43 (470 mg, 0.667 mmol), alcohol 35[7] (310 mg, 0.866 mmol), 4-Å molecular sieves (~0.8 g), and 10 mL of dichloromethane was stirred for 1 h at 25 °C and then treated with nitrosyl tetrafluoroborate (80 mg, 0.689 mmol). The mixture was stirred for a further 2 h and then filtered. The filtrate was extracted with 1% aqueous $NaHCO_3$, dried (Na_2SO_4), and concentrated. Chromatography of the residue gave syrupy **44** (230 mg, 34%): $[\alpha]_D$ −28° (*c* 1, $CHCl_3$); ^{13}C NMR ($CDCl_3$) δ 170.3, 169.7, 169.5 (2×) ($COCH_3$), 138.4, 138.3, 138.2, 138.1 (aromatic quaternary carbons), 128.4–127.3 (aromatic carbons), 99.8 (2×) ($^1J_{C,H}$ = 170 Hz), 99.1 ($^1J_{C,H}$ = 171 Hz) (C-1_A,1_B,1_C), 80.3, 80.1 (C-4_A,4_B), 79.7, 78.8 (C-3_A,3_B), 76.6, 74.2 (C-2_A,2_B), 75.3, 75.1, 72.3, 72.2 [CH_2 (Bn)], 69.4, 69.0, 68.8, 68.6, 67.6, 65.9 (C-5_A,5_B, C-2_C,3_C,4_C,5_C), 62.0 (C-6_C), 54.4 (OCH_3), 20.7, 20.5 (3×) (CH_3CO), 17.9 (2×) (C-6_A,6_B).

Methyl 2-*O*-(2,3,4,6-Tetra-*O*-acetyl-α-L-mannopyranosyl)-3,4-di-*O*-benzyl-α-L-rhamnopyranoside (45). A mixture of thiomannoside **40** (230 mg, 0.608 mmol), alcohol **35**[7] (265 mg, 0.739 mmol), 4-Å molecular sieves (~1 g), and 8 mL of dichloromethane was stirred for 1 h at 25 °C and then treated with nitrosyl tetrafluoroborate (75 mg, 0.646 mmol). After stirring for 1.5 h at 25 °C, the mixture was filtered, and the filtrate was treated with 3 mL of pyridine and 3 mL of acetic anhydride for 12 h at 25 °C. Removal of solvents left a syrup, which was chromatographed with 4:1 hexane–ethyl acetate as eluant to give first methyl 2-*O*-acetyl-3,4-di-*O*-benzyl-α-L-rhamnopyranoside[7] (83 mg). Further elution gave unidentified products (~100 mg) followed by syrupy **45** (215 mg, 51.4%): $[\alpha]_D$ −30° (*c* 0.5, $CHCl_3$); ^{13}C NMR ($CDCl_3$) δ 170.4, 169.7 (2×) 169.5 ($COCH_3$), 138.3, 138.1 (aromatic quaternary carbons), 128.2–127.2 (aromatic carbons), 99.4 ($^1J_{C,H}$ = 172 Hz), 99.2 ($^1J_{C,H}$ = 169 Hz) (C-1_A,1_B), 80.4 (C-4_A), 79.4 (C-3_A), 76.0 (C-2_A), 75.3, 72.2 [CH_2 (Bn)], 69.2, 68.9, 68.8, 67.8, 66.1 (C-5_A, C-2_B,3_B,4_B,5_B), 62.5 (C-6_B), 54.4 (OCH_3), 20.6, 20.5 (3×) (CH_3CO), 17.8 (C-6_A).

1-*O*-{2-*O*-[2-*O*-(α-L-Rhamnopyranosyl)-α-L-rhamnopyranosyl]-α-L-rhamnopyranosyl}-D-glucitol (2). A solution of compound **29** (120 mg, 0.068 mmol) in 5 mL of methanol was treated with sodium methoxide until the pH of the solution reached ~11 (indicator paper); then the solution was left standing at 25 °C for 24 h. The solution was neutralized (Dowex 50, H^+) and concentrated. A mixture of the residue and 10% palladium on carbon (~200 mg) in 95% ethanol (5 mL) and glacial acetic acid (1 mL) was stirred under hydrogen (1 atm) for 24 h at 25 °C. Removal of the catalyst by filtration followed by concentration gave a syrupy residue, which was purified through a column of Sephadex G-15 eluted with water. Freeze-drying of the major fraction gave **2** as an amorphous white powder (28 mg, 66.6%); $[\alpha]_D$ −52° (*c* 3.2, H_2O). For ^1H and ^{13}C NMR data, see Tables I and II, respectively.

1-*O*-(α-L-Rhamnopyranosyl)-D-glucitol (3). Deprotection of compound **23** as described for the deprotection of **29**, except that a Sephadex G-10 column was used for the final purification, gave amorphous **3** (73%); $[\alpha]_D$ −37° (*c* 1.7, H_2O). For ^1H and ^{13}C NMR data, see Tables I and II, respectively.

Methyl 2-*O*-(α-L-Mannopyranosyl)-α-L-rhamnopyranoside (4). Deprotection of compound **45** as described for compound **23** afforded amorphous **4** (75%); $[\alpha]_D$ −49° (*c* 0.4, H_2O) [lit.[41] $[\alpha]_D$ −54° (*c* 1, H_2O)]. For ^1H and ^{13}C NMR data, see Tables I and II, respectively.

1-*O*-[2-*O*-(α-L-Rhamnopyranosyl)-α-L-rhamnopyranosyl]-D-glucitol (5). Deprotection of compound **25** as described for compound **29** gave **5** as an amorphous powder (65%); $[\alpha]_D$ −40° (*c* 1.0, H_2O). For ^1H and ^{13}C NMR data, see Tables I and II, respectively.

Methyl 2-*O*-[2-*O*-(α-L-Mannopyranosyl)-α-L-rhamnopyranosyl]-α-L-rhamnopyranoside (6). Removal of protecting groups from compound **44** as described for compound **45** gave amorphous **6** (68%); $[\alpha]_D$ −54° (*c* 1.1, H_2O). For ^1H and ^{13}C NMR data, see Tables I and II, respectively.

Acknowledgment. We thank Hector Seguin of this Division for the elemental analyses.

(41) Norberg, T.; Oscarson, S.; Szönyi, M. *Carbohydr. Res.* **1986**, *156*, 214.

Regiospecific Addition of Monooxygenated Dienes to Halo Quinones

Louise Boisvert and Paul Brassard*

Département de chimie, Université Laval, Québec, Québec, Canada G1K 7P4

Received September 15, 1986

In spite of their decreased polarity with respect to previously studied electron-rich analogues, monooxygenated dienes also react regiospecifically with halo quinones. The corresponding adducts can easily be aromatized on silica gel to isomeric polysubstituted naphthoquinones of unambiguous structure and therefore provide ready access to substrates for subsequent regiospecific annulations. The scope of this approach is illustrated by advantageous syntheses of several natural products: chimaphilin, 6-methylalizarin, 6-methylxanthopurpurin, and barleriaquinone. The adducts can also give rise to a series of products in which the oxygen function of the dienes is preserved as a hydroxyl group in the quinone. To this end adducts derived from 1-oxygenated dienes and halo quinones were oxidized effectively with Jones' reagent while those obtained from the 2-oxygenated isomers responded better to manganese dioxide. Relative positions of substituents in the adducts were readily confirmed by comparison of some of the hydroxylated oxidation products with known compounds of unambiguous structure. The method is again illustrated by the ready synthesis of a number of natural products including plumbagin, soranjidiol, isochrysophanol and its 8-methyl ether, and isozyganein and its 5-methyl ether.

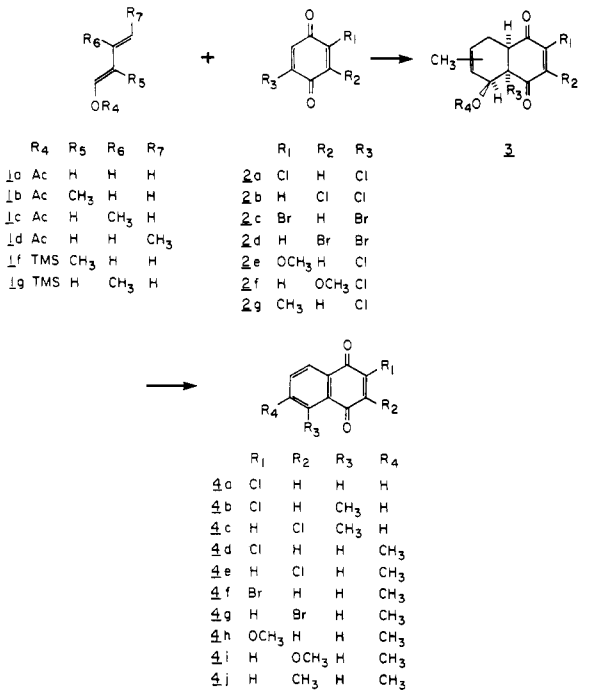
Regioselective annulations of quinones by the Diels–Alder strategy have been described with weakly or moderately polar dienes, appropriately substituted dienophiles, or catalysis by Lewis acids. Various combinations of these factors can produce remarquable effects[1] and highly selective results.[2] However, these approaches depend on structural features that can curtail their applicability and usefulness or, as in the case of catalysis, render the outcome unpredictable.

(1) Potts, K. T.; Bhattacharjee, D.; Walsh, E. B. *J. Chem. Soc., Chem. Commun.* **1984**, 114. Grieco, P. A.; Yoshida, K.; Garner, P. *J. Org. Chem.* **1983**, *48*, 3137. Schmidt, C.; Breining, T. *Tetrahedron* **1983**, *39*, 3929. Bohlmann, F.; Trantow, T. *Liebigs Ann. Chem.* **1983**, 1689. Agarwal, N. L.; Scheeren, H. W. *Chem. Lett.* **1982**, 1057. Tegmo-Larsson, I.-M.; Rozeboom, M. D.; Houk, K. N. *Tetrahedron Lett.* **1981**, *22*, 2043. Kelly, T. R. *Tetrahedron Lett.* **1978**, 1387. Giles, R. G. F.; Roos, G. H. P. *J. Chem. Soc., Perkin Trans 1* **1976**, 1632.

(2) (a) Hendrickson, J. B.; Singh, V. *J. Chem. Soc., Chem. Commun.* **1983**, 837. (b) Gupta, R. C.; Jackson, D. A.; Stoodley, R. J. *J. Chem. Soc., Chem. Commun.* **1982**, 929. (c) Boeckman, R. K., Jr.; Dolak, T. M.; Culos, K. O. *J. Am. Chem. Soc.* **1978**, *100*, 7098. (d) Tou, J. S.; Reusch, W. *J. Org. Chem.* **1980**, *45*, 5013. (e) Russell, R. A.; Collin, G. J.; Sterns, M.; Warrener, R. N. *Tetrahedron Lett.* **1979**, 4229. (f) Kelly, T. R.; Montury, M. *Tetrahedron Lett.* **1978**, 4311. (g) Stork, G.; Hagedorn, A. A., III, *J. Am. Chem. Soc.* **1978**, *100*, 3609.

