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Synthesis of Tri-, Tetra-, and Pentacarbonyl Derivatives via Ozonolysis of 1,4-Dienes and Cyclization to Polyaromatic Systems

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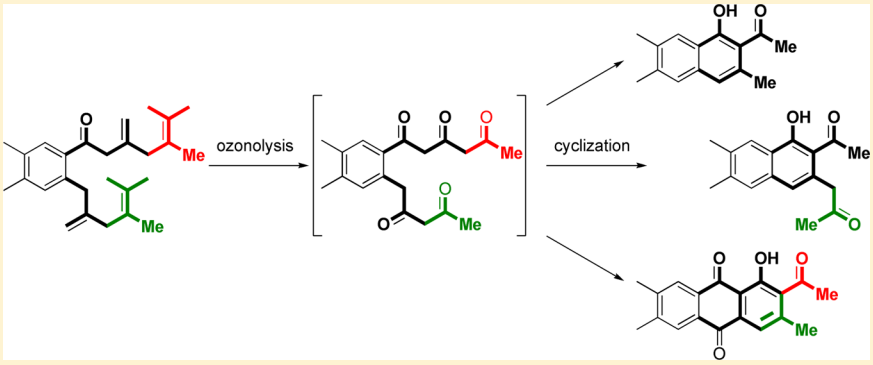
Supporting Information



ABSTRACT: The aim of this work was the synthesis of polyaromatic systems by cyclization of β-polycarbonyls. Useful synthons for β-polycarbonyl derivatives are branched 1,4-dienes generated by cobalt-catalyzed hydrovinylation of terminal alkenes and 2,3-dimethyl-1,3-butadiene. Thus, a series of tri-, tetra-, and pentacarbonyl synthons was successfully synthesized. Subsequently, these synthons were examined in an ozonolysis/cyclization reaction sequence. Polyaromatic derivatives were obtained in good yields and the method was applied in the synthesis of the natural product Kwanzoquinone A.

INTRODUCTION

Nature uses β-polycarbonyls to generate polyketides such as phenols, naphthols, and anthrols. Polyketides are one of the largest classes of natural compounds with great structural diversity. The division of this class is based on their common biosynthesis pathway. The formation of polyketides contains a repeating Claisen-type condensation of acetyl-CoA to form, for example, β-polycarbonyl compounds, followed by its intramolecular condensation (Scheme 1).[1,2] A wide range of complex functionalized compounds is generated because after each step of chain elongation the β-oxofunction can also be modified by further enzymes, such as a ketoreductase. Therefore, β-polycarbonyls are not formed in the polyketide biosynthesis pathway exclusively.

The biomimetic synthesis of polycarbonyl compounds is of great interest for organic chemists with respect to the construction of complex molecules with bioactive properties. A pioneer in the field of the synthesis and investigation of polycarbonyls was Thomas Harris, who used condensation of polyanions of polyketones with acylating agents.[3] Later, Yamaguchi explored a very similar strategy based on the condensation of the methyl acetoacetate dianion with glutarates (**1**) and successive intramolecular condensation to form polycyclic moieties **3**.[4,5] Recently, Barrett reported an approach using diketo-dioxinones as masked β-tetracarbonyl synthons. The transient ketene **5** derived from dioxinone **4** is further trapped by an alcohol which results in the formation of a β-triketoester. Late-stage biomimetic aromatization gives resorcylate derivatives **6** (Scheme 2).[6,7] This powerful methodology based on the cyclization of triketoester derivatives, and a similar method based on the cyclization of dioxinone derivatives to produce resorcylates, were applied in a multitude of natural product syntheses.[8,9]

An alternative approach to β-polycarbonyl compound formation was reported by Birch in the early 20th century.[10] He employed aromatic rings as synthetic equivalents for β-polycarbonyl compounds. Initiated by reduction with sodium in liquid ammonia, aromatic derivatives were converted to cyclic 1,4-dienes (Birch reduction), which were then applied in an ozonolysis reaction to generate 1,3-dicarbonyls. Evans applied this reaction sequence for the synthesis of nonaromatic polyketide arrays.[11] Inspired by Birch, we proved in previous work that branched 1,4-dienes are useful moieties for the synthesis of 1,3-dicarbonyl derivatives by ozonolysis.[12] These branched 1,4-dienes were generated under mild conditions via 1,4-hydrovinylation of terminal alkenes with a cobalt catalyst system.[13] Accordingly, the harsh conditions of the Birch reduction were circumvented. For the isolation and characterization of the β-polyketones, the 1,3-dicarbonyl function was complexed with a BF_2-fragment, eliminating the keto−enol tautomerization. In addition to the transformations described thus far,[14,15] we were interested in the followup chemistry of

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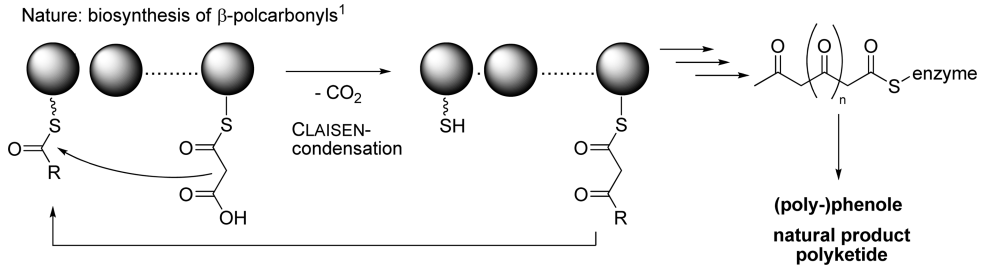
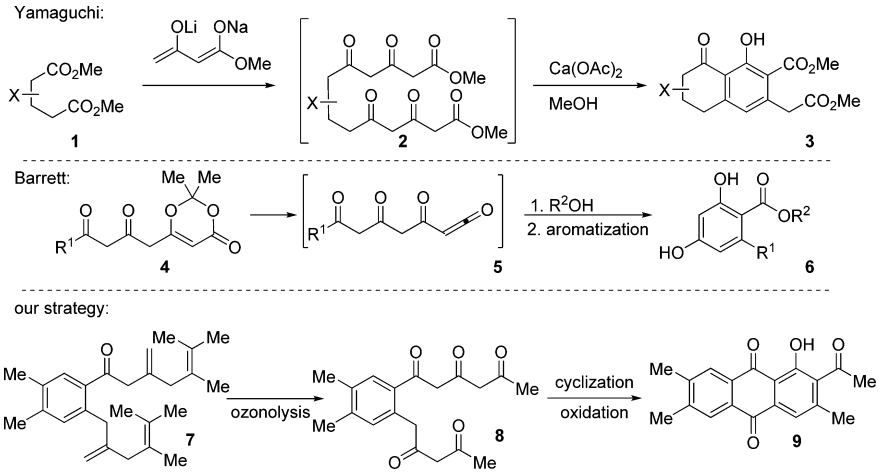
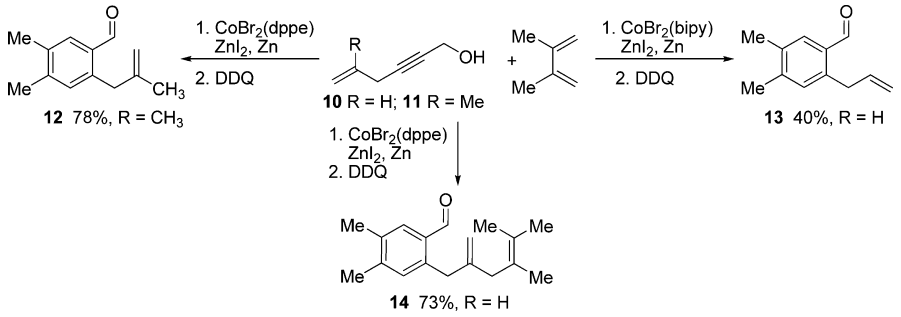
Scheme 1



Scheme 2



Scheme 3



these polycarbonyl derivatives. Hence, the scope of this investigation is the ozonolysis of 1,4-polyenes to polycarbonyls and subsequent biomimetic cyclization to aromatic and polycyclic systems. Our strategy is based on the application of aromatic-substituted polyenes, such as **7**, as polycarbonyl precursors. There are several possible condensation reaction pathways. Due to steric repulsion, alternative "bent" cyclization modes of the corresponding aromatic-substituted polycarbonyl compound **8** should be inhibited by the aromatic backbone, favoring the linear cyclization mode shown instead.[4] Finally, the reaction sequence should be applied in the natural product synthesis of Kwanzoquinone A. A different method based on an intramolecular cobalt-catalyzed [2 + 2 + 2] cycloaddition for the synthesis of anthraquinone derivatives, including natural products, was reported by Groth.[16]

