1.0 mmol), benzene (15 mL), TBAHS (0.030 mmol), and solid anhydrous potassium carbonate (10 mmol) was saturated with methanethiol in a reaction flask equipped with a dry-ice cold finger. The mixture was vigorously stirred at room temperature for 2 h.[12] Water (15 mL) was added and the organic layer was separated. The aqueous phase was extracted with CH_2Cl_2 (3 × 15 mL), and the combined organic extracts were dried over anhydrous $MgSO_4$ and concentrated under vacuum. The crude product was submitted to dry-flash chromatography.

Aromatic **5** (X = SCH_3) was isolated as a white solid. Mp 121–123 °C after dry-flash chromatography separation using, as eluant, a gradient of *n*-hexane/acetone. δ_H (200 MHz, $CDCl_3$, Me_4Si): 2.12–2.26 (m, 2H), 2.15 (s, 3H), 2.41 (s, 3H), 4.06 (br s, 1H), 4.17 (br s, 1H), 6.73 (dd, 1H, J_1 = 5.1 Hz; J_2 = 2.9 Hz), 6.84 (dd, 1H, J_1 = 5.1 Hz; J_2 = 2.9 Hz). δ_C (75 MHz, $CDCl_3$, Me_4Si): 14.1, 18.7, 46.7, 47.2, 69.2, 117.7, 126.3, 133.2, 139.6, 141.6, 142.0, 143.2, 144.8. Elemental analysis (%) ($C_{13}H_{14}O_2S$) calcd.: C 66.6, H 6.0; found: C 66.9, H 6.1.

Using CH_3OH in a liquid–liquid system

A mixture of epoxide **4** (R = R′ = H; 0.75 mmol), benzene (10 mL), water (11 mL), and sodium methoxide (8.3 mmol) was vigorously stirred at room temperature until complete consumption of the epoxide, as indicated by TLC. The organic layer was separated and the aqueous layer was extracted with CH_2Cl_2. The combined organic extracts were washed twice with water, dried over anhydrous $MgSO_4$, and concentrated under vacuum. The crude product was submitted to dry-flash chromatography separation using a gradient of *n*-hexane/ethyl acetate as eluant. Compound **10** was isolated as white crystals. Mp 105–107 °C. δ_H (300 MHz, $CDCl_3$, Me_4Si): 1.38 (dd, 1H, J_1 = 4.5 Hz; J_2 = 1.2 Hz), 1.72 (d, 1H, J = 11.9 Hz), 1.78 (d, 1H, J = 11.9 Hz), 1.82 (d, 3H, J = 1.8 Hz), 2.54 (br d, 1H, J = 4.5 Hz), 2.65 (br s,

1H), 2.86 (d, 1H, J = 2.1 Hz), 3.41 (s, 3H), 4.63 (br s, 1H), 6.60 (br s, 1H). δ_C (75 MHz, $CDCl_3$, Me_4Si): 15.2, 23.5, 27.0, 29.2, 33.3, 40.7, 49.7, 53.3, 85.8, 102.9, 136.7, 140.6, 195.1. Elemental analysis (%) ($C_{13}H_{14}O_3$) calcd.: C 71.5, H 6.5; found: C 71.3, H 6.2.

Pyrolysis of adduct 2 (R = R′ = H; X = SCH_3)

Adduct **2** (R = R′ = H; X = SCH_3; 0.25 mmol) was heated under vacuum (0.1 mm Hg) at 200 °C in a Kugelrohr, and 3-methylsulfanyltoluquinone (**1**; X = SCH_3; 0.20 mmol) was collected as a red oil. δ_H (200 MHz, $CDCl_3$, Me_4Si): 2.19 (s, 3H), 2.59 (s, 3H), 6.74 (d, 2H, J = 1.2 Hz). δ_C (75 MHz, $CDCl_3$, Me_4Si): 14.09, 17.22, 136.31, 137.15, 142.75, 145.02, 183.03, 184.03. Elemental analysis (%) ($C_8H_8SO_2$) calcd.: C 57.1, H 4.8; found: C 56.8, H 4.8.