0022-3263/88/1953-4052$01.50/0 © 1988 American Chemical Society

Scheme I



	R_4	R_5	R_6	R_7
1a	Ac	H	H	H
1b	Ac	CH_3	H	H
1c	Ac	H	CH_3	H
1d	Ac	H	H	CH_3
1f	TMS	CH_3	H	H
1g	TMS	H	CH_3	H

	R_1	R_2	R_3
2a	Cl	H	Cl
2b	H	Cl	Cl
2c	Br	H	Br
2d	H	Br	Br
2e	OCH_3	H	Cl
2f	H	OCH_3	Cl
2g	CH_3	H	Cl

3

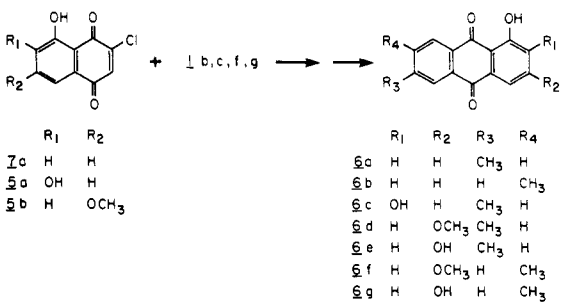
	R_1	R_2	R_3	R_4
4a	Cl	H	H	H
4b	Cl	H	CH_3	H
4c	H	Cl	CH_3	H
4d	Cl	H	H	CH_3
4e	H	Cl	H	CH_3
4f	Br	H	H	CH_3
4g	H	Br	H	CH_3
4h	OCH_3	H	H	CH_3
4i	H	OCH_3	H	CH_3
4j	H	CH_3	H	CH_3

Regiospecific cycloadditions have been achieved consistently in many instances where halo quinones are reacted with electron-rich dienes such as vinylketene acetals[3] and vinylogous ketene acetals.[4] The current study shows that complete regiochemical control can also be assured with a variety of 1- and 2-oxygenated dienes and the usual halogenated substrates.[5] Because of their particular importance in the synthesis of natural products, only methyl-substituted dienes have been considered for this investigation (Scheme I).

The simplicity of this approach, which affords a wide range of dienes by simple enolization of unsaturated aldehydes and ketones, is additionally attractive in that the intermediate adducts can either be aromatized with loss of the directing groups or oxidized, which allows retention of the oxygenated function. In both cases the products obtained from appropriately substituted benzoquinones may participate in subsequent regiospecific conversions, and since this overall process is essentially convergent, the method is readily amenable to optimization.

The required 1-acetoxybutadienes (**1a–d**) were obtained from the corresponding aldehydes (crotonaldehyde, tiglaldehyde, β-methylcrotonaldehyde,[6] and pent-2-enal) by simple acid-catalyzed enolacetylation with isopropenyl acetate,[7] but **1c** is best prepared from 1,1-dimethylpropargyl alcohol.[8] In contrast to many more highly oxygenated analogues, dienes **1a–d** reacted smoothly with both benzoquinones and naphthoquinones. Cycloadditions were generally complete after 48–96 h in refluxing benzene with the less electrophilic chloromethoxybenzoquinones and the more hindered 4-methyl dienes requiring the longer reaction times. In comparison to the chloro compounds, adducts formed with bromo quinones showed a greater tendency to aromatize and in some cases they did so spontaneously.

Scheme II



	R_1	R_2
7c	H	H
8a	OH	H
8b	H	OCH_3

	R_1	R_2	R_3	R_4
9c	H	H	CH_3	H
9b	H	H	H	CH_3
9c	OH	H	CH_3	H
9d	H	OCH_3	CH_3	H
9e	H	OH	CH_3	H
9f	H	OCH_3	H	CH_3
9g	H	OH	H	CH_3

The regiospecificity of the process can be determined upon isolation of the adduct (readily separated from unreacted benzoquinone with CCl_4). The NMR spectra of such compounds show clear, readily interpreted patterns and indicate the absence of a detectable amount of the other regioisomers. Indeed, the 5-C proton, geminal to the acetoxyl group, gives a signal well removed from others and particularly sensitive to the presence of chlorine atoms at 3-C. Signals for 3-chloro compounds regularly show downfield shifts of about 0.08 ppm with respect to those of the 2-chloro isomers and this provides a first confirmation of the expected regiochemistry.

I. Aromatization of the Adducts

Aromatization of adducts by pyrolysis was found to be difficult and inefficient, but two or three percolations through a column of silica gel, eluting rapidly with benzene, gave excellent results (in general, yields exceed 80% overall). In the case of naphthoquinones, the identity of the isomeric substances is even clearer in spite of the scarcity of authentic reference compounds. However, as it has been pointed out previously, additivity rules[9] would be expected to apply to the chemical shifts of protons in these quinones. Once again the signals corresponding to 5-C protons are particularly responsive to the proximity of a chlorine atom on the adjacent ring (at 3-C) but are little affected by the one at 2-C. Unambiguous proof of structure can only be obtained when the adducts are oxidized to the corresponding juglones, some of which are well-known compounds (see section II).

In view of the limited polarity of this type of diene, it seemed essential to establish the influence of other substituents disposed in such a way as to oppose the effect of the principal directing group. Diene **1b** with quinone **2a** should obviously give the same result as **1c** with **2b** (as would **1b** with **2b** and **1c** with **2a**). Although the relative positions of the substituents in the first instance are less satisfactory, the selectivity in both cases is within experimental error, total. Diene **1d** presents an even greater problem since terminal methyl groups are known to exert unexpectedly large effects,[10] yet the regiospecificity remains unaffected in spite of longer reaction times. Finally, when quinones **2e** and **2f** were used, and even though methoxyl groups are known to exert strong directional effects, no loss of regiochemical integrity was observed.

A number of di- and polysubstituted naphthoquinones can be laboriously prepared from simple substrates[11] and

(3) Savard, J.; Brassard, P. *Tetrahedron Lett.* **1979**, 4911.
(4) Guay, V.; Brassard, P. *J. Org. Chem.* **1984**, *49*, 1853 and references therein.
(5) For a preliminary communication, see: Boisvert, L.; Brassard, P. *Tetrahedron Lett.* **1983**, *24*, 2453.
(6) Fishman, D.; Klug, J. T.; Shani, A. *Synthesis* **1981**, 137.
(7) Hagemeyer, H. J., Jr.; Hull, D. C. *Ind. Eng. Chem.* **1949**, *41*, 2920.
(8) Banks, R. E.; Miller, J. A.; Nunn, M. J.; Stanley, P.; Weakley, T. J. R.; Ullah, Z. *J. Chem. Soc., Perkin Trans 1* **1981**, 1096.
(9) (a) Crecely, R. W.; Crecely, K. M.; Goldstein, J. H. *J. Mol. Spectrosc.* **1969**, *32*, 407. (b) Parker, K. A.; Sworin, M. E. *J. Org. Chem.* **1981**, *46*, 3218.
(10) Danishefsky, S.; Kahn, M. *Tetrahedron Lett.* **1981**, 489 and reference therein.
(11) Baillie, A. C.; Thomson, R. H. *J. Chem. Soc. C* **1966**, 2184. Fieser, L. F.; Brown, R. H. *J. Am. Chem. Soc.* **1949**, *71*, 3615.

strongly directing groups such as hydroxyls, methoxyls, and halogens can also orient substitution and other processes quite effectively.[12] In the presence of less polar substituents, selective syntheses have generally remained elusive and earlier claims[13] that methyl groups effectively control the regiochemistry have not been borne out by the present investigation. Indeed, samples prepared by prescribed methods or supplied by the originators were invariably found to be mixtures of the isomers now prepared regiospecifically for the first time.

The usefulness as well as the regiochemistry of this method can be illustrated by the following extremely simple syntheses of some naturally occurring products having well-established structures (Scheme II). Thus diene **1c** and benzoquinone **2g** rapidly gave an adduct which aromatized to give a compound showing physical and spectral properties identical with those of chimaphilin[14] (**4j**). A similar diene (**1f**) and 3-chlorojuglone (**7a**) afforded the recently isolated barleriaquinone[15] (**6b**) while **1g** with 3-chloro-6-hydroxyjuglone[16] (**5a**) gave 6-methylalizarin[17] (**6c**), both in nearly quantitative yield.

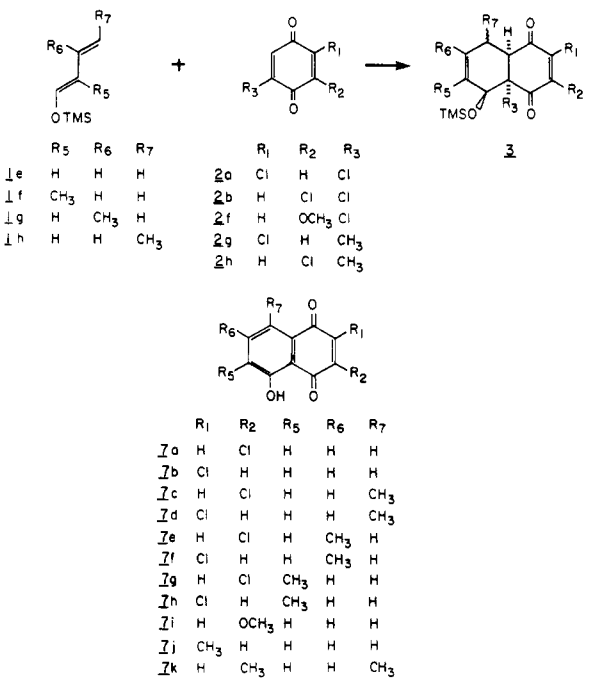
Reactions of dienes **1c** and **1b** with 3-chloro-7-methoxyjuglone[18] (**5b**) provided ready access to 6-methylxanthopurpurin 3-methyl ether[19] (**6d**) and the nonnatural 7-methyl analogue (**6f**). Demethylation of these two anthraquinones in a molten mixture of aluminum and sodium chlorides confirmed the identities of earlier preparations[20,21] and established that structures proposed for a substance isolated from *Claviceps purpurea* Tul. (and described as a 1,3-dihydroxy-6(or 7-)-methylanthraquinone[22]) are quite incorrect. The absence of spectral data in the communication in question precludes any conjecture as to the real nature of this substance.

II. Oxidation of the Adducts

Oxidation to juglones of the Diels–Alder adducts formed with nonhalogenated quinones has previously been carried out with PCC after hydrolysis of the trimethylsiloxylated intermediates under mild conditions.[23] The extension of this approach to halogenated substrates would not only improve the regiochemical outcome but would also add an extra dimension to the method by allowing unlimited access to intermediates suitable for subsequent regiospecific conversions.