RESULTS AND DISCUSSION

We began our studies by exploring the synthesis of aromatic β-polycarbonyl synthons via cobalt-catalyzed Diels–Alder and 1,4-hydrovinylation reactions. For this purpose, two different hydroxyl-functionalized enynes **10** and **11** were converted to unsaturated benzaldehydes in a Diels–Alder reaction (for **12**, **13**) or combined Diels–Alder/1,4-hydrovinylation reaction (for **14**), and subsequent DDQ (2,3-dichloro-5,6-dicyano-1,4-benzoquinone) oxidation (Scheme 3).[14]

Aldehydes **12** and **14** were synthesized using cobalt 1,2-bis(diphenylphosphino)ethane dibromide as catalyst precursor and were obtained in good yields after DDQ oxidation (73–78%). Aldehyde **13** was isolated in moderate yield (40%) by applying cobalt 2,2′-bipyridine dibromide as precatalyst in the Diels–Alder reaction. Since it was necessary to suppress the 1,4-hydrovinylation to obtain aldehyde **13** instead of **14** this catalyst precursor, which catalyzes the Diels–Alder reaction selectively, was applied.[17]

Aldehyde **14**, bearing a branched 1,4-diene unit, already constitutes a tricarbonyl synthon and was additionally used for the generation of tetra- and pentacarbonyl synthons **18**, **21**, and **7**. The synthons were generated in a two-step procedure in

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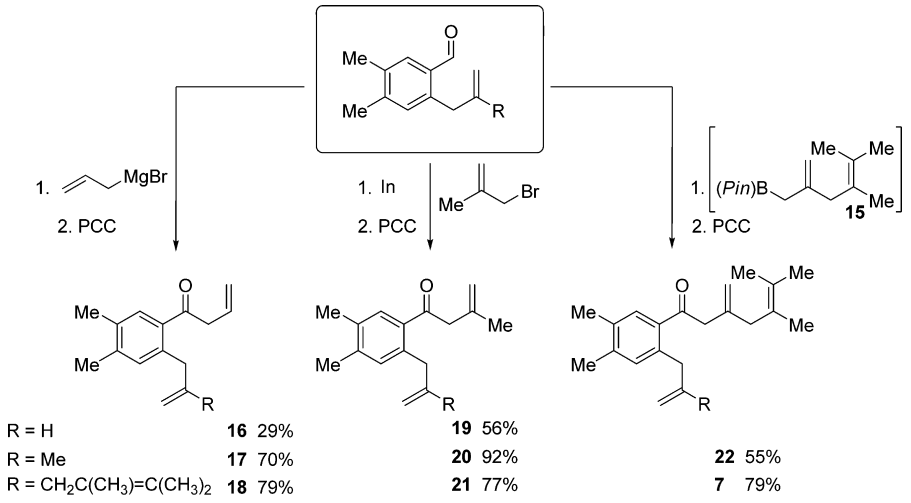
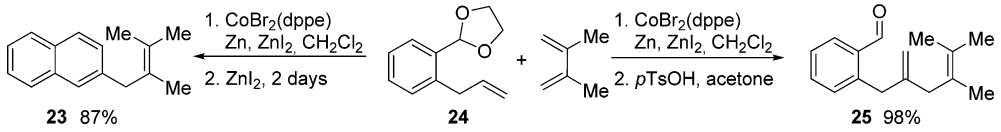
Scheme 4



Scheme 5



Scheme 6

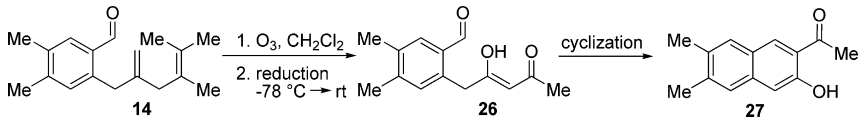


Table 1. Optimization of the Ozonolysis of Diene 14 and Subsequent Cyclization

entry	reducing agent[a]	cyclization	yield
1	$P(OMe)_3$[b]	-	38%
2	$P(OMe)_3$[c]	SiO_2, 1−7 d	32−47%
3	$P(OMe)_3$[c]	SiO_2,))), 1 d	44%
4	$P(OMe)_3$[d]	$NaOH_{aq}$ (5 wt %), 1 h	58%
5	PPh_3 (2.5 equiv)[d]	$NaOH_{aq}$ (5 wt %), 1 h	75%
6	PPh_3[d]	HOAc, 1 h	70%
7	Zn/HOAc, 1 h	-	40%

[a]Conditions of the ozonolysis: (1) Diene (1.0 equiv), O_3, CH_2Cl_2, −78 °C. (2) Addition of the reducing agent (3.0 equiv) −78 °C → rt, 1 h. [b]The product was purified by flash column chromatography. [c]The polycarbonyl derivative was purified by aqueous extraction. [d]The solvent was removed under reduced pressure and the crude polycarbonyl derivative was further treated as described for the cyclization.

good yields starting with the synthesis of the corresponding alcohol and further oxidation (Scheme 4). For syntheses of the tetracarbonyl synthons **18** and **21**, a Grignard reaction or an indium-mediated Barbier-type reaction, respectively, was performed as the first step. The pentacarbonyl precursor was obtained by an allylboration of aldehyde **14**, with a boron-functionalized 1,4-diene **15** that is easily accessible by cobalt-catalyzed 1,4-hydrovinylation.[15] Finally, the alcohols were oxidized to the corresponding ketones **18**, **21**, and **7** utilizing pyridinium chlorochromate (PCC). The same methodology was applied to convert the other two benzaldehydes **12** and **13** to tri- and tetracarbonyl synthons **16**, **17**, **19**, **20**, and **22**.

The described approach for the synthesis of an aldehyde bearing a branched 1,4-diene group was successful, but the diversification via combined Diels−Alder/1,4-hydrovinylation/oxidation reaction is limited to accessible and applicable 1,3-dienes. A second approach was accomplished for the synthesis of this kind of aldehydes by cobalt-catalyzed 1,4-hydrovinylation of allylphenyldioxolane **24** with 2,3-dimethyl-1,3-butadiene (DMB) and successive acidic workup (Scheme 5). Thereby, the corresponding aldehyde **25** is obtained in excellent yield. Prolonged reaction times resulted in the formation of naphthalene **23** as a side product. Naphthalene derivate **23** was obtained as the main product when additional amounts of ZnI_2 were added and the mixture was stirred for 2 days. The advantage of this pathway to aldehydes with a 1,4-diene subunit is the easier functionalization of the dioxolanes, which leads to better access to more complex products.

Subsequently, we focused on the transformation of the successfully prepared polycarbonyl synthons to polyaromatic systems by ozonolysis and subsequent cyclization. The cyclization behavior of several tricarbonyls with different

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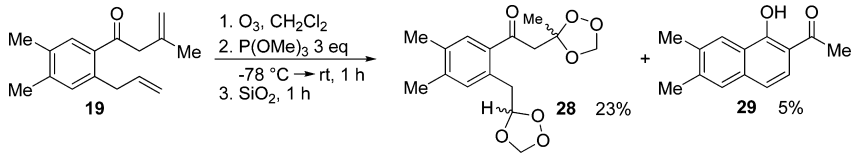
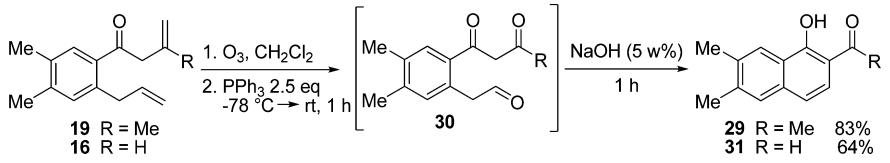
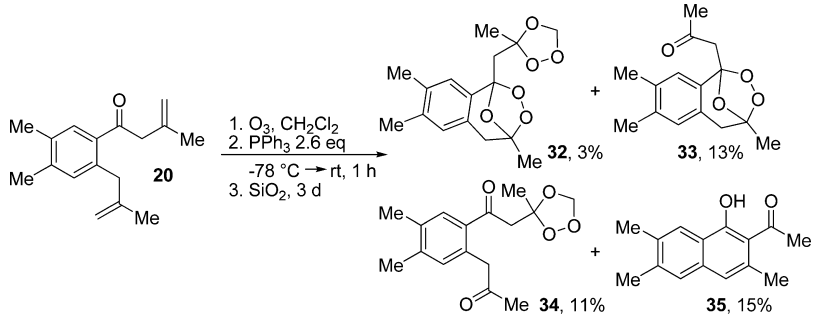
Scheme 7



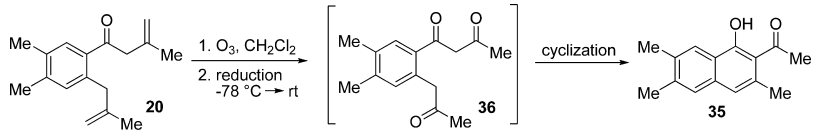
Scheme 8



Scheme 9



Scheme 10



terminal carbonyl groups (aldehyde, ketone) generated by ozonolysis was examined. We started with the less complex tricarbonyl synthon **14** with a non-enolizable aldehyde function (Scheme 6). Thereafter, increasingly more complex molecules should be examined. Trimethyl phosphite was applied as reducing agent after ozonolysis, since trimethyl phosphate is easy to remove by aqueous extraction and good results had been obtained by our group in earlier work regarding the synthesis of pentacarbonyl derivatives.[14]

Ozonolysis of diene **14**, reduction with trimethyl phosphite, and aqueous workup resulted in almost quantitative formation of tricarbonyl **26** (keto:enol form = 31:69), as well as naphthol **27**, as observed by NMR spectroscopy of the crude product. Purification of the tricarbonyl derivative by flash column chromatography over silica gel resulted in the isolation of the desired cyclic product **27** in 38% yield, whereas no tricarbonyl **26** was obtained (entry 1, Table 1). This was not surprising, since in several reactions described in the literature silica gel was sufficient for performing cyclization reactions.[6,9] The results of further optimization experiments of the reaction sequence illustrated in Scheme 6 are summarized in Table 1.