3-Phenylsulfanyltoluquinone (**1**; X = SC_6H_5; 0.070 mmol) was obtained by a process similar to the above described as a red oil, starting from adduct **2** (R = R′ = H; X = SC_6H_5; 0.28 mmol). δ_H (200 MHz, $CDCl_3$, Me_4Si): 2.21 (s, 3H), 6.78 (s, 2H), 7.29 (m, 5H). δ_C (75 MHz, $CDCl_3$, Me_4Si): 15.08, 127.44, 129.17, 130.70, 133.56, 136.52, 137.10, 142.98, 146.96, 182.34, 185.18. Elemental analysis (%) ($C_{13}H_{10}SO_2$) calcd.: C 67.8, H 4.4; found: C 67.6, H 4.4.

Supplementary data

Supplementary data for this article (general methods, instrumentation, preparation, and diffraction data) are available on the journal Web site (canjchem.nrc.ca). CCDC 766956 contains the X-ray data in CIF format for this manuscript. These data can be obtained, free of charge, via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax +44 1223 336033; or deposit@ccdc.cam.ac.uk).

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(11) In the presence or absence of the catalyst, the reaction proceeds at similar rates, and it probably occurs at the benzene/water interface.

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(13) The reaction was quenched after 2 h, although without complete consumption of starting epoxide to avoid further aromatization.

(14) Adduct **2** (R = R′ = H; X = SCH_3) is the precursor of **7** and **8**, as proved by the formation of the latter compounds in a 2:1 ratio by treatment of **2** (R = R′ = H; X = SCH_3) with benzene/H_2O/NaOH/$HSCH_3$.

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(16) After 24 h of stirring, only 2% of CH_3SSCH_3 was detected by GLC in the benzene layer of the heterogeneous system (benzene/H_2O/NaOH/$HSCH_3$).

(17) Aromatic **5** (X = SCH_3; 0.080 g; 0.34 mmol) was dissolved in acetone (2 mL) and to the stirred solution at RT, an aqueous saturated solution of $Fe(NO_3)_3$ was dropwised until complete consumption of the starting material by TLC (Hexane:EtOAc, 6:1). The reaction mixture was poured into water (10 mL) and extracted with Et_2O. After drying ($MgSO_4$), concentration and purification by dry-flash chromatography (Hexane:EtOAc, 20:1), quinone **9**, a red oil, was obtained (0.074 g; 3.2 mmol; 94% yield). δ_H (200 MHz, $CDCl_3$, Me_4Si): 2.16 (s, 3H), 2.27 (dt, 2H; J_1 = 7.0 Hz; J_2 = 1.6 Hz), 2.30 (dt, 2H; J_1 = 7.0 Hz; J_2 = 1.6 Hz), 2.55 (s, 3H), 4.09 (m, 2H), 6.84 (m, 1H). δ_C (75 MHz; $CDCl_3$, Me_4Si): 14.4, 17.7, 48.6, 48.9, 73.2, 142.4 (2C), 142.5, 143.4, 160.6, 161.0, 180.0, 181.4. Elemental

analysis (%) ($C_{13}H_{12}O_2S$) calcd.: C 67.2, H 5.2; found: C 67.0, H 5.4.

(18) Compound **9** is rapidly formed by bubbling air into a solution of **5** (X = SCH_3) in a mixture of benzene/H_2O/NaOH. Therefore, although working in the absence of oxygen, the possibility of an in situ oxidation of **5** (X = SCH_3) to quinone **9** by residual oxygen cannot be excluded under the heterogeneous conditions. It should be noted that when compound **5** (X = SCH_3) was submitted to the reaction with-benzene/H_2O/NaOH/$HSCH_3$, **7** and **8** were quantitatively formed in a 2:1 ratio after 24 h of stirring.

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