Initial attempts to oxidize adducts obtained with 1-acetoxybutadiene using various reagents such as PCC, PDC,[24] CAN,[25] or DDQ[26] were uniformly unsuccessful and gave only the elimination product. NBS,[27] effective in an analogous instance, produced some of the expected juglone

Scheme III



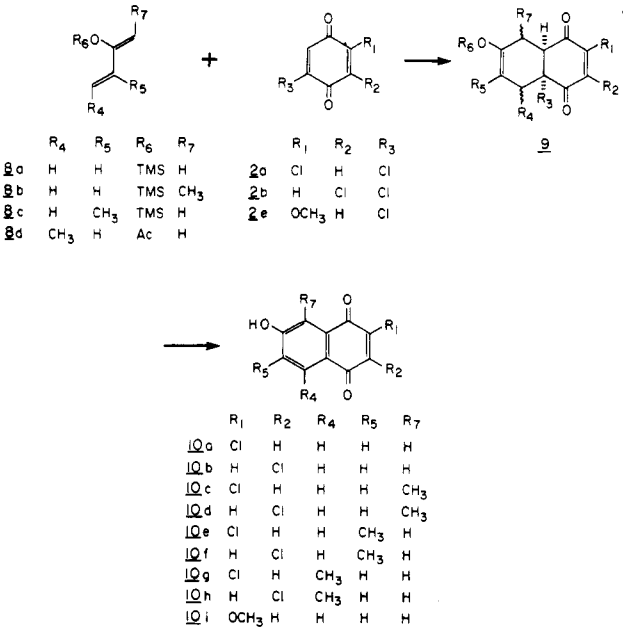
	R_5	R_6	R_7
1e	H	H	H
1f	CH_3	H	H
1g	H	CH_3	H
1h	H	H	CH_3

	R_1	R_2	R_3
2a	Cl	H	Cl
2b	H	Cl	Cl
2f	H	OCH_3	Cl
2g	Cl	H	CH_3
2h	H	Cl	CH_3

3

	R_1	R_2	R_5	R_6	R_7
7a	H	Cl	H	H	H
7b	Cl	H	H	H	H
7c	H	Cl	H	H	CH_3
7d	Cl	H	H	H	CH_3
7e	H	Cl	H	CH_3	H
7f	Cl	H	H	CH_3	H
7g	H	Cl	CH_3	H	H
7h	Cl	H	CH_3	H	H
7i	H	OCH_3	H	H	H
7j	CH_3	H	H	H	H
7k	H	CH_3	H	H	CH_3

Scheme IV



	R_4	R_5	R_6	R_7
8a	H	H	TMS	H
8b	H	H	TMS	CH_3
8c	H	CH_3	TMS	H
8d	CH_3	H	Ac	H

	R_1	R_2	R_3
2a	Cl	H	Cl
2b	H	Cl	Cl
2e	OCH_3	H	Cl

9

	R_1	R_2	R_4	R_5	R_7
10a	Cl	H	H	H	H
10b	H	Cl	H	H	H
10c	Cl	H	H	H	CH_3
10d	H	Cl	H	H	CH_3
10e	Cl	H	H	CH_3	H
10f	H	Cl	H	CH_3	H
10g	Cl	H	CH_3	H	H
10h	H	Cl	CH_3	H	H
10i	OCH_3	H	H	H	H

but in a difficultly separable mixture. Turning to the corresponding trimethylsiloxylated dienes, it was found that Krohn's method again gave the same result whether applied to the silylated or hydrolyzed adducts, elimination in all cases taking precedence over oxidation.

Ultimately the use of chromium trioxide in acetic acid[28] (2.5 molar equiv) not only provided the expected juglone cleanly and, considering the ease of preparation, in quite good yield (51–76%) but also eliminated the need for prior hydrolysis of the intermediates. However, adducts bearing methyl substituents in the 5- or 8-position were quite resistant to these conditions, reflecting the difficulty of bringing bulky groups so situated into the plane of the aromatic ring. They responded well to Jones' reagent[29] (2.0

(12) Thomson, R. H. *J. Org. Chem.* **1948**, *13*, 870. Cameron, D. W.; Feutrill, G. I.; Griffiths, P. G. *Aust. J. Chem.* **1981**, *34*, 1513.
(13) Lyons, J. M.; Thomson, R. H. *J. Chem. Soc.* **1953**, 2910.
(14) Burnett, A. R.; Thomson, R. H. *J. Chem. Soc. C* **1968**, 857.
(15) Gopalakrishnan, S.; Neelakantan, S.; Raman, P. V.; Okuyama, T.; Shibata, S. *Chem. Pharm. Bull. Jpn.* **1984**, *32*, 4137.
(16) Simoneau, B.; Brassard, P. to be submitted.
(17) Brew, E. J. C.; Thomson, R. H. *J. Chem. Soc. C* **1971**, 2001.
(18) Savard, J.; Brassard, P. *Tetrahedron* **1984**, *40*, 3455.
(19) Stoessl, A. *Can. J. Chem.* **1969**, *47*, 767.
(20) Perkin, A. G.; Hummel, J. J. *J. Chem. Soc.* **1894**, *65*, 851.
(21) Mayer, F.; Günther, H. *Ber.* **1930**, *63*, 1455.
(22) Schneider, R.; Mutschler, E.; Rochelmeyer, H. *Pharmazie* **1970**, *25*, 367.
(23) Krohn, K. *Tetrahedron Lett.* **1980**, 3557.
(24) Corey, E. J.; Schmidt, G. *Tetrahedron Lett.* **1979**, 399.
(25) Trahanovsky, W. S.; Young, L. B.; Brown, G. L. *J. Org. Chem.* **1967**, *32*, 2349.
(26) Ward, R. S.; Satyanarayana, P.; Rao, B. V. G. *Tetrahedron Lett.* **1981**, 3021.
(27) Hiranuma, H.; Miller, S. I. *J. Org. Chem.* **1982**, *47*, 5083.
(28) Fieser, L. F.; Dunn, J. T. *J. Am. Chem. Soc.* **1937**, *59*, 1024.

molar equiv), generally giving better results than in the preceding case (58–79%) (Scheme III).

2-Acetoxypentadiene **8d**, in which the electronic effects of the substituents are complementary, reacted smoothly with quinones **2a** and **2b** to give regiospecific products which could be oxidized by Fieser's reagent to the corresponding naphthoquinones in fair overall yield (43–45%) (again taking into account the extreme ease of preparation). When similar cycloadditions with 2-acetoxybutadiene were carried out, a mixture of regioisomers was detected. By changing to the trimethylsiloxy derivative, the process again became regiospecific but the adducts could not be oxidized with either the Fieser or Jones reagent. Eventually commercial MnO_2[30] in benzene was found to give acceptable yields of the corresponding naphthoquinones (31–70%). The adduct formed from diene **8a** and quinone **2e** could not be oxidized by any of the foregoing reagents; however, a 36% yield of the desired product (**10i**) was obtained with triethylamine in benzene (Scheme IV).

As expected, diene **8b** and quinones **2a** and **2b** gave products confirming the observation that terminal methyl groups rather than the adjacent ethers control the direction of cycloaddition.[10] Only one substitution pattern on the diene, that found in **8c**, gave mixtures of regioisomers (**10e** and **10f**), which indicates that a β-methyl group also exerts an inordinately large effect on this type of reaction.

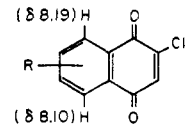
As noted above, adducts obtained from bromo quinones were found to aromatize much more readily than the corresponding chloro compounds. The greater stability of the latter singled them out as the ideal substrates for oxidation processes although with appropriate care the bromo derivatives can be oxidized quite as effectively. Cycloaddition products formed from benzoquinones were observed to eliminate more easily than those obtained with naphthoquinones and this behavior suggested that when a choice of sequences is available for the synthesis of anthraquinones, an oxidative procedure would be wisely deferred to the last step.

Inspection of the ^1H NMR data shows that in 2- and 3-chloronaphthoquinones bearing commonly encountered substituents an accurate regiochemical assignment can be made on the sole basis of the chemical shifts observed for peri protons. In fact, a long history of errors and ambiguities in the structural determination of substituted naphthoquinones had preceded the advent of regiospecific syntheses and accurate diagnostic methods. Parker and Sworin[9b] had previously noted that the NMR spectra of 3-hydroxy- and 3-aminojuglones show noticeable upfield shifts for C-6 protons (as well as for those at C-7 in the case of the 2-amino isomers) while those of 2-bromo analogues exhibit a pronounced downfield effect on protons at C-8.

We have now been able to show that chloro substituents at C-2 or C-3 in naphthoquinones exert a predictable influence on both peri protons as determined by NMR chemical shifts and that other substituents on the aromatic ring also produce additive effects. These contributions (Table I) therefore allow accurate structural assignments to be made in the case of compounds obtained by nonregiospecific methods. This rule fails in only one instance, that is, when a methyl group is situated next to a *peri*-methoxyl substituent. In these cases extreme steric hindrance seems to impede resonance of the methoxyl group with the aromatic system.

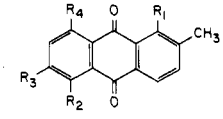
(29) Baker, R.; Rao, V. B.; Ravenscroft, P. D.; Swain, C. J. *Synthesis* **1983**, 572.
(30) Mashraqui, S.; Keehn, P. *Synth. Commun.* **1982**, *12*, 637.

Table I. Contributions of Substituents to the Chemical Shifts of Protons at C-5 and C-8 in 2-(or 3-)Chloronaphthoquinones



R	Δδ	R	Δδ
o-CH_3	−0.22	*m*-OH	−0.07
m-CH_3	−0.13	*p*-OH	−0.45
p-CH_3	−0.08	*p*-OCH_3	−0.35
o-OH	−0.64		

The usefulness of the approach was illustrated by some very advantageous syntheses of several naturally occurring quinones. Thus, often prepared plumbagin[31] (**7j**) could be obtained directly from benzoquinone **2g** and diene **1e** while naphthoquinone **7g** and diene **8a** easily gave soranjidiol (**11e**), the synthesis of which is quite involved by other means. Application of the approach to a number of anthraquinones showed in particular that a group of peri-dihydroxylated examples and their partially methylated derivatives are accessible in high yield from readily available naphthoquinones. By two successive cycloaddition–oxidation sequences, 3-chlorojuglone (**7a**) and its 5-methyl ether were first formed and with diene **1f** then converted to isochrysophanol[32] (**11a**) and its 8-methyl ether[33] (**11b**), respectively. Similarly 2-chlorojuglone (**7b**) and the 5-methyl ether afforded isozyganein[34] (**11c**) and the corresponding 5-methyl ether[34] (**11d**). In no case did untoward electronic effects decrease the effectiveness or the specificity of the approach.



	R_1	R_2	R_3	R_4
11a	OH	H	H	OH
11b	OH	H	H	OCH_3
11c	OH	OH	H	H
11d	OH	OCH_3	H	H
11e	OH	H	OH	H

Finally, the efficiency of an anthraquinone synthesis requiring both oxidation and elimination steps was tested by permuting the two sequences. In the preparation of barleriaquinone[15] (**6b**), cycloaddition of diene **1f** to 3-chlorojuglone (**7a**) (obtained by oxidation in 75% yield) had earlier, after elimination, given nearly quantitative conversion to the natural product. However, oxidation of the adduct formed from 3-chloro-6-methylnaphthoquinone (obtained by elimination in 88% yield) and diene **1e** was somewhat less satisfactory.