The addition of silica gel to the crude tricarbonyl **26** after aqueous workup only slightly improved the yield. Neither prolonged reaction times nor performing the reaction in an ultrasonic bath increased the yield above 47% (entry 2, 3). Furthermore, performing the cyclization under basic conditions with aqueous NaOH (5 wt %) increased the yield to 58% (entry 4). Changing of the reducing agent to triphenylphosphine resulted in the best yield of 75% (entry 5). Acidic conditions, as well as using Zn/HOAc as reducing agent, did not further improve the yield of the desired product **27** (entry 6, 7).

After the successful optimized synthesis of naphthol **27** in good yield, the investigations were expanded to tricarbonyls with an enolizable aldehyde function. Initially, mild conditions were applied. Trimethyl phosphite was used as reducing agent and silica gel was added for the cyclization. Surprisingly, trimethyl phosphite was not strong enough to reduce the ozonide functions entirely. The main product was identified to be the ozonide **28**, which was isolated in 23% yield, whereas naphthol **29** was formed in only 5% yield (Scheme 7).

Thereafter, the ozonides were treated with triphenylphosphine (2.5 equiv) followed by addition of aqueous NaOH (5 wt %) and the desired product **29** was obtained in good yield (83%) in two steps. Under the same reaction conditions, synthon **16** was converted to the naphthol derivative **31** with an easily functionizable aldehyde group in 64% yield (Scheme 8). Upon applying SiO_2 for cyclization, instead of NaOH, product **29** was obtained in 59% yield after stirring for 1 d.

Subsequently, for triketone synthon **20** the ozonolysis/cyclization reaction sequence was explored. Triphenylphosphine was added and, at first, silica gel was chosen to perform

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Table 2. Optimization of the Ozonolysis of Diene 20 and Subsequent Cyclization

entry	reducing agent[a]	cyclization	yield
1	PPh_3 (3.0 equiv)[b] +Zn/HOAc, 1 h	-	56%
2	Zn/HOAc, 1 h	-	23%
3	PPh_3 (8.0 equiv), 18 h[b]	$NaOH_{aq}$ (5 wt %), 2 h	37%
4	PPh_3 (5.0 equiv), 18 h[b]	HOAc, 16 h	67%

[a]Conditions of the ozonolysis: (1) Diene (1.0 equiv), O_3, CH_2Cl_2, −78 °C. (2) Addition of the reducing agent −78 °C → rt, 1 h. [b]The solvent was removed under reduced pressure and the crude polycarbonyl derivative **36** was treated as described for the cyclization.

the cyclization. After purification by flash column chromatography a series of partially reduced secondary ozonides **32**, **33**, and **34** was isolated, as well as the desired naphthol **35** in 15% yield (Scheme 9). Ozonides of type **33** are formed by intramolecular reaction of the intermediate carbonyloxid with the already existing benzylic carbonyl group. Similar ozonides are generated after the ozonolysis of indene derivatives and have been described in the literature as relatively stable compounds,[18] explaining the isolation of ozonides **32**, **33**, and **34** by flash column chromatography.

Further attempts were undertaken to increase the yield for naphthol **35** in this reaction sequence (Scheme 10) by reducing the unwanted ozonides entirely. The results are summarized in Table 2.

To ensure complete reduction of all ozonides, zinc and glacial acetic acid were added as additional reductants (entry 1). The yield increased to 56% and no ozonides were detected by thin layer chromatography (TLC). Using Zn/HOAc alone did not improve the yield of **35** (entry 2). When a large excess of triphenylphosphine (8.0 equiv) was applied after ozonolysis, no more ozonides were detected by TLC after stirring overnight. The subsequent usage of NaOH (5 wt %) for the cyclization brought no improvement (entry 3). The best result was obtained when applying 5.0 equiv of triphenylphosphine as reducing agent and applying glacial acetic acid for the cyclization. The naphthol derivative **35** was obtained in 67% yield (entry 4).

Finally, tricarbonyl synthon **17** was converted to naphthaldehyde **37**. The best result was achieved by addition of triphenylphosphine after ozonolysis and further stirring for 4 h (Scheme 11). Apparently, no additional reagent was necessary, due to the increased reactivity of the intermediate tricarbonyl compound containing an aldehyde function, compared to triketone **36**. Using triphenylphosphine (2.5 equiv, 2 h) as a reductant, and subsequent addition of silica gel (1 d) or addition of Zn/HOAc (1 h), resulted in diminished yields for product **37**.

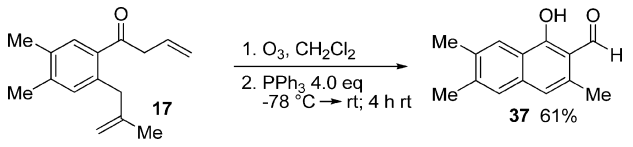
Overall, the cyclization of tricarbonyl derivatives, as well as their formation by ozonolysis, was accomplished in good yields. The formation of stable ozonides was found to be one reason for the initial low yields of naphthols after ozonolysis of tricarbonyl precursors and subsequent cyclization. The results were improved by applying an excess of triphenylphosphine and longer reaction times.

The synthesis and cyclization of tetracarbonyl compounds was envisaged further. The ozonolysis of triene **22** and subsequent acetic cyclization led to the formation of the semiacetal **39**, as well as the dehydrated benzopyrone **40** (Scheme 12). Complete dehydration to obtain benzopyrone **40** as the main product might be possible by applying other acids, but was not further examined.

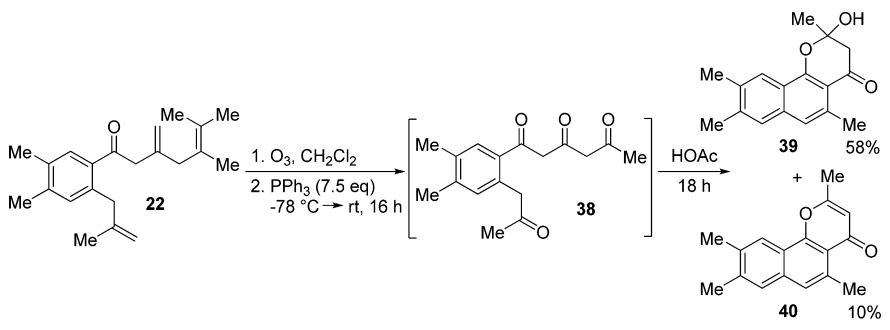
Using the same reaction conditions for tetraketone precursor **21**, the desired product **41** was obtained in a good yield of 74%. Under the same conditions, the product **42** was obtained in moderate 52% yield starting from the tetracarbonyl synthon **18**. Nevertheless, the naphthaldehyde **42** was obtained in good 79% yield by reducing the reaction time of the reduction and further adding Zn/HOAc (Scheme 13). These results can be explained by the fact that higher substituted ozonides derived from synthon **21** are more stable, and the increased reactivity of the tetracarbonyl derivative derived from **18** containing an aldehyde function. Therefore, a short reaction time was sufficient to reduce the ozonides of tetraene **18**, perform the cyclization, and circumvent the formation of side products. When applying these conditions to triene **21**, the product **41** was obtained in only 26% yield.