Experimental Section

All melting points were taken for samples in capillary tubes with a Thomas-Hoover apparatus and are not corrected. The UV spectra were determined on a Hewlett-Packard 8450A spectro-

(31) Thomson, R. H. *Naturally Occurring Quinones*, 2nd ed.; London, 1971; p 228.
(32) Brew, E. J. C.; Thomson, R. H. *J. Chem. Soc. C* **1971**, 2007.
(33) Imre, S. *Z. Naturforsch. C: Biochem., Biophys., Biol., Virol.* **1973**, *28C*, 436.
(34) Gonzalez, A. G.; Cardona, R. J.; Lopez Dorta, H.; Medina, J. M.; Rodriguez Luis, F. *An. Quim.* **1977**, *73*, 869.

photometer and the IR spectra on a Beckman Model IR-4250 instrument and calibrated with a film of polystyrene. NMR spectra were recorded with a Varian XL-200 spectrometer using tetramethylsilane as internal standard. Mass spectra were obtained with a Hewlett-Packard 5995A spectrometer. Merck silica gel $60F_{254}$, for dry column chromatography, was used throughout in a product-to-adsorbent ratio of 1:50–100. Elemental analyses were carried out by Galbraith Laboratories, Inc., Knoxville, TN. Ether refers to diethyl ether.

I. Aromatization of the Adducts. A. Preparation of Naphthoquinones 4a–j. General Method. To the benzoquinone **2a–g** (2.0 mmol) in dry benzene (18 mL) was added the diene **1a–g** (2.2 mmol) in the same solvent (2 mL). The mixture was refluxed (48–96 h), cooled, and filtered (once or several times as required) through a column of silica gel, eluting rapidly with benzene.

2-Chloronaphthoquinone (4a). Application of the foregoing method to benzoquinone **2a** and diene[7] **1a** (48 h) gave naphthoquinone **4a** (355 mg; 92%), after two percolations: mp 112–113 °C (ethanol) (lit.[35] mp 113–114 °C); NMR δ ($CDCl_3$) 7.23 (1 H, s, 3-H), 7.73–7.84 (2 H, m, 6,7-H), 8.10 (1 H, m, 5-H), and 8.19 (1 H, m, 8-H).

2-Chloro-5-methylnaphthoquinone (4b). Cycloaddition of diene **1d** to quinone **2b** (96 h) gave an adduct which was adsorbed and eluted four times in order to effect aromatization to naphthoquinone **4b** (371 mg; 90%): mp 110–111 °C (ethanol); UV λ_{max} (95% EtOH) 230, 266, 316, and 319 nm (log ϵ 4.07, 3.36, 3.36 and 3.87); IR ν_{max} (KBr) 1670, 1650, 1610, 1590, and 1565 cm^{-1}; NMR δ ($CDCl_3$) 2.75 (3 H, s, 5-CH_3), 7.16 (1 H, s, 3-H), 7.58 (1 H, A part of an ABX system, J_{calcd} = 7.9 and 1.3 Hz, 6-H), 7.62 (1 H, B part of ABX, J_{calcd} = 7.9 and 8.0 Hz, 7-H), and 8.11 (1 H, X part of ABX, J_{calcd} = 8.0 and 1.3 Hz, 8-H); MS, m/z 206/208 $(M)^+$, 127 (100) (Found: C, 63.66; H, 3.58; Cl, 16.99. $C_{11}H_7O_2Cl$ requires: C, 63.94; H, 3.41; Cl, 17.16).

3-Chloro-5-methylnaphthoquinone (4c). In a reaction similar to the preceding one, quinone **2a** and diene **1d** gave naphthoquinone **4c** (328 mg; 80%): mp 116–117 °C (ethanol); UV λ_{max} (95% EtOH) 248, 269, 331, and 343 nm (log ϵ 4.04, 3.36, 3.36, and 3.64); IR ν_{max} (KBr) 1665, 1605, and 1585 cm^{-1}; NMR δ ($CDCl_3$) 2.78 (3 H, s, 5-CH_3), 7.20 (1 H, s, 2-H), 7.57 (1 H, A part of ABX system, J_{calcd} = 7.6 and 0.6 Hz, 6-H), 7.64 (1 H, B part of ABX, J_{calcd} = 7.6 and 8.0 Hz, 7-H), and 8.02 (1 H, X part of ABX, J_{calcd} = 8.0 and 0.6 Hz, 8-H); MS, m/z 206/208 $(M)^+$ (Found: C, 64.20; H, 3.53; Cl, 17.16).

2-Chloro-6-methylnaphthoquinone (4d). (a) The general method using diene[8] **1c** and quinone **2b** (60 h), after a single percolation, gave the expected naphthoquinone **4d** (327 mg; 80%): mp 134.5–135.5 °C (ethanol); UV λ_{max} (95% EtOH) 250, 258, 273, and 344 nm (log ϵ 4.21, 4.14, 4.12, and 3.40); IR ν_{max} (KBr) 1670, 1655, 1595, and 1590 cm^{-1}; NMR δ ($CDCl_3$) 2.51 (3 H, s, 6-CH_3), 7.17 (1 H, s, 3-H), 7.56 (1 H, br d, J = 7.9 Hz, 7-H), 7.86 (1 H, m, 5-H), and 8.04 (1 H, d, J = 7.9 Hz, 8-H); MS, m/z 206/208 $(M)^+$, 143 (100) (Found: C, 64.12; H, 3.40; Cl, 17.22).

(b) Compound **4d** (323 mg; 79%) was also obtained from benzoquinone **2a** and diene **1b** (the latter was prepared from tiglaldehyde by the usual method[7] in 81% yield, bp 74 °C/35 mmHg).

3-Chloro-6-methylnaphthoquinone (4e). (a) As in the foregoing case benzoquinone **2a** and diene **1c** gave naphthoquinone **4e** (359 mg; 88%): mp 122–123 °C (ethanol); λ_{max} (95% EtOH) 253, 258, 273, 348, and 371 nm (log ϵ 4.11, 4.14, 4.05, 3.28, and 3.15); IR ν_{max} 1675, 1655, 1600, and 1590 cm^{-1}; NMR δ ($CDCl_3$) 2.51 (3 H, s, 6-CH_3), 7.18 (1 H, s, 2-H), 7.57 (1 H, br d, J = 8.2 Hz, 7-H), 7.95 (1 H, s, 5-H) and 7.97 (1 H, br d, J = 8.2 Hz, 8-H); MS, m/z 206/208 $(M)^+$, 143 (100) (Found: C, 64.05; H, 3.47; Cl, 17.20).

(b) Quinone **4e** (260 mg; 65%) was also obtained from benzoquinone **2b** and diene **1b**.

2-Bromo-6-methylnaphthoquinone (4f). A similar reaction using benzoquinone **2d** and diene **1c** (60 h) after one percolation gave naphthoquinone **4f** (408 mg; 81%): mp 139–140 °C (ethanol); UV λ_{max} (95% EtOH) 252, 258, 282, and 346 nm (log ϵ 4.07, 4.08, 4.05, and 3.34); IR λ_{max} (KBr) 1670, 1655, 1600, and 1580 cm^{-1}; NMR δ ($CDCl_3$) 2.51 (3 H, s, 6-CH_3), 7.48 (1 H, s, 3-H), 7.56 (1 H, br d, J = 7.9 Hz, 7-H), 7.88 (1 H, m, 5-H), and 8.07 (1 H, d, J = 7.9 Hz, 8-H); MS, m/z 250/252 $(M)^+$ (Found: C, 52.76; H, 2.95; Br, 31.53. $C_{11}H_7O_2Br$ requires: C, 52.62; H, 2.81; Br, 31.82).

3-Bromo-6-methylnaphthoquinone (4g). When benzoquinone **2d** reacted with diene **1b** as in the preceding case, naphthoquinone **4g** was obtained (454 mg; 91%): mp 127.5–128.5 °C (ethanol); UV λ_{max} (95% EtOH) 252, 258, 281, and 352 nm (log ϵ 4.06, 4.09, 3.98, and 3.30); IR ν_{max} (KBr) 1670, 1650, 1595, 1585, and 1570 cm^{-1}; NMR δ ($CDCl_3$) 2.52 (3 H, s, 6-CH_3), 7.49 (1 H, s, 2-H), 7.58 (1 H, br d, J = 8.0 Hz, 7-H), 7.96 (1 H, s, 5-H), and 7.98 (1 H, br d, J = 8.0 Hz, 8-H); MS, m/z 250/252 $(M)^+$ (Found: C, 52.45; H, 2.86; Br, 31.58).

2-Methoxy-6-methylnaphthoquinone (4h). The adduct obtained from 6-chloro-2-methoxybenzoquinone[36] (**2f**) and diene **1c** (72 h) was filtered over silica gel (C_6H_6–AcOEt 20:1) and gave naphthoquinone **4h** (294 mg; 79%): mp 165 °C (ethanol); UV λ_{max} (95% EtOH) 238, 246, 254, 280, and 333 nm (log ϵ 4.08, 4.08, 4.00, 3.18, and 4.04); IR ν_{max} (KBr) 1685, 1655, 1645, and 1600 cm^{-1}; NMR δ ($CDCl_3$) 2.49 (3 H, s, 6-CH_3), 3.90 (3 H, s, 2-OCH_3), 6.14 (1 H, s, 3-H), 7.50 (1 H, br d, J = 7.7 Hz, 7-H), 7.88 (1 H, m, 5-H), and 8.02 (1 H, d, J = 7.7 Hz, 8-H); MS, m/z 202 $(M)^+$ (Found: C, 71.45; H, 5.01. $C_{12}H_{10}O_3$ requires: C, 71.28; H, 4.98).

3-Methoxy-6-methylnaphthoquinone (4i). In an experiment similar to the foregoing one, benzoquinone[36] **2e** and diene **1c** yielded naphthoquinone **4i** (389 mg; 96%): mp 187–188 °C (ethanol); UV λ_{max} KBr (95% EtOH) 246, 252, 282, and 342 nm (log ϵ 4.12, 4.13, 3.97, and 3.18); IR ν_{max} (KBr) 1680, 1650, 1610, 1595, and 1570 cm^{-1}; NMR δ ($CDCl_3$) 2.49 (3 H, s, 6-CH_3), 3.90 (3 H, s, 3-OCH_3), 6.14 (1 H, s, 2-H), 7.54 (1 H, br d, J = 8.1 Hz, 7-H), 7.93 (1 H, m, 5-H), and 7.97 (1 H, d, J = 8.1 Hz, 8-H); MS m/z 202 $(M)^+$ (Found: C, 71.36; H, 5.03).

3,6-Dimethylnaphthoquinone (4j) (Chimaphilin). Application of the method to benzoquinone[37] **2g** and diene **1c** afforded chimaphilin (**4j**) (263 mg; 71%): mp 112–113 °C (ethanol) (lit.[14] mp 114 °C); UV λ_{max} (95% EtOH) 250, 255, 266, and 342 nm (log ϵ 4.20, 4.23, 4.02, and 3.32); IR ν_{max} (KBr) 1665, 1615, and 1600 cm^{-1}; NMR δ ($CDCl_3$) 2.18 (3 H, br s, 3-CH_3), 2.49 (3 H, s, 6-CH_3), 6.80 (1 H, q, J = 1.3, 2-H), 7.52 (1 H, br d, J = 7.9 Hz, 7-H), 7.89 (1 H, m, 5-H), and 7.95 (1 H, d, J = 7.9 Hz, 8-H); MS, m/z 186 $(M)^+$ (Found: C, 77.23; H, 5.49. Calcd for $C_{12}H_{10}O_2$: C, 77.40; H, 5.41).

B. Preparation of Anthraquinones 6a–g. 2-Methylanthraquinone (Tectoquinone). To a suspension of naphthoquinone **4a** (385 mg, 2.00 mmol) in dry THF (1 mL) was added diene **1b** (504 mg, 4.00 mmol). The mixture was stirred for 48 h at room temperature and evaporated and the adduct aromatized on silica gel (C_6H_6). A single percolation gave tectoquinone (277 mg; 93%): mp 175–176 °C (ethanol) (lit.[38] 178–179°); UV λ_{max} (95% EtOH) 256, 275, and 328 nm (log ϵ 4.66, 4.19, and 3.69); IR ν_{max} 1665 and 1585 cm^{-1}; NMR δ ($CDCl_3$) 2.54 (3 H, s, 2-CH_3), 7.60 (1 H, br d, J = 7.9 Hz, 3-H), 7.75–7.84 (2 H, m, 6,7-H), 8.11 (1 H, m, 1-H), 8.21 (1 H, d, J = 7.9 Hz, 4-H), and 8.26–8.36 (2 H, m, 5,8-H); MS, m/z 222 $(M)^+$ (Found: C, 80.92; H, 4.73. Calcd for $C_{15}H_{10}O_2$: C, 81.07; H, 4.53).

1-Hydroxy-6-methylanthraquinone (6a). A solution of 3-chlorojuglone[39] (**7a**) (209 mg, 1.00 mmol) and 3-methyl-1-(trimethylsiloxy)butadiene[40] (**1g**) (172 mg, 1.10 mmol) in THF (6 mL) was stirred for 24 h at room temperature and evaporated. The residue was converted in the usual way (two adsorptions and elutions with C_6H_6) to quinone **6a** (234 mg; 98%): mp 145.5–146.5 °C (ethanol); UV λ_{max} (MeOH) 213, 257, 281, 330, and 400 nm (log ϵ 4.48, 4.60, 4.16, 3.54, and 3.88); IR ν_{max} (KBr) 1680, 1625, and 1605 cm^{-1}; NMR δ ($CDCl_3$) 2.52 (3 H, s, 6-CH_3), 7.26 (1 H,

(35) Gaertner, R. *J. Am. Chem. Soc.* **1954**, *76*, 6150.

(36) Raiford, L. C.; Lichty, J. G. *J. Am. Chem. Soc.* **1930**, *52*, 4576. Asp, L.; Lindberg, B. *Acta Chem. Scand.* **1950**, *4*, 60. Ioffe, I. S.; Sukhina, A. F. *Zh. Obshch. Khim.* **1953**, *23*, 295; *Chem. Abstr.* **1954**, *48*, 2640*d*.

(37) Andrews, K. J. M.; Marrian, D. H.; Maxwell, D. R. *J. Chem. Soc.* **1956**, 1844.

(38) Burnett, A. R.; Thomson, R. H. *J. Chem. Soc. C* **1967**, 2100.

(39) Thomson, R. H. *J. Org. Chem.* **1948**, *13*, 377.

(40) Ishida, A.; Mukaiyama, T. *Bull. Chem. Soc. Jpn.* **1977**, *50*, 1161. This method was modified as follows: the reaction mixture was heated to 70 °C for 16 h under an efficient condenser, and after cooling, the salts were precipitated by addition of petroleum ether, bp 30–60 °C (the yields were unchanged).

dd, J = 1.3 and 8.3 Hz, 2-H), 7.56 (1 H, br d, J = 7.9 Hz, 7-H), 7.63 (1 H, dd, J = 7.5 and 8.3 Hz, 3-H), 7.78 (1 H, dd, J = 1.3 and 7.5 Hz, 4-H), 8.03 (1 H, m, 5-H), 8.15 (1 H, d, J = 7.9 Hz, 8-H), and 12.63 (1 H, s, 1-OH); MS, m/z 238 $(M)^+$ (100) (Found: C, 75.80; H, 4.26. Calcd for $C_{15}H_{10}O_3$: C, 75.62; H, 4.23).

1-Hydroxy-7-methylanthraquinone (6b) (Barleriaquinone). From a reaction similar to the foregoing one using 2-methyl-1-(trimethylsiloxy)butadiene[40] (**1f**) and the same quinone **7a** (three adsorptions and elutions) was isolated barleriaquinone (**6b**) (236 mg; 99%): mp 175–176 °C (ethanol) (lit.[15] mp 171–172 °C); UV λ_{max} (MeOH) 216, 258, 282, 330, 388, and 402 nm (log ϵ 4.33, 4.50, 4.03, 3.42, 3.62, and 3.71); IR ν_{max} (KBr) 1660, 1630, and 1580 cm^{-1}; NMR δ ($CDCl_3$) 2.53 (3 H, s, 7-CH_3), 7.28 (1 H, dd, J = 8.4 and 1.5 Hz, 2-H), 7.58 (1 H, br d, J = 7.5 Hz, 6-H), 7.66 (1 H, dd, J = 8.4 and 7.6 Hz, 3-H), 7.81 (1 H, dd, J = 7.6 and 1.5 Hz, 4-H), 8.08 (1 H, m, 8-H), 8.17 (1 H, d, J = 7.5 Hz, 5-H), and 12.60 (1 H, s, 1-OH); MS, m/z 238 $(M)^+$ (Found: C, 75.50; H, 4.28. Calcd for $C_{15}H_{10}O_3$: C, 75.62; H, 4.23).

1,2-Dihydroxy-6-methylanthraquinone (6c) (6-Methylalizarin). Solutions of 3-chloro-6-hydroxyjuglone[16] (**5a**) (225 mg, 1.00 mmol) in THF (8 mL) and 3-methyl-1-(trimethylsiloxy)butadiene (**1g**) (253 mg, 1.60 mmol) in the same solvent (2 mL) were brought together and stirred for 2 h at room temperature. Aromatization of the adduct was effected by addition of concentrated HCl (2 mL), and dilution with water (30 mL) precipitated 6-methylalizarin (**6c**) in nearly quantitative yield (254 mg): mp 228–229 °C (CH_2ClCH_2Cl) (lit.[17] mp 222–224 °C); UV λ_{max} (MeOH) 231, 261, 284, 331, and 426 nm (log ϵ 4.36, 4.66, 4.30, 3.65, and 3.87); IR ν_{max} (KBr) 3470, 1660, 1635, and 1600 cm^{-1}; NMR δ ($CDCl_3$) 2.54 (3 H, s, 6-CH_3), 6.24 (1 H, s, 2-OH), 7.26 (1 H, br d, J = 8.2 Hz, 3-H), 7.58 (1 H, br d, J = 8.1 Hz, 7-H), 7.84 (1 H, d, J = 8.2 Hz, 4-H), 8.11 (1 H, m, 5-H), 8.19 (1 H, d, J = 8.1 Hz, 8-H), and 12.89 (1 H, s, 1-OH); MS, m/z 254 $(M)^+$ (Found: C, 70.63; H, 3.98. Calcd for $C_{15}H_{10}O_4$: C, 70.86; H, 3.96).

1-Hydroxy-3-methoxy-6-methylanthraquinone (6d) (6-Methylxanthopurpurin 3-(Methyl ether)). A mixture of 3-chloro-7-methoxyjuglone[18] (**5b**) (239 mg, 1.00 mmol) and diene **1c** (252 mg, 2.00 mmol) in dry THF (20 mL) was refluxed for 24 h and evaporated. Chromatography of the residue (C_6H_6) gave anthraquinone **6d** (254 mg, 95%): mp 183–184 °C (ethanol) (lit.[19] mp 184–185 °C); UV λ_{max} (95% EtOH) 228, 252, 262, 279, 336, and 410 nm (log ϵ 4.13, 4.29, 4.26, 4.27, 3.38, and 3.72); IR ν_{max} (KBr) 1675, 1625, and 1595 cm^{-1}; NMR δ ($CDCl_3$) 2.52 (3 H, s, 6-CH_3), 3.94 (3 H, s, 3-OCH_3), 6.70 (1 H, d, J = 2.6 Hz, 2-H), 7.36 (1 H, d, J = 2.6 Hz, 4-H), 7.58 (1 H, br d, J = 8.1 Hz, 7-H), 8.06 (1 H, m, 5-H), 8.17 (1 H, d, J = 8.1 Hz, 8-H), and 12.93 (1 H, s, 1-OH); MS, m/z 268 $(M)^+$ (Found: C, 71.73; H, 4.58. Calcd for $C_{16}H_{12}O_4$: C, 71.64; H, 4.51).

1,3-Dihydroxy-6-methylanthraquinone (6e) (6-Methylxanthopurpurin). Anthraquinone **6d** (50 mg) was demethylated by heating for 2 min in a mixture of molten $AlCl_3$ (6.25 g) and NaCl (1.25 g) at 180 °C and after chromatography (C_6H_6–AcOEt 1:1) gave 6-methylxanthopurpurin (**6e**) (38 mg; 80%): mp 272–273 °C (methanol) (lit.[20] mp 269 °C); IR ν_{max} (KBr) 3410, 1660, and 1595 cm^{-1}; NMR δ (pyridine-d_5) 2.29 (3 H, s, 6-CH_3), 7.04 (1 H, d, J = 2.4 Hz, 2-H), 7.49 (1 H, br d, J = 8.4 Hz, 7-H), 7.72 (1 H, d, J = 2.4 Hz, 4-H), 8.13 (1 H, m, 5-H), and 8.27 (1 H, d, J = 8.4 Hz, 8-H).

1-Hydroxy-3-methoxy-7-methylanthraquinone (6f) (7-Methylxanthopurpurin 3-(Methyl ether)). In a preparation similar to that of quinone **6d**, 3-chloro-7-methoxyjuglone (**5b**) and diene **1b** gave 7-methylxanthopurpurin 3-(methyl ether) (**6f**) (200 mg, 75%): mp 213–214 °C (ethanol) (lit.[2f] mp 221–13 °C ?); IR ν_{max} (KBr) 1675, 1630, and 1595 cm^{-1}; NMR δ ($CDCl_3$) 2.54 (3 H, s, 7-CH_3), 3.94 (3 H, s, 3-OCH_3), 6.70 (1 H, d, J = 2.6 Hz, 2-H), 7.38 (1 H, d, J = 2.6 Hz, 4-H), 7.57 (1 H, br d, J = 7.6 Hz, 6-H), 8.09 (1 H, m, 8-H), 8.17 (1 H, br d, J = 7.6 Hz, 5-H), and 12.91 (1 H, s, 1-OH).