The knowledge gained concerning the treatment of ozonides, and the cyclization behavior of tri- and tetracarbonyl derivatives, was applied to the transformation of the complex pentacarbonyl synthon **7**. Since our goal was the application of

Scheme 11



Scheme 12



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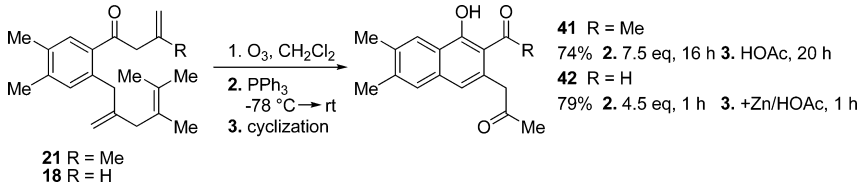
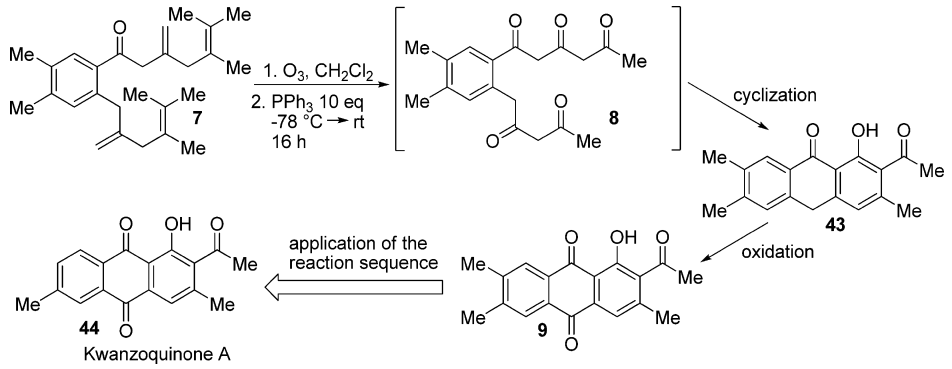
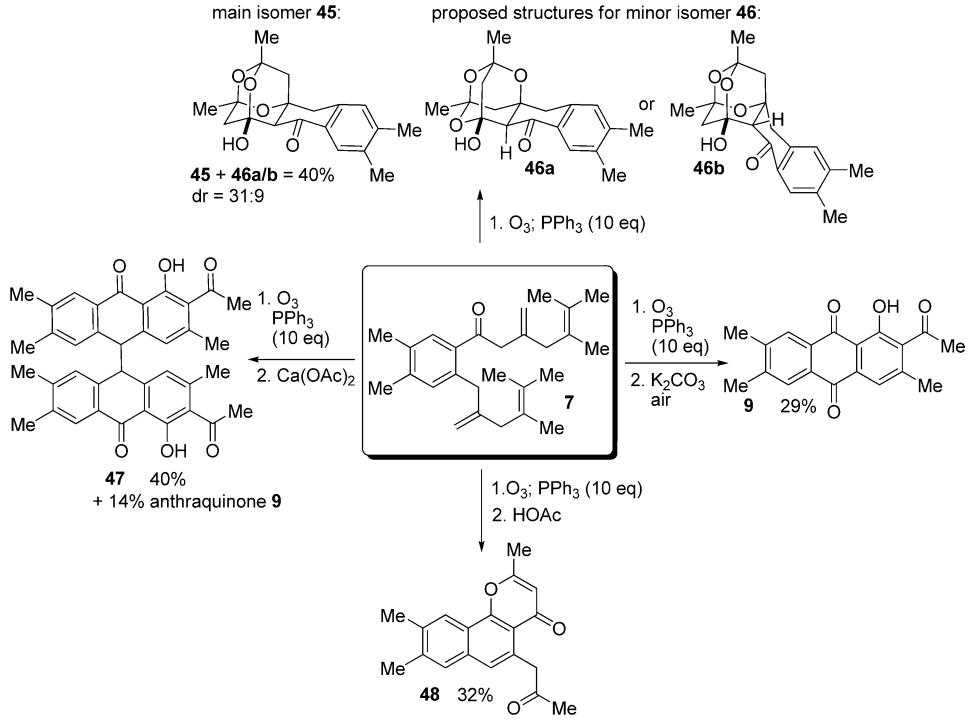
Scheme 13



Scheme 14



Scheme 15



the ozonolysis/cyclization reaction sequence in the total synthesis of the anthraquinone Kwanzoquinone A (**44**), the desired cyclization product was anthrone **43** (Scheme 14). The pentacarbonyl synthon **7** was chosen as a test substrate, as it is more easily accessible by cobalt catalysis.

Surprisingly, and in contrast to prior examined polyketones, we found that the pentacarbonyl compound **8** undergoes different cyclization modes depending on the reaction conditions (Scheme 15). The pentacarbonyl precursor **7** was ozonolyzed, an excess triphenylphosphine was used as reducing agent to ensure complete reduction of the ozonides. Purification of the crude polycarbonyl derivative **8** by flash column chromatography over silica gel gave a mixture of two trioxaadamantane isomers, **45** and **46**. Addition of silica gel to the crude pentacarbonyl compound **8**, and additional stirring for 18 h,[19] did not improve the yield of the trioxaadamantane.

The structure of the main isomer **45** was confirmed by X-ray analysis (see Supporting Information). The structure of the minor isomer **46** could not be determined unambiguously by NMR spectroscopy, the two potential structures are shown in Scheme 15.

Moreover, pentacarbonyl **8** underwent cyclization using glacial acid to give the benzochromen-4-one **48** as the main product. The product was obtained in 32% yield, which could

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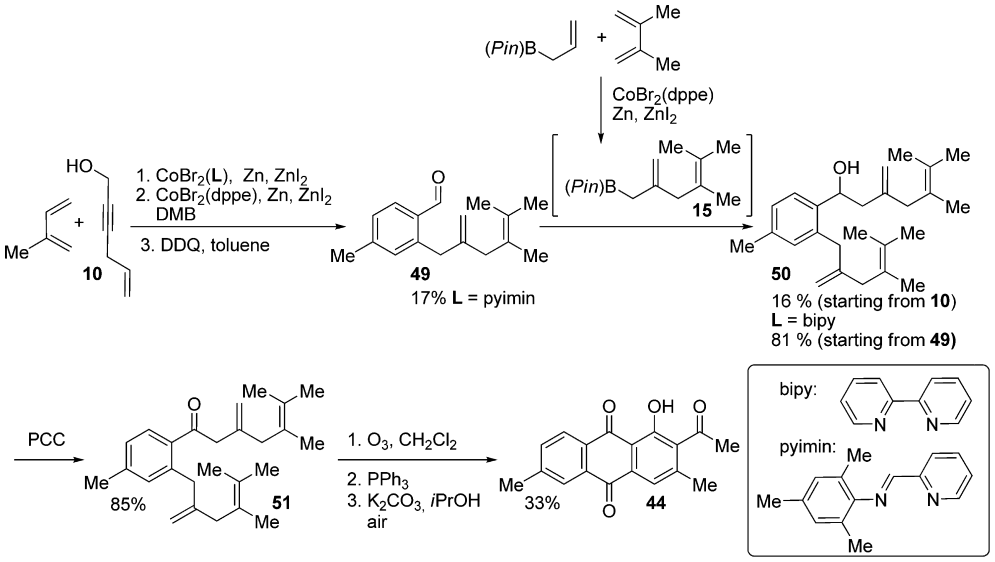
Table 3. Optimization of the Reaction Sequence to Synthesize Anthraquinone 9

entry	cyclization[a]	solvent	time	yield (9)
1	$Ca(OAc)_2$ (5 equiv) then	MeOH	4 h	21%
	K_2CO_3 (7 equiv)/O_2	CH_2Cl_2	16 h	
2	CsOAc (10 equiv)	MeOH	2 d	24%
3	Cs_2CO_3 (3 equiv)	THF	2 d	22%
4	K_2CO_3 (10 equiv)	*i*PrOH/CH_2Cl_2	16 h	29%
5	K_2CO_3 (10 equiv), 3 Å MS[b]	*i*PrOH/CH_2Cl_2	16 h	22% + 15% **45**
6	K_2CO_3 (10 equiv)/O_2	CH_2Cl_2	3 d	12% +15% **45**

[a]Conditions of the ozonolysis: (1) Tetraene **7** (1.0 equiv), O_3, CH_2Cl_2, −78 °C. (2) Addition of PPh_3 (10 equiv) −78 °C → rt, 16−24 h. (3) The solvent was removed under reduced pressure and the crude polycarbonyl derivative **8** was treated as described for the cyclization. [b]Molecular sieve.

Scheme 16



not be improved by the application of trifluoracetic acid, instead of HOAc. The treatment of the pentacarbonyl derivative **8** with calcium acetate to obtain anthrone **9** according to a procedure by Yamaguchi,[4] afforded the bisanthrone **47** as the main product in 40% yield, as well as the desired anthraquinone **9** in only 14% yield. The formation of the products proceeded via dimerization and oxidation of anthrone **43**, which was not isolated. The structure of the bisanthrone **47** was confirmed by X-ray analysis (see Supporting Information).

Finally, we focused on the formation of anthraquinone **9** as the main product (Table 3). We tried to suppress the dimerization, and to favor the oxidation of anthrone **43** to anthraquinone **9**. Since the anthrone **43** was formed as an intermediate in over 50% yield in the reaction described above, by applying $Ca(OAc)_2$ we were confident to obtain the anthraquinone **9** in good yields.