1,3-Dihydroxy-7-methylanthraquinone (6g) (7-Methylxanthopurpurin). Demethylation of **6f** as in the preparation of anthraquinone **6e** gave 7-methylxanthopurpurin (**6g**) (37 mg; 78%): mp 295 °C (methanol) (lit.[21] mp 297 °C); IR ν_{max} (KBr) 3385, 1660, 1630, and 1595 cm^{-1}; NMR δ (pyridine-d_5) 2.30 (3 H, s, 7-CH_3), 7.03 (1 H, d, J = 2.6 Hz, 2-H), 7.45 (1 H, br d, J = 7.7 Hz, 6-H), 7.72 (1 H, d, J = 2.6 Hz, 4-H), 8.16 (1 H, m, 8-H), and 8.25 (1 H, d, J = 7.7 Hz, 5-H).

II. Oxidation of the Adducts. Method A. To a solution of the foregoing adduct (**3** or **9**) in glacial acetic acid (3 mL) was added a suspension of CrO_3 (0.50 g) in the same solvent (10 mL). The mixture was refluxed for the required time, taken up in ether, washed several times with water until free of acid, and finally purified by chromatography (C_6H_6).

Method B. A solution of CrO_3 (0.27 g) in 20% H_2SO_4 (1 mL) was added dropwise (15 min) to the adduct (**3**) in dry acetone and the mixture was stirred at room temperature until oxidation was complete. Excess reagent was eliminated by addition of 2-propanol (10 mL) and the filtered reaction mixture was dissolved in ether and then washed with water (4×). The crude product was finally purified by chromatography.

Method C. To the original reaction mixture was added activated MnO_2 (Aldrich Chemical Co.) (1.8 g). The suspension was stirred at room temperature for the indicated time and filtered and the crude product purified by chromatography (C_6H_6–AcOEt 5:1).

C. Synthesis of 5-Hydroxynaphthoquinones (Juglones) (7a–k). 3-Chlorojuglone (7a). A solution of benzoquinone **2b** and diene **1e** was refluxed for 40 h and the crude adduct oxidized according to method A (Δ 2 h); chromatography of the crude product gave juglone **7a** (311 mg; 75%): mp 164–165 °C (ethanol) (lit.[39] mp 166 °C); UV λ_{max} (95% EtOH) 252, 273, and 426 nm (log ϵ 3.79, 4.00, and 3.49); IR ν_{max} (KBr) 1670, 1650, 1605, and 1580 cm^{-1}; NMR δ ($CDCl_3$) 7.20 (1 H, s, 2-H), 7.31 (1 H, X part of ABX system, J_{calcd} = 1.4 and 8.4 Hz, 6-H), 7.64 (1 H, A part of ABX, J_{calcd} = 1.4 and 7.3 Hz, 8-H), 7.67 (1 H, B part of ABX, J_{calcd} = 7.3 and 8.4 Hz, 7-H), and 11.67 (1 H, s, 5-OH); MS, m/z 208/210 $(M)^+$.

2-Chlorojuglone (7b). In a reaction analogous to the foregoing, benzoquinone **2a** and diene **1e** gave juglone **7b** (241 mg; 58%): mp 109–110 °C (ethanol) (lit.[39] mp 112 °C); UV λ_{max} (95% EtOH) 247, 274, and 430 nm (log ϵ 3.72, 3.91, and 3.45); IR ν_{max} (KBr) 1680, 1650, and 1600 cm^{-1}; NMR δ ($CDCl_3$) 7.19 (1 H, s, 3-H), 7.31 (1 H, X part of ABX system, J_{calcd} = 1.3 and 8.6 Hz, 6-H), 7.65 (1 H, A part of ABX J_{calcd} = 7.7 and 8.6 Hz, 7-Hz), 7.72 (1 H, B part of ABX, J_{calcd} = 1.3 and 7.7 Hz, 8-H), and 11.79 (1 H, s, 5-OH); MS, m/z 208/210 $(M)^+$.

3-Chloro-8-methyljuglone (7c). The cycloaddition of diene **1h** to benzoquinone **2b** required 42 h under reflux and gave an adduct which was oxidized according to method B (60 min). Chromatography (C_6H_6–AcOEt 10:1) of the crude product gave quinone **7c** (315 mg; 71%): mp 165–166 °C (ethanol); UV λ_{max} (MeOH) 243, 251, 273, 320, 336, 351, and 434 nm (log ϵ 4.01, 3.98, 3.98, 3.56, 3.59, 3.63, and 3.56); IR ν_{max} (KBr) 1630, 1600, and 1585 cm^{-1}; NMR δ ($CDCl_3$) 2.64 (3 H, s, 8-CH_3), 7.14 (1 H, s, 2-H), 7.21 (1 H, d, J = 8.8 Hz, 6-H), 7.49 (1 H, d, J = 8.8 Hz, 7-H), and 12.28 (1 H, s, 5-OH); MS, m/z 222/224 $(M)^+$ (Found: C, 59.14; H, 3.24; Cl, 15.71. $C_{11}H_7O_3Cl$ requires: C, 59.35; H, 3.17; Cl, 15.92).

2-Chloro-8-methyljuglone (7d). Application of the foregoing procedure to quinone **2a** and diene **1h** gave juglone **7d** (257 mg; 58%): mp 164–165 °C (ethanol); UV λ_{max} (MeOH) 240, 251, 259, 273, and 438 nm (log ϵ 3.84, 3.92, 3.99, 4.09, and 3.70); IR ν_{max} (KBr) 1645, 1635, and 1595 cm^{-1}; NMR δ ($CDCl_3$) 2.66 (3 H, s, 8-CH_3) 7.18 (1 H, s, 3H), 7.22 (1 H, d, J = 8.8 Hz, 6-H), 7.47 (1 H, d, J = 8.8 Hz, 7-H), and 12.43 (1 H, s, 5-OH); MS, m/z 222/224 $(M)^+$ (Found: C, 59.15; H, 3.16; Cl, 15.88).

3-Chloro-7-methyljuglone (7e). The adduct obtained from quinone **2b** and diene **1g** (room temperature, 4 h) was converted (method A, Δ 30 min) to the corresponding naphthoquinone **7e** (227 mg; 51%): mp 189.5–190.0 °C (ethanol) (lit.[3] mp 190–191 °C); UV λ_{max} (MeOH) 254, 260, 277, and 426 nm (log ϵ 4.04, 4.04, 4.14, and 3.68); IR ν_{max} (KBr) 1660, 1640, 1595, and 1570 cm^{-1}; NMR δ ($CDCl_3$) 2.45 (3 H, s, 7-CH_3), 7.10 (1 H, m, 6-H), 7.16 (1 H, s, 2-H), 7.46 (1 H, m, 8-H), and 11.64 (1 H, s, 5-OH); MS, m/z 222–224 $(M)^+$, 159 (100).

2-Chloro-7-methyljuglone (7f). A procedure, similar to the preceding one, using quinone **2a** and diene **1g**, gave naphthoquinone **7f** (340 mg; 76%): mp 123–124 °C (ethanol) (lit.[3] mp 121–122 °C); UV λ_{max} (MeOH) 254, 260, 278, and 430 nm (log ϵ 4.00, 3.99, 4.06, and 3.64); IR ν_{max} (KBr) 1680, 1635, 1585, and 1565 cm^{-1}; NMR δ ($CDCl_3$) 2.45 (3 H, s, 7-CH_3), 7.11 (1 H, m, 6-H), 7.16 (1 H, s, 3-H), 7.54 (1 H, m, 8-H), and 11.75 (1 H, s, 5-OH); MS, m/z 222/224 $(M)^+$, 187 (100).

3-Chloro-6-methyljuglone (7g). The adduct formed in the usual way from quinone **2b** and diene **1f** (Δ 42 h) was oxidized according to method B (1 h, room temperature) and elution with C_6H_6 gave juglone **7g** (290 mg; 65%): mp 156–157 °C (ethanol) (lit.[3] mp 157–158 °C); UV λ_{max} (MeOH) 242, 247 sh, 254 sh, 262, 277, and 434 nm (log ε 3.89, 4.01, 3.99, 4.02, 4.06, and 3.64); IR ν_{max} (KBr) 1660, 1640, and 1595 cm^{-1}; NMR δ ($CDCl_3$) 2.36 (3 H, s, 6-CH_3), 7.15 (1 H, s, 2-H), 7.53 (2 H, s, 7,8-H), and 12.03 (1 H, s, 5-OH); MS, *m/z* 222/224 $(M)^+$.

2-Chloro-6-methyljuglone (7h). Cycloaddition of diene **1f** to quinone **2a** followed by oxidation as for **7g** gave naphthoquinone **7h** (324 mg; 73%): mp 157–158 °C (ethanol) (lit.[3] mp 159.5–160.5 °C); UV λ_{max} (MeOH) 240, 247 sh, 252 sh, 263, 277, and 422 nm (log ε 3.69, 3.75, 3.79, 3.87, 3.89, and 3.49); IR ν_{max} (KBr) 1670, 1630, and 1590 cm^{-1}; NMR δ ($CDCl_3$) 2.36 (3 H, s, 6-CH_3), 7.15 (1 H, s, 3-H), 7.49 (1 H, br d, *J* = 7.7 Hz, 7-H), 7.63 (1 H, d, *J* = 7.7 Hz, 8-H), and 12.15 (1 H, s, 5-OH); MS, *m/z* 222/224 $(M)^+$.

3-Methoxyjuglone (7i). Diene **1e** reacts with chloromethoxybenzoquinone **2f** (Δ 40 h) in the usual way and oxidation of the resulting adduct by method A (Δ 1 h) affords the expected quinone (**7i**) (321 mg; 79%): mp 223–224 °C (CH_2Cl–CH_2Cl) (lit.[41] mp 240 °C dec); UV λ_{max} (MeOH) 241, 281, and 408 nm (log ε 3.93, 4.10, and 3.59; IR ν_{max} (KBr) 1640, 1600, and 1580 cm^{-1}; NMR δ ($CDCl_3$) 3.92 (3 H, s, 3-OCH_3), 6.16 (1 H, s, 2-H), 7.24 (1 H, dd, X part of an ABX system—no apparent AB coupling, J_{app} = 3.7 and 5.9 Hz, 6-H), 7.63 (1 H, d, J_{app} = 3.7 Hz, 8-H), 7.64 (1 H, d, J_{app} = 5.9 Hz, 7-H), and 11.74 (1 H, s, 5-OH); MS, *m/z* 204 $(M)^+$ (Found: C, 64.48; H, 3.96. $C_{11}H_8O_4$ requires: C, 64.71; H, 3.95).