The reactions were performed under conditions inspired by the literature procedures of similar cyclization reactions (Table 3). The best result was obtained by cyclization with potassium carbonate, after ozonolysis followed by acidification according to a procedure by Krohn,[20] which resulted in the formation of anthraquinone **9** as the main product in 29% yield (entry 4). Other conditions were tested to increase the yield of the desired anthraquinone **9**. Anthrone **43** was not isolated in any case. Oxidation of the anthrone with K_2CO_3/O_2, after cyclization with $Ca(OAc)_2$ following a procedure of Yamaguchi,[4] yielded the product in 21% (entry 1). Similar results were obtained by applying CsOAc in methanol (entry 2), or Cs_2CO_3 in THF, according to a procedure described by Barrett (entry 3).[6] The use of K_2CO_3 under oxygen atmosphere (entry 6), as well as the addition of molecular sieve (entry 5), brought no improvement and, as a side product, the trioxaadamantane **45** was obtained in both cases.

The established reaction sequence for the synthesis of anthraquinone **9** by ozonolysis of tetraene **7**, and successive cyclization, was then applied in the natural product synthesis of Kwanzoquinone A (**44**) (Scheme 16). The anthraquinone **44** was obtained in an overall yield of 4% over eight steps.

The low yield observed for the first four steps is attributed to the cobalt-catalyzed Diels−Alder reaction with isoprene. The problem lies within the separation of the resulting regioisomers of **49**, as well as the diminished yield of the Diels−Alder reaction when using $CoBr_2$(bipy) instead of $CoBr_2$(dppe) as the catalyst precursor (compare Scheme 3). Initially, $CoBr_2$(pyimin) was tested as precatalyst for the Diels−Alder reaction with isoprene. After 1,4-hydrovinylation with DMB, and subsequent oxidation with DDQ, the desired aldehyde **49** was isolated isomerically pure in 17% yield. The structure of aldehyde **49** was determined by two-dimensional NMR spectroscopy (HMBC). The next step was the allylboration with a boron-functionalized 1,4-diene **15** that is accessible by cobalt-catalyzed 1,4-hydrovinylation. Alcohol **50** was obtained in 81% yield. In a second approach, $CoBr_2$(bipy) was tested in the Diels−Alder reaction, since it has shown similar selectivity and slightly improved yields compared to $CoBr_2$(pyimin) in earlier work. This time, the regioisomeric mixture of aldehyde

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49 was converted immediately to alcohol **50**, because we hoped that the regioisomeric mixture of alcohols would be more easily separable by column chromatography on silica gel. This was not the case. Similar results were obtained compared to the route over two steps. The alcohol was obtained with a purity of 94% in 16% yield (starting from enyne **10**).

The following oxidation of the alcohol **50** was performed with PCC in good yield (85%). Subsequently, the polyene **51** was converted to the corresponding pentacarbonyl derivative by ozonolysis. The cyclization and oxidation with air to anthraquinone **44** was accomplished by K_2CO_3 in *iso*-propanol/dichloromethane in 33% over three steps (ozonolysis, cyclization, and oxidation).

CONCLUSION

In summary, we present a straightforward way to access aromatic-substituted 1,4-dienes and polyenes via mild cobalt-catalyzed reactions. These derivatives are β-polycarbonyl synthons, and the synthesized tri-, tetra-, and pentacarbonyl precursors were examined in an ozonolysis/cyclization reaction sequence. In the case of tricarbonyl precursors, the formation of stable ozonides was found to be the main reason for the initial low yields of naphthols. This problem was solved by applying an excess of triphenylphosphine as reductant, in conjunction with longer reaction times. The cyclization of tri- and tetracarbonyl derivatives was accomplished using basic as well as acidic conditions, and the corresponding naphthol derivatives were obtained in good yields. Furthermore, even tri- and tetracarbonyl synthons with terminal double bonds can be applied, and naphthols with easily functionalizable aldehyde groups are accessible. Moreover, pentacarbonyl synthon **7** was examined in the ozonolysis/cyclization reaction sequence, and different products were formed depending on the reaction conditions. After column chromatography, a trioxaadamantane was obtained as a mixture of two diastereomeres, whereas a benzochromen-4-one was isolated under acetic conditions. A bisanthrone was formed as the main product when using $Ca(OAc)_2$ in methanol. The best yield for the desired anthraquinone was obtained under basic conditions using K_2CO_3. Finally, the established reaction sequence for the anthraquinone was successfully applied in the synthesis of the natural product Kwanzoquinone A. The anthraquinone was obtained in an overall yield of 4% over eight steps.

EXPERIMENTAL SECTION

General Methods. All reactions were carried out under an argon atmosphere in heat-gun-dried glassware. Unless otherwise noted, all reactions were performed with anhydrous solvents. ZnI_2 was dried in vacuo at 150 °C prior to use. Commercially available materials were used without further purification. Ozonolysis was conducted using an ozone generator; O_2/O_3 mixture was dried by a P_4O_5 column. Flash column chromatography was performed on silica gel 60 (230−400 mesh), and analytical thin layer chromatography (TLC) was carried out on silica gel 60 F-254 precoated aluminum plates.

The enynes hex-5-en-2-yn-1-ol (**10**)[21] and 5-methylhex-5-en-2-yn-1-ol (**11**)[22] were prepared following a literature procedure.[21] 2-(4,5-Dimethyl-2-methylenehex-4-enyl)-4,5-dimethylbenzaldehyde (**14**) was prepared following a tandem Diels−Alder/1,4-hydrovinylation/DDQ-oxidation sequence.[14] These are known compounds, and the analytical data for these compounds were in accordance with the literature.

General Procedure 1 for the Cobalt-Catalyzed Diels−Alder/DDQ-Oxidation Sequence with 2,3-Dimethyl-1,3-butadiene (DMB) (GP 1). Zinc iodide (20−30 mol %), zinc powder (20−30 mol %), and $CoBr_2$(**L**) (10−15 mol %) (**L** = 2,2′-bipyridine (for aldehyde **13**); **L** = 1,2-bis(diphenylphosphino)ethane (for aldehyde **12**)) were suspended in dichloromethane (1.0 M). Then 2,3-dimethyl-1,3-butadiene (1.2−1.4 equiv) and the enyne (1.0 equiv) were added and the mixture was stirred at room temperature until complete conversion of the starting material. Afterward, the suspension was filtered over a short pad of silica gel and the solvent was removed in vacuo. The residue was dissolved in toluene (0.1 M) and was treated with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (2.6 equiv, DDQ). The mixture was stirred at room temperature until complete oxidation was monitored by GC/MS analysis and was then filtered over a short pad of deactivated silica gel. The solvent was removed in vacuo and the residue was purified by flash column chromatography on silica gel.

*4,5-Dimethyl-2-(2-methylallyl)benzaldehyde (**12**).* Colorless oil; 139 mg (0.74 mmol, 78%); eluent: pentane:diethyl ether = 25:1; ^{1}H NMR (300 MHz, $CDCl_3$) δ 10.16 (s, 1H), 7.62 (s, 1H), 7.03 (s, 1H), 4.82 (s, 1H), 4.46 (s, 1H), 3.66 (s, 2H), 2.32−2.28 (m, 6H), 1.76 (s, 3H); ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$) δ 192.0, 145.6, 143.7, 139.8, 135.5, 133.1, 132.4, 131.7, 112.3, 39.8, 23.0, 20.2, 19.3; MS (EI) *m*/*z* (%) 188 (13, M^+), 173 (100), 155 (15), 145 (16), 128 (15), 115 (13), 91 (9), 77 (7); HRMS (EI, *m*/*z*) calcd for $C_{13}H_{16}O$ 188.1201, found 188.1198; IR (film, cm^{-1}) 2971, 2921, 2859, 1687, 1650, 1610, 1560, 1500, 1449, 1399, 1373, 1293, 1258, 1217, 1184, 1072, 1022, 890, 777.

*2-Allyl-4,5-dimethylbenzaldehyde (**13**).* Colorless oil; 183 mg (1.05 mmol, 40%); eluent: pentane:diethyl ether = 25:1; ^{1}H NMR (300 MHz, $CDCl_3$) δ 10.17 (s, 1H), 7.60 (s, 1H), 7.05 (s, 1H), 6.02 (ddt, *J* = 16.4, 10.1, 6.2 Hz, 1H), 5.06 (dq, *J* = 10.1, 1.5 Hz, 1H), 4.98 (dq, *J* = 17.1, 1.7 Hz, 1H), 3.75 (d, *J* = 6.2 Hz, 2H), 2.31 (s, 3H), 2.30 (s, 3H); ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$) δ 192.2, 143.9, 139.9, 137.5, 135.4, 132.8, 132.6, 131.9, 116.2, 36.2, 20.2, 19.3; MS (EI) *m*/*z* (%) 174 (21, M^+), 159 (100), 146 (15), 141 (22), 131 (31), 115 (51), 103 (11), 91 (37), 77 (23), 63 (14); HRMS (EI, *m*/*z*) calcd for $C_{12}H_{14}O$ 174.1045, found 174.1048; IR (film, cm^{-1}) 3346, 2924, 1688, 1614, 1565, 1452, 1413, 1381, 1323, 1297, 1259, 1225, 1193, 1102, 1063, 1022, 998, 889, 775.

*2-(2,3-Dimethylbut-2-enyl)naphthalene (**23**).* Zinc iodide (20 mol %), zinc powder (20 mol %), and cobalt 1,2-bis(diphenylphosphino)-ethane dibromide (10 mol %) were suspended in dichloromethane (1 mL). Then DMB (1.71 mmol) and 2-(2-allylphenyl)-1,3-dioxolane (**24**) (1.18 mmol) were added and the mixture was stirred at room temperature (3 h). Additional ZnI_2 (0.94 mmol) was added and the reaction mixture was stirred for 2 d. Afterward, the suspension was filtered over a short pad of silica gel and the solvent was removed in vacuo. Pale yellow oil; 216 mg (1.03 mmol, 87%). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.83−7.77 (m, 3H), 7.57 (s, 1H), 7.49−7.37 (m, 2H), 7.30 (d, *J* = 8.5 Hz, 1H), 3.56 (s, 2H), 1.85 (s, 3H), 1.78 (s, 3H), 1.63 (s, 3H); ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$) δ 138.8, 133.8, 132.2, 127.9, 127.7, 127.60, 127.56, 126.5, 126.4, 126.2, 125.9, 125.2, 40.5, 20.9, 20.8, 18.6; MS (EI) *m*/*z* (%) 210 (65, M^+), 195 (100), 180 (23), 165 (40), 153 (19), 141 (37), 128 (38), 115 (28); HRMS (EI, *m*/*z*) calcd for $C_{16}H_{18}$ 210.1409, found 210.1409; IR (film, cm^{-1}) 3052, 2957, 2922, 2862, 1634, 1599, 1508, 1451, 1374, 1163, 1120, 1019, 954, 892, 851, 811, 778, 747, 620.

*2-(4,5-Dimethyl-2-methylenehex-4-enyl)benzaldehyde (**25**).* Zinc iodide (20 mol %), zinc powder (20 mol %) and cobalt 1,2-bis(diphenylphosphino)ethane dibromide (10 mol %) were suspended in dichloromethane (4 mL). Then DMB (4.80 mmol) and 2-(2-allylphenyl)-1,3-dioxolane (**24**) (3.67 mmol) were added and the mixture was stirred at room temperature until complete conversion of the alkene, as monitored by GC/MS analysis (5 h). Afterward, the suspension was filtered over a short pad of silica gel and the solvent was removed in vacuo. The residue was dissolved in acetone (20 mL) and was treated with *para*-toluenesulfonic acid (0.32 mmol, *p*TsOH). After stirring for an additional hour, the mixture was neutralized with saturated aqueous $NaHCO_3$ solution. The product was extracted with ethyl acetate (3×), the combined organic phases were washed with brine and dried over anhydrous magnesium sulfate. The solvent was removed in vacuo. Pale yellow oil; 827 mg (3.63 mmol, 98%); ^{1}H NMR (300 MHz, $CDCl_3$) δ 10.20 (s, 1H), 7.87 (dd, *J* = 7.7, 1.4 Hz, 1H), 7.52 (dt, *J* = 7.5, 1.5 Hz, 1H), 7.38 (t, *J* = 7.2 Hz, 1H), 7.29−7.24 (m, 1H), 4.83 (dd, *J* = 2.7, 1.3 Hz, 1H), 4.42−4.39 (m, 1H), 3.67 (s, 2H), 2.82 (s, 2H), 1.69 (s, 3H), 1.63−1.57 (m, 6H); ^{13}C{^{1}H} NMR

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(75 MHz, $CDCl_3$) δ 192.0, 147.7, 142.4, 134.5, 133.9, 131.8, 130.2, 127.0, 126.9, 124.8, 112.6, 41.9, 38.4, 20.8, 20.6, 18.4; HRMS (ESI, *m/z*) calcd for $C_{16}H_{20}O+H^+$ 229.1587, found 229.1588; IR (film, cm^{-1}) 3072, 2987, 2912, 2859, 2732, 2359, 1694, 1646, 1598, 1447, 1376, 1288, 1203, 1114, 896, 809, 755, 637.

General Procedure 2 for the Grignard Reaction with Allylmagnesium Bromide (GP 2). Allylmagnesium bromide (1.2–1.3 equiv; 1.0 M in THF) was added dropwise to the aldehyde (1.0 equiv) dissolved in THF at 0 °C and the mixture was stirred at room temperature. After complete conversion of the aldehyde, saturated aqueous NH_4Cl solution was added, and the product was extracted with diethyl ether (3×). The combined organic phases were washed with water and brine, and then dried over anhydrous magnesium sulfate. The solvent was removed in vacuo and the residue was purified by flash column chromatography. The products were converted to the corresponding ketones; see below.

General Procedure 3 for the Indium-Mediated Barbier-Type Reaction (GP 3). Following a literature procedure,[23] indium (1.5 equiv) was added to dimethylformamide (1 mL). After addition of 2-methyl-3-bromopropen (2.5–3.0 equiv), the reaction mixture was stirred at room temperature for 10 min until the colorless solution turned yellow. Then the aldehyde (1.0 equiv) dissolved in dimethylformamide (1 mL) was added, and the solution was stirred for 1 h at room temperature. After acidification of the mixture with HCl (2 M), the product was extracted with diethyl ether (3×). The combined organic phases were dried over anhydrous magnesium sulfate and the solvent was removed in vacuo. The residue was purified by flash column chromatography. The products were converted to the corresponding ketones; see below.

General Procedure 4 for the Cobalt-Catalyzed 1,4-Hydrovinylation–Allylboration Reaction Sequence (GP 4). Zinc iodide (20–40 mol %), zinc powder (20–40 mol %), and cobalt 1,2-bis(diphenylphosphino)ethane dibromide (10–20 mol %) were suspended in dichloromethane (1.0 M). Then, 2,3-dimethyl-1,3-butadiene (DMB) (1.7 equiv) and the 2-allyl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (1.5 equiv) were added, and the mixture was stirred at room temperature until complete conversion of the alkene monitored by GC/MS analysis. Afterward, the reaction was cooled to 0 °C and the aldehyde (1.0 equiv) was added. The reaction mixture was stirred at 0 °C for an hour and another hour at room temperature. Triethanolamine (1.8–2.0 equiv) was added and the reaction mixture was stirred for an additional hour. The mixture was filtered over a short pad of silica gel, the solvent was removed in vacuo and the residue was purified by flash column chromatography.

*1-(2-(4,5-Dimethyl-2-methylenhex-4-enyl)-4-methylphenyl)-5,6-dimethyl-3-methylene-hept-5-en-1-ol (**50**).* Zinc iodide (20 mol %), zinc powder (20 mol %), and cobalt 2,2′-bipyridine dibromide (10 mol %) were suspended in dichloromethane (2 mL). Then, isoprene (3.0 mmol) and the enyne **10** (2.10 mmol) were added and the mixture was stirred at room temperature until complete conversion of the enyne (15 h). Afterward, the suspension was filtered over a short pad of silica gel and the solvent was removed in vacuo. The residue was dissolved in dichloromethane (2.0 mL) and added to zinc iodide (20 mol %), zinc powder (20 mol %), and cobalt 1,2-bis-(diphenylphosphino)ethane dibromide (10 mol %) and 2,3-dimethyl-1,3-butadiene (2.6 mmol) in 2.0 mL dichloromethane and stirred for 3 h at room temperature. The suspension was filtered over a short pad of silica gel and the solvent was removed in vacuo. The residue was dissolved in toluene (0.1 M) and was treated with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (5.0 mmol, DDQ). The mixture was stirred at room temperature for 18 h and was then filtered over a short pad of deactivated silica gel. The solvent was removed in vacuo and the residue was purified by flash column chromatography. The obtained aldehyde **49** was then applied in a cobalt-catalyzed 1,4-hydrovinylation–allylboration reaction sequence as described in the GP 4. Colorless oil; 122 mg (0.33 mmol, 16%; purity: 94%); eluent: pentane:diethyl ether = 20:1; ^1H NMR (300 MHz, $CDCl_3$) δ 7.43 (d, J = 7.9 Hz, 1H), 7.08 (dd, J = 7.9, 1.3 Hz, 1H), 6.94 (s, 1H), 4.99–4.91 (m, 2H), 4.86 (dd, J = 3.4, 1.6 Hz, 1H), 4.81 (d, J = 1.3 Hz, 1H), 4.50 (s, 1H), 3.38–3.22 (m, 2H), 2.78 (s, 4H), 2.37–2.30 (m, 5H), 2.02 (s, 1H), 1.69 (s, 6H), 1.67–1.59 (m, 12H); $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$) δ 147.5, 144.9, 139.8, 136.8, 136.0, 131.3, 127.7, 126.8, 126.7, 125.9, 125.0, 124.9, 112.8, 111.8, 67.9, 45.8, 41.8, 41.3, 39.2, 21.2, 20.8, 20.7, 20.6, 20.6, 18.6, 18.5; MS (EI) *m/z* (%) 366 (<1, M^+), 348 (8), 265 (19), 243 (13), 225 (33), 209 (23), 195 (18), 155 (38), 143 (51), 109 (15), 83 (100), 55 (40); HRMS (EI, *m/z*) calcd for $C_{26}H_{38}O$ 366.2923, found 366.2918; IR (film, cm^{-1}) 3444, 3075, 2987, 2915, 2861, 1741, 1644, 1497, 1441, 1377, 1335, 1277, 1218, 1109, 1049, 894, 819.

General Procedure 5 for the Oxidation of Alcohols with Pyridinium Chlorochromate (PCC) (GP 5). Alcohol (1.0 equiv) was added to pyridinium chlorochromate (1.5 equiv, PCC) suspended in dichloromethane (0.2 M) at 0 °C. The reaction mixture was stirred at room temperature until complete conversion of the starting material. Afterward, the suspension was filtered over silica gel, followed by evaporation of the solvent. Then, the residue was purified by flash column chromatography. For the synthesis of ketone **22**, Dess-Martin-periodinane was used instead of PCC.

*1-(2-Allyl-4,5-dimethylphenyl)but-3-en-1-one (**16**).* Colorless oil; 85 mg (0.40 mmol, 50%); eluent: pentane:diethyl ether = 50:1; ^1H NMR (300 MHz, $CDCl_3$) δ 7.43 (s, 1H), 7.04 (s, 1H), 6.12–5.87 (m, 2H), 5.24–5.13 (m, 2H), 5.06–4.93 (m, 2H), 3.67 (dt, J = 6.8, 1.4 Hz, 2H), 3.58 (d, J = 6.5 Hz, 2H), 2.28 (s, 6H); $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$) δ 201.7, 140.8, 138.0, 137.8, 135.3, 134.4, 132.8, 131.5, 130.2, 118.5, 115.4, 46.5, 37.8, 19.9, 19.5; MS (EI) *m/z* (%) 214 (7, M^+), 199 (19), 173 (100), 158 (13), 145 (90), 130 (48), 115 (37), 105 (15), 91 (13), 77 (9); HRMS (EI, *m/z*) calcd for $C_{15}H_{18}O$ 214.1358, found 214.1358; IR (film, cm^{-1}) 3078, 3013, 2976, 2920, 1682, 1638, 1611, 1556, 1500, 1445, 1392, 1319, 1266, 1225, 1199, 1117, 1088, 993, 913, 877.

*1-(4,5-Dimethyl-2-(2-methylallyl)phenyl)but-3-en-1-one (**17**).* Colorless oil; 256 mg (1.12 mmol, 75%); eluent: pentane:diethyl ether = 100:1; ^1H NMR (300 MHz, $CDCl_3$) δ 7.39 (s, 1H), 7.02 (s, 1H), 6.02 (ddt, J = 17.1, 10.4, 6.8 Hz, 1H), 5.24–5.10 (m, 2H,), 4.75 (s, 1H), 4.45 (s, 1H), 3.63 (dt, J = 6.8, 1.4 Hz, 2H), 3.52 (s, 2H), 2.28 (s, 3H), 2.27 (s, 3H), 1.71 (s, 3H); $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$) δ 202.1, 145.8, 140.4, 137.0, 136.1, 134.4, 133.2, 131.6, 130.0, 118.5, 111.5, 46.6, 41.0, 23.0, 19.9, 19.5; MS (EI) *m/z* (%) 228 (13, M^+), 213 (100), 199 (10), 186 (22), 172 (23), 159 (15), 141 (14), 128 (27), 115 (16), 91 (9), 77 (8), 69 (18); HRMS (EI, *m/z*) calcd for $C_{16}H_{20}O$ 228.1514, found 228.1519; IR (film, cm^{-1}) 3078, 3014, 2970, 2938, 2920, 1685, 1644, 1612, 1557, 1499, 1447, 1388, 1373, 1319, 1266, 1197, 1117, 1089, 1022, 992, 978, 913, 887, 772.

*1-(2-(4,5-Dimethyl-2-methylenehex-4-enyl)-4,5-dimethylphenyl)-but-3-en-1-one (**18**).* Colorless oil; 983 mg (3.32 mmol, 80%); eluent: pentane:diethyl ether = 50:1; ^1H NMR (300 MHz, $CDCl_3$) δ 7.37 (s, 1H), 7.01 (s, 1H), 6.01 (ddt, J = 17.1, 10.3, 6.8 Hz, 1H), 5.22–5.12 (m, 2H), 4.71 (s, 1H), 4.41 (s, 1H), 3.62 (dt, J = 6.8, 1.3 Hz, 2H), 3.47 (s, 2H), 2.73 (s, 2H), 2.28 (s, 3H), 2.27 (s, 3H), 1.68 (s, 3H), 1.59 (br s, 6H); $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$) δ 202.0, 147.6, 140.0, 136.8, 136.2, 134.1, 133.1, 131.5, 129.7, 126.2, 125.1, 118.2, 110.9, 46.4, 41.6, 39.4, 20.5, 20.4, 19.7, 19.3, 18.4; HRMS (ESI, *m/z*) calcd for $C_{21}H_{28}O+H^+$ 297.2213, found 297.2213; IR (film, cm^{-1}) 3078, 2981, 2917, 2862, 1687, 1641, 1612, 1557, 1499, 1446, 1390, 1320, 1264, 1221, 1117, 1088, 988, 911, 892.

*1-(2-Allyl-4,5-dimethylphenyl)-3-methylbut-3-en-1-one (**19**).* Colorless oil; 231 mg (1.01 mmol, 66%); eluent: pentane:diethyl ether = 25:1; ^1H NMR (300 MHz, $CDCl_3$) δ 7.45 (s, 1H), 7.04 (s, 1H), 5.98 (ddt, J = 17.7, 9.4, 6.5 Hz, 1H), 5.04–4.96 (m, 3H), 4.83 (s, 1H), 3.58 (m, 4H), 2.27 (s, 6H), 1.80 (s, 3H); $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$) δ 201.7, 140.8, 140.0, 138.0, 137.8, 135.5, 134.3, 132.8, 130.4, 115.4, 115.0, 50.7, 37.8, 23.0, 19.9, 19.5; MS (EI) *m/z* (%) 228 (14, M^+), 213 (70), 198 (17), 185 (30), 173 (100), 157 (23), 145 (82), 141 (18), 128 (46), 115 (40), 105 (15), 91 (17), 77 (15); HRMS (EI, *m/z*) calcd for $C_{16}H_{20}O$ 228.1514, found 228.1511; IR (film, cm^{-1}) 3077, 2974, 2919, 1682, 1644, 1610, 1556, 1499, 1379, 1320, 1264, 1226, 1100, 995, 949, 896.

*1-(4,5-Dimethyl-2-(2-methylallyl)phenyl)-3-methylbut-3-en-1-one (**20**).* Colorless oil; 342 mg (1.41 mmol, 88%); eluent: pentane:diethyl ether = 100:1; ^1H NMR (300 MHz, $CDCl_3$) δ 7.41

(s, 1H), 7.02 (s, 1H), 4.96 (s, 1H), 4.82 (s, 1H), 4.76 (s, 1H), 4.46 (s, 1H), 3.57 (s, 2H), 3.53 (s, 2H), 2.28 (s, 3H), 2.27 (s, 3H), 1.79 (s, 3H), 1.72 (s, 3H); $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$) δ 201.9, 145.8, 140.3, 140.0, 136.9, 136.3, 134.2, 133.1, 130.1, 115.0, 111.5, 50.8, 40.9, 22.97, 22.95, 19.8, 19.5; MS (EI) m/z (%) 242 (15, M^+), 227 (69), 209 (38), 187 (100), 179 (23), 159 (94), 144 (24), 128 (34), 115 (23), 91 (9), 77 (10); HRMS (EI, m/z) calcd for $C_{17}H_{22}O$ 242.1671, found 242.1671; IR (film, cm^{-1}) 3077, 2971, 2922, 1684, 1649, 1612, 1556, 1499, 1445, 1376, 1320, 1262, 1226, 1098, 1020, 950, 889, 772.

*1-(2-(4,5-Dimethyl-2-methylenehex-4-enyl)-4,5-dimethylphenyl)-3-methylbut-3-en-1-one (**21**).* Colorless oil; 597 mg (1.92 mmol, 84%); eluent: pentane:diethyl ether = 50:1; ^1H NMR (300 MHz, $CDCl_3$) δ 7.41 (s, 1H), 7.01 (s, 1H), 4.95 (s, 1H), 4.81 (s, 1H), 4.72 (s, 1H), 4.43 (s, 1H), 3.56 (d, J = 0.6 Hz, 2H), 3.49 (s, 2H), 2.75 (s, 2H), 2.28 (s, 3H), 2.26 (s, 3H), 1.79 (s, 3H), 1.68 (s, 3H), 1.62−1.58 (m, 6H); $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$) δ 202.0, 147.7, 140.2, 140.0, 137.0, 136.5, 134.1, 133.2, 130.1, 126.4, 125.2, 114.9, 111.0, 50.7, 41.7, 39.5, 23.0, 20.7, 20.5, 19.8, 19.5, 18.6; MS (EI) m/z (%) 310 (3, $[M^+]$), 292 (7), 255 (12), 227 (100), 211 (4), 185 (11), 173 (11), 128 (7), 91 (5), 83 (11), 55 (16); HRMS (EI, m/z) calcd for $C_{22}H_{30}O$ 310.2297, found 310.2296; IR (film, cm^{-1}) 3077, 2977, 2917, 2863, 1737, 1685, 1646, 1611, 1556, 1499, 1445, 1377, 1320, 1263, 1223, 1098, 1020, 951, 891, 771.

*1-(4,5-Dimethyl-2-(2-methylallyl)phenyl)-5,6-dimethyl-3-methylenehept-5-en-1-one (**22**).* Colorless oil; 125 mg (0.40 mmol, 62%); eluent: pentane:diethyl ether = 30:1; ^1H NMR (300 MHz, $CDCl_3$) δ 7.38 (s, 1H), 7.01 (s, 1H), 4.92 (d, J = 1.5 Hz, 1H), 4.84 (s, 1H), 4.77 (d, J = 0.9 Hz, 1H), 4.47 (s, 1H), 3.54 (s, 2H), 3.50 (s, 2H), 2.83 (s, 2H), 2.27 (s, 6H), 1.72 (s, 3H), 1.69 (s, 3H), 1.61 (s, 6H); $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$) δ 202.0, 145.8, 142.0, 140.2, 137.0, 136.3, 134.2, 133.0, 130.3, 127.0, 124.9, 114.5, 111.6, 48.6, 41.7, 40.9, 23.0, 20.8, 20.6, 19.8, 19.5, 18.4; MS (EI) m/z (%) 310 (9, M^+), 295 (17), 292 (30), 249 (14), 226 (30), 208 (13), 187 (100), 170 (16), 159 (75), 144 (14), 129 (18), 107 (10), 91 (9); HRMS (EI, m/z) calcd for $C_{22}H_{30}O$ 310.2297, found 310.2295; IR (film, cm^{-1}) 3077, 2968, 2919, 2858, 1682, 1647, 1612, 1557, 1498, 1446, 1373, 1317, 1266, 1218, 1198, 1152, 1094, 1022, 985, 945, 888, 845, 779.

*1-(2-(4,5-Dimethyl-2-methylenehex-4-enyl)-4,5-dimethylphenyl)-5,6-dimethyl-3-methylenehept-5-en-1-one (**7**).* Colorless oil; 761 mg (2.01 mmol, 87%); eluent: pentane:diethyl ether = 50:1; ^1H NMR (300 MHz, $CDCl_3$) δ 7.36 (s, 1H), 7.00 (s, 1H), 4.91 (d, J = 1.6 Hz, 1H), 4.83 (d, J = 0.7 Hz, 1H), 4.71 (s, 1H), 4.43 (d, J = 0.8 Hz, 1H), 3.48 (s, 4H), 2.83 (s, 2H), 2.75 (s, 2H), 2.27 (s, 6H), 1.68 (s, 6H), 1.60 (s, 12H); $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$) δ 202.1, 147.7, 142.0, 140.1, 137.1, 136.4, 134.1, 133.2, 130.3, 127.0, 126.4, 125.3, 125.0, 114.4, 111.0, 48.6, 41.8, 41.7, 39.6, 20.8, 20.7, 20.63, 20.56, 19.8, 19.5, 18.6, 18.4; HRMS (ESI, m/z) calcd for $C_{27}H_{38}O+H^+$ 379.2995, found 379.2992; IR (film, cm^{-1}) 3077, 2984, 2914, 1682, 1643, 1612, 1556, 1498, 1443, 1376, 1317, 1266, 1216, 1154, 1093, 1019, 985, 950, 890.

*1-(2-(4,5-Dimethyl-2-methylenehex-4-enyl)-4-methylphenyl)-5,6-dimethyl-3-methylenehept-5-en-1-one (**51**).* Colorless oil; 136 mg (0.37 mmol, 85%); eluent: pentane:diethyl ether = 30:1; ^1H NMR (300 MHz, $CDCl_3$) δ 7.52 (d, J = 8.3 Hz, 1H), 7.07 (m, 2H), 4.91 (d, J = 1.6 Hz, 1H), 4.84 (s, 1H), 4.73 (s, 1H), 4.43 (s, 1H), 3.53 (s, 2H), 3.49 (s, 2H), 2.82 (s, 2H), 2.75 (s, 2H), 2.35 (s, 3H), 1.68 (s, 6H), 1.60 (s, 12H); $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$) δ 201.9, 147.6, 141.9, 141.5, 139.8, 136.1, 132.6, 129.1, 127.0, 126.7, 126.4, 125.2, 124.9, 114.5, 111.2, 48.6, 41.8, 41.7, 40.0, 21.5, 20.74, 20.71, 20.6, 20.5, 18.6, 18.4; MS (EI) m/z (%) 364 (3, M^+), 346 (30), 321 (9), 303 (6), 281 (33), 261 (13), 241 (29), 233 (18), 221 (22), 207 (19), 193 (25), 171 (23), 159 (48), 109 (23), 91 (24), 83 (100), 55 (82); HRMS (EI, m/z) calcd for $C_{26}H_{36}O$ 364.2766, found 364.2766; IR (film, cm^{-1}) 2985, 2912, 2859, 1749, 1682, 1643, 1607, 1564, 1435, 1374, 1315, 1264, 1210, 1114, 1005, 890, 808.

General Procedure 6 for the Ozonolysis Reaction (GP 6). The polyene (1.0 equiv) was dissolved in dichloromethane and the solution was cooled to −78 °C. A mixture of oxygen and ozone was bubbled through the solution until a blue color appeared. The mixture was purged with oxygen to obtain a colorless or slightly yellowish solution which was directly treated with the corresponding reducing agent and allowed to warm to room temperature.

General Procedure 7 for the Cyclization of Tricarbonyl Compounds with Aqueous NaOH (5 wt %) (GP 7). After ozonolysis of polyene (0.4 mmol) in dichloromethane (12 mL), following the GP 6 for the ozonolysis reaction, triphenylphosphine (1.0 mmol) was added and the reaction mixture was warmed to room temperature over an hour. The solvent was removed in vacuo and aqueous NaOH (6.4 mL, 5 wt %) was added. After stirring for an hour, the suspension was acidified with 2 M HCl, the product was extracted with dichloromethane (3×), washed with brine, and dried over anhydrous magnesium sulfate. Silica gel was added and after evaporation of the solvent the residue was purified by flash column chromatography.

*1-Hydroxy-3,6,7-trimethyl-2-naphthaldehyde (**27**).* Yellow solid; 63 mg (0.30 mmol, 75%); eluent: pentane:diethyl ether = 10:1; mp = 168−171 °C; ^1H NMR (500 MHz, $CDCl_3$) δ 11.54 (s, 1H), 8.21 (s, 1H), 7.53 (s, 1H), 7.42 (s, 1H), 7.14 (s, 1H), 2.75 (d, J = 0.8 Hz, 3H), 2.40 (s, 3H), 2.38 (s, 3H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 204.7, 156.8,140.5, 137.4, 133.9, 132.6, 128.6, 126.0, 125.9, 120.8, 111.3, 26.9, 20.6, 20.0; MS (EI) m/z (%) 214 (75, M^+), 199 (100), 171 (11), 143 (53), 128 (30), 115 (30), 102 (5), 77 (8); HRMS (EI, m/z) calcd for $C_{14}H_{14}O_2$ 214.0994, found 214.0991; IR (film, cm^{-1}) 3010, 2921, 2857, 1650, 1569, 1459, 1381, 1337, 1288, 1220, 1157, 1112, 1056, 1021, 952, 899, 857, 770, 715.

*1-(2-((1,2,4-Trioxolan-3-yl)methyl)-4,5-dimethylphenyl)-2-(3-methyl-1,2,4-trioxolan-3-yl)ethanone (**28**).* After ozonolysis of diene **19** (0.32 mmol) in dichloromethane (12 mL), following GP 1 for the ozonolysis reaction, triphenylphosphine (0.95 mmol) was added and the reaction mixture was warmed to room temperature over a period of an hour. Silica gel was added and the reaction mixture was stirred for 1 h at room temperature. The solvent was removed under reduced pressure and the residue was purified by flash chromatography. Eluent: pentane:diethyl ether = 5