2-Methyljuglone (Plumbagin) (7j). A reaction using chlorotoluquinone[37] **2g** and diene **1e** (Δ 20 h) gave an adduct which was oxidized (method A, Δ 90 min) to the corresponding naphthoquinone. Extraction with 2% NaOH and precipitation with concentrated HCl gave plumbagin (**7j**) (160 mg; 43%): mp 73–74 °C (ethanol–water) (lit.[42] mp 77 °C; UV λ_{max} (MeOH) 252, 264, and 414 nm (log ε 4.14, 4.16, and 3.68); IR ν_{max} (KBr) 1665, 1645, 1610, and 1595 cm^{-1}; NMR δ ($CDCl_3$) 2.19 (3 H, d, *J* = 1.5 Hz, 2-CH_3), 6.81 (1 H, q, *J* = 1.5 Hz, 3-H), 7.25 (1 H, X part of an ABX system, dd, J_{app} = 2.6 and 7.0 Hz, 6-H), 7.61 (1 H, d, no apparent AB coupling, J_{app} = 7.0 Hz, 7-H), 7.62 (1 H, d, J_{app} = 2.6 Hz, 8-H), and 11.97 (1 H, s, 5-OH; MS, *m/z* 188 $(M)^+$ (Found: C, 70.16; H, 4.35. $C_{11}H_8O_3$ requires: C, 70.21; H, 4.29).

3,8-Dimethyljuglone (7k). The adduct obtained from toluquinone[43] **2h** and diene **1h** (Δ 72 h) was oxidized according to method B (room temperature, 4 h). Chromatography of the crude product provided naphthoquinone **7k** (111 mg; 28%): mp 141–142 °C (methanol); UV λ_{max} (MeOH) 264, 426, and 444 nm (log ε 4.06, 3.64, and 3.60); IR ν_{max} (KBr) 1630, 1615, and 1585 cm^{-1}; NMR δ ($CDCl_3$) 2.17 (3 H, d, *J* = 1.5 Hz, 3-CH_3), 2.63 (3 H, s, 8-CH_3), 6.76 (1 H, q, *J* = 1.5 Hz, 2-H), 7.16 (1 H, d, *J* = 8.6 Hz, 6-H), 7.42 (1 H, d, *J* = 8.6 Hz, 7-H), and 12.67 (1 H, s, 5-OH); MS, *m/z* 202 $(M)^+$ (Found: C, 71.34; H, 5.04. $C_{12}H_{10}O_3$ requires: C, 71.28; H, 4.98).

D. Synthesis of 6-Hydroxynaphthoquinones (10a–i).

3-Chloro-6-hydroxynaphthoquinone (10a). Reaction of diene **8a** with benzoquinone **2a** (Δ 5.5 h) gave an adduct which, following method C (room temperature, 70 h), gave naphthoquinone **10a** (186 mg; 45%): mp 216–217 °C (CH_2ClCH_2Cl) (lit.[44] mp 217–218 °C); λ_{max} (MeOH) 267, 342, and 410 nm (log ε 4.38, 3.10, and 3.30); IR ν_{max} (KBr) 3410, 1680, 1650, 1605, and 1580 cm^{-1}; NMR δ ($CDCl_3$) 7.17 (1 H, s, 2-H), 7.20 (1 H, m, 7-H), 7.55 (1 H, d, *J* = 2.5 Hz, 5-H), 8.03 (1 H, *J* = 8.6 Hz, 8-H); MS, *m/z* 208/210 $(M)^+$.

2-Chloro-6-hydroxynaphthoquinone (10b). In an experiment similar to the foregoing, benzoquinone **2b** and diene **8a** gave naphthoquinone **10b** (296 mg; 70%): mp 238 °C dec (CH_2ClCH_2Cl) (lit.[44] mp 229–230 °C); UV λ_{max} (MeOH) 269, 338, 355, 357, and 405 nm (log ε 4.39, 3.23, 3.15, 3.13, and 3.32); IR ν_{max} (KBr) 3410, 1665, 1655, 1590, and 1570 cm^{-1}; NMR δ ($CDCl_3$) 7.17 (1 H, dd, *J* = 2.9 and 8.4 Hz, 7-H), 7.18 (1 H, s, 3-H), 7.45 (1 H, d, *J* = 2.9 Hz, 5-H), 8.11 (1 H, d, *J* = 8.4 Hz, 8-H); MS, *m/z* (208/210 $(M)^+$.

3-Chloro-6-hydroxy-5-methylnaphthoquinone (10c). The adduct obtained from benzoquinone **2b** and diene **8b** (room temperature, 20 h) upon oxidation by method C (room temperature, 24 h) gave quinone **10c** (255 mg; 57%): mp 186–187 °C (benzene); UV λ_{max} (MeOH) 266, 359, and 412 nm (log ε 4.39, 3.22, and 3.52); IR ν_{max} (KBr) 3610, 3520, 3350, 1670, 1650, 1605, and 1575 cm^{-1}; NMR δ ($CDCl_3$) 2.66 (3 H, s, 5-CH_3), 7.12 (1 H, d, *J* = 8.6 Hz, 7-H), 7.14 (1 H, s, 2-H), 7.95 (1 H, d, *J* = 8.6 Hz, 8-H); MS, *m/z* 222/224 $(M)^+$ (Found: C, 59.19; H, 3.23; Cl, 15.82. $C_{11}H_7O_3Cl$ requires: C, 59.35; H, 3.17; Cl, 15.92).

2-Chloro-6-hydroxy-5-methylnaphthoquinone (10d). As in the preceding case, benzoquinone **2a** and diene **8b**, after oxidation, gave naphthoquinone **10d** (137 mg; 31%): mp 203–204 °C (darkens at 170 °C) (benzene); UV λ_{max} (MeOH) 266, 359, and 410 nm (log ε 4.55, 3.60, and 3.71); IR ν_{max} (KBr) 3300 br, 1660, 1640, 1600, and 1570 cm^{-1}; NMR δ ($CDCl_3$) 2.64 (3 H, s, 5-CH_3), 7.10 (1 H, d, *J* = 8.6 Hz, 7-H), 7.12 (1 H, s, 3-H), 8.04 (1 H, d, *J* = 8.6 Hz, 8-H); MS, *m/z* 222/224 $(M)^+$ (Found: C, 59.75; H, 3.19; Cl, 15.73).

7-Acetoxy-2-chloro-5-methylnaphthoquinone (Acetate of 10g). The cycloaddition of diene **8d** to benzoquinone **2a** was carried out in the usual way (Δ 36 h). After oxidation by method A (Δ 90 min), the product was treated with acetic anhydride (2–3 mL) and concentrated H_2SO_4 (1 drop) at room temperature for 1 h and provided the acetate of **10g** (230 mg; 43%): mp 142–143 °C (benzene–petroleum ether, bp 65–110 °C); UV λ_{max} (MeOH) 255, 272, and 348 nm (log ε 4.24, 4.18, and 3.52); IR ν_{max} (KBr) 1770, 1680, 1650, 1605, and 1590 cm^{-1}; NMR δ ($CDCl_3$) 2.36 (3 H, s, 7-$OCOCH_3$), 2.75 (3 H, s, 5-CH_3), 7.16 (1 H, s, 3-H), 7.32 (1 H, d, *J* = 2.6 Hz, 6-H), and 7.83 (1 H, d, *J* = 2.6 Hz, 8-H); MS, *m/z* 264/266 $(M)^+$ (Found: C, 59.01; H, 3.50; Cl, 13.68. $C_{13}H_9O_4Cl$ requires: C, 59.00; H, 3.43; Cl, 13.39).

7-Acetoxy-3-chloro-5-methylnaphthoquinone (Acetate of 10h). A reaction analogous to the foregoing one using benzoquinone **2b** and diene **8d** gave the acetate of **10h** (240 mg; 45%): mp 121–122 °C (benzene–petroleum ether, bp 65–110 °C); UV λ_{max} (MeOH) 252, 272, and 342 nm (log ε 4.22, 4.12, and 3.49); IR ν_{max} (KBr) 1775, 1680, 1670, 1650, 1615, and 1600 cm^{-1}; NMR δ ($CDCl_3$) 2.35 (3 H, s, 7-$OCOCH_3$), 2.78 (3 H, s, 5-CH_3), 7.21 (1 H, s, 2-H), 7.31 (1 H, d, *J* = 2.4 Hz, 6-H), and 7.75 (1 H, d, *J* = 2.4 Hz, 8-H); MS, *m/z* 264/266 $(M)^+$ (Found: C, 59.05; H, 3.62).

6-Hydroxy-3-methoxynaphthoquinone (10i). To the adduct obtained from benzoquinone **2e** and diene **8a** (Δ 70 h) was added dry triethylamine (223 mg, 2.20 mmol) in benzene (5 mL). The mixture was stirred at room temperature for 2 h and extracted twice with 5% HCl and several times with water. Chromatography (AcOEt–C_6H_6 2:1) of the crude product gave naphthoquinone **10i** (148 mg; 36%): mp 243.5–244.5 °C (methanol) (lit.[45] mp 245–246 °C); UV λ_{max} (MeOH) 219, 264, 288, 334, and 405 nm (log ε 4.11, 4.36, 4.13, 3.45, and 3.31); IR ν_{max} (KBr) 3390, 3340 br, 1680, 1640, 1610, 1590, and 1575 cm^{-1}; NMR δ (DMSO-d_6) 3.82 (3 H, s, 3-OCH_3), 6.21 (1 H, s, 2-H), 7.14 (1 H, dd, *J* = 2.6 and 8.4 Hz, 7-H), 7.29 (1 H, d, *J* = 2.6 Hz, 5-H), 7.82 (1 H, d, *J* = 8.4 Hz, 8-H), and 10.82 (1 H, s, 6-OH); MS, *m/z* 204 $(M)^+$.

E. Synthesis of Naturally Occurring Anthraquinones 6b and 11a–e.

1-Hydroxy-7-methylanthraquinone (Barleriaquinone) (6b). To a solution of 3-chloro-6-methylnaphthoquinone (**4d**) (206 mg, 1.00 mmol) in dry THF (10 mL) was added diene **1e** (156 mg, 1.10 mmol) in the same solvent (1 mL). The mixture was heated to reflux (24 h) and the adduct treated according to method A to yield barleriaquinone (**6b**) (144 mg; 61%).

1,8-Dihydroxy-2-methylanthraquinone (Isochrysophanol) (11a). The adduct obtained from 3-chlorojuglone (**7a**) (209 mg, 1.00 mmol) in dry THF (5 mL) and diene **1f** (172 mg, 1.10 mmol) in the same solvent (2 mL) (room temperature, 24 h) was oxidized according to method B (room temperature, 4 h). Purification by chromatography (C_6H_6) gave isochrysophanol (204 mg; 81%): mp 174.0–174.5 °C (ethanol) (lit.[46] mp 174–175 °C); UV λ_{max} (MeOH) 226, 255, 276, 286, and 430 nm (log ε 4.59, 4.36, 3.97, 3.99, and 4.06); IR ν_{max} (KBr) 1675, 1635, 1595, and 1565 cm^{-1}; NMR δ ($CDCl_3$) 2.37 (3 H, s, 2-CH_3), 7.28 (1 H, dd, *J* = 1.3 and 8.4 Hz, 7-H), 7.54 (1 H, br d, *J* = 7.7 Hz, 3-H), 7.67 (1 H, dd, *J* = 7.6 and

(41) Aizenberg, L. N.; Vlad, L. A.; Aizenberg, R. S. *Tr. Kishinev. Sel.-Khoz. Inst.* **1966**, *43*, 179; *Chem. Abstr.* **1967**, *67*, 53906*q*.
(42) Bruce, D. B.; Thomson, R. H. *J. Chem. Soc.* **1952**, 2759.
(43) Kehrmann, F. *Chem. Ber.* **1915**, *48*, 2021.
(44) Brisson, C.; Brassard, P. *J. Org. Chem.* **1981**, *46*, 1810.
(45) Guay, V.; Brassard, P. *J. Nat. Prod.* **1986**, *49*, 122.
(46) Imre, S.; Oztunc, A. *Z. Naturforsch. C: Biosci.* **1976**, *31C*, 403.

8.4 Hz, 6-H), 7.74 (1 H, d, J = 7.7 Hz, 4-H), 7.82 (1 H, dd, J = 1.3 and 7.6 Hz, 5-H), 12.09 (1 H, s, 8-OH), and 12.39 (1 H, s, 1-OH); MS, m/z 254 $(M)^+$.

1-Hydroxy-8-methoxy-2-methylanthraquinone (Isochrysophanol 8-(Methyl ether)) (11b). A mixture of 3-chloro-5-methoxynaphthoquinone[47] (223 mg, 1.00 mmol) and diene **1f** (172 mg, 1.10 mmol) in dry benzene (11 mL) was stirred at room temperature for 1 h and heated to reflux for 24 h. Oxidation of the adduct by method B (room temperature, 4 h) and purification by chromatography (C_6H_6–AcOEt 5:1) gave anthraquinone **11b** (243 mg; 91%): mp 196–198 °C (ethanol) (lit.[32] mp 192–193 °C); UV λ_{max} (MeOH) 224, 255, 280 sh, 416, and 438 nm (log ϵ 4.62, 4.41, 4.03, 4.04, and 3.93); IR ν_{max} (KBr) 1670, 1635, 1590, and 1570 cm^{-1}; NMR δ ($CDCl_3$) 2.37 (3 H, s, 2-CH_3), 4.08 (3 H, s, 8-OCH_3), 7.35 (1 H, dd, J = 1.1 and 8.4 Hz, 7-H), 7.48 (1 H, d, J = 7.7 Hz, 3-H), 7.69 (1 H, d, J = 7.7 Hz, 4-H), 7.73 (1 H, dd, J = 7.7 and 8.4 Hz, 6-H), 7.96 (1 H, dd, J = 1.1 and 7.7 Hz, 5-H) and 13.29 (1 H, s, 1-OH); MS, m/z 268 $(M)^+$ (Found: C, 71.49; H, 4.53. $C_{16}H_{12}O_4$ requires: C, 71.64, H, 4.51.

1,5-Dihydroxy-2-methylanthraquinone (Isozyganein) (11c). The usual procedure applied to 2-chlorojuglone (**7b**) (209 mg, 1.00 mmol) and diene **1f** (172 mg, 1.10 mmol) in dry benzene (7 mL) (room temperature, 24 h) gave the adduct which was oxidized (method B, room temperature for 4 h). Purification by chromatography (C_6H_6) gave isozyganein (**11c**) (187 mg; 74%): mp 186–187 °C (ethanol) (lit.[18] mp 189–190 °C); UV λ_{max} (MeOH) 226, 254, 278, 288, 422, and 436 nm (log ϵ 4.70, 4.49, 4.09, 4.10, 4.14, and 4.14); IR ν_{max} (KBr) 1625 br, 1605, and 1580 cm^{-1}; NMR δ ($CDCl_3$) 2.38 (3 H, s, 2-CH_3), 7.29 (1 H, dd, J = 1.1 and 8.4 Hz, 6-H), 7.53 (1 H, br d, J = 7.7 Hz, 3-H), 7.66 (1 H, dd, J = 7.7 and 8.4 Hz, 7-H), 7.73 (1 H, d, J = 7.7 Hz, 4-H), 7.82 (1 H, dd, J = 1.1 and 7.7 Hz, 8-H), 12.70 (1 H, s, 5-OH), and 12.97 (1 H, s, 1-OH); MS, m/z 254 $(M)^+$.

1-Hydroxy-5-methoxy-2-methylanthraquinone (Isozyganein 5-(Methyl ether)) (11d). A similar reaction involving 2-chloro-5-methoxynaphthoquinone[48] (223 mg, 1.00 mmol) and diene **1f** (1.10 mmol) in benzene (11 mL) (room temperature, 40 h), after oxidation (method B, room temperature for 3.5 h) and chromatography (C_6H_6–AcOEt 5:1), gave anthraquinone **11d** (235 mg; 88%): mp 183–184 °C (ethanol) (lit.[34] mp 189–191 °C); UV λ_{max} (MeOH) 224, 253, 280, and 412 nm (log ϵ 4.57, 4.39, 4.00, and 3.99); IR ν_{max} (KBr) 1670, 1640, and 1590 cm^{-1}; NMR δ ($CDCl_3$) 2.35 (3 H, s, 2-CH_3), 4.04 (3 H, s, 5-OCH_3), 7.34 (1 H, d, J = 8.4 Hz, 6-H), 7.50 (1 H, br d, J = 7.7 Hz, 3-H), 7.66–7.75 (2 H, m, 4,7-H), 7.96 (1 H, dd, J = 1.1 and 7.7 Hz, 8-H), and 12.98 (1 H, s, 1-OH); MS, m/z 268 $(M)^+$ (Found: C, 71.54; H, 4.49. $C_{16}H_{12}O_4$ requires: C, 71.64; H, 4.51).

1,6-Dihydroxy-2-methylanthraquinone (Soranjidiol) (11e). To a solution of juglone **7g** (222 mg, 1.00 mmol) in dry benzene (10 mL) was added 2-(trimethylsiloxy)butadiene (**8a**) (156 mg, 1.10 mmol) in the same solvent (2 mL). After the mixture was refluxed for 24 h, the adduct was oxidized according to method C (3 days). Purification of the crude product by chromatography gave soranjidiol (75 mg, 30%): mp 286–287 °C (EtOH–CCl_4) (lit.[49] mp 283 °C); NMR δ (DMSO-d_6) 2.28 (3 H, s, 2-CH_3), 7.23 (1 H, dd, J = 2.6 and 8.8 Hz, 7-H), 7.46 (1 H, d, J = 2.6 Hz, 5-H), 7.58 (1 H, d, J = 7.7 Hz, 3-H), 7.64 (1 H, d, J = 7.7 Hz, 4-H), 8.10 (1 H, d, J = 8.8 Hz, 8-H), 11.18 (1 H, s, 6-OH), and 13.11 (1 H, s, 1-OH).

Acknowledgment. We gratefully acknowledge financial support from the Natural Sciences and Engineering Research Council of Canada and the Fonds F.C.A.R. (Gouvernement du Québec) as well as bursaries (to L.B.) from the Fonds Georges-Elie Amyot. We also wish to thank Prof. S. Neelakantan for a sample of barleriaquinone.

Registry No. **1a**, 1515-76-0; **1b**, 72808-94-7; **1c**, 17616-47-6; **1d**, 17616-45-4; **1e**, 6651-43-0; **1f**, 98670-68-9; **1g**, 65420-54-4; **1h**, 72237-32-2; **2a**, 615-93-0; **2b**, 697-91-6; **2c**, 1633-14-3; **2d**, 19643-45-9; **2e**, 24605-23-0; **2f**, 54490-80-1; **2g**, 19832-87-2; **2h**, 1123-64-4; **4a**, 1010-60-2; **4b**, 87170-63-6; **4c**, 87170-62-5; **4d**, 87170-60-3; **4e**, 87170-61-4; **4f**, 87170-64-7; **4g**, 87170-65-8; **4h**, 78758-29-9; **4i**, 57855-16-0; **4j**, 482-70-2; **5b**, 115077-55-9; **5c**, 65120-69-6; **6a**, 68963-22-4; **6b**, 68963-23-5; **6c**, 34641-56-0; **6d**, 22225-63-4; **6e**, 6219-65-4; **6f**, 70063-64-8; **6g**, 115077-54-8; **7a**, 18855-92-0; **7b**, 4923-57-3; **7c**, 115077-56-0; **7d**, 115077-57-1; **7e**, 62993-89-9; **7f**, 62993-88-8; **7g**, 95393-69-4; **7h**, 78308-30-2; **7i**, 15254-76-9; **7j**, 481-42-5; **7k**, 115077-58-2; **8a**, 38053-91-7; **8b**, 54781-39-4; **8c**, 54781-31-6; **8d**, 17616-46-5; **10a**, 69119-29-5; **10b**, 76665-65-1; **10c**, 115077-59-3; **10d**, 115077-60-6; **10g**, 115077-61-7; **10h**, 115077-62-8; **10i**, 104904-71-4; **11a**, 34425-60-0; **11b**, 51996-00-0; **11c**, 64809-73-0; **11d**, 64809-72-9; **11e**, 518-73-0; tectoquinone, 84-54-8; 2-chloro-5-methoxynaphthoquinone, 95684-12-1.

(47) Giles, R. G. F.; Roos, G. H. P. *J. Chem. Soc., Perkin Trans 1* **1976**, 2057; prepared from **7b** (CH_3I–Ag_2O).
(48) Guay, V.; Brassard, P. *Tetrahedron* **1984**, *40*, 5039.
(49) de Silva, S. O.; Watanabe, M.; Snieckus, V. *J. Org. Chem.* **1979**, *44*, 4802.

Hydroboration of Terpenes. 9. A Simple, Improved Procedure for Upgrading the Optical Purity of Commercially Available α- and β-Pinenes. Conversion of (+)-α-Pinene to (+)-β-Pinene via Hydroboration–Isomerization

Herbert C. Brown* and Navalkishore N. Joshi[1]

H. C. Brown and R. B. Wetherill Laboratories of Chemistry, Purdue University, West Lafayette, Indiana 47907

Received February 24, 1988

An improved method for the preparation of optically pure diisopinocampheylborane (Ipc_2BH) from commercially available (+)- and (−)-α-pinene (91–92% ee) is described. The procedure, which is based on selective incorporation of the major enantiomer of α-pinene in crystalline dialkylborane, is both simple and efficient. Treatment with benzaldehyde liberates the parent olefin in very high enantiomeric excess (>99.5%). The intermediate Ipc_2BH can be thermally isomerized (130 °C, 12 h) to dimyrtanylborane, which is readily converted into the otherwise inaccessible (+)-β-pinene (>99.5% ee). In the course of this study it was established that the optical purification of commercial (−)-β-pinene too can be easily achieved by the formation and recrystallization of tri-*cis*-myrtanylborane. Thus, simple manipulations via hydroboration provide easy access to all four enantiomers of α- and β-pinenes in very high optical purity.

α-Pinene, in both (+)- and (−)-isomeric forms, is one of the most easily accessible optically active terpenes. With the advances in boron chemistry, α-pinene has become an extremely versatile intermediate for asymmetric synthesis.

0022-3263/88/1953-4059$01.50/0 © 1988 American Chemical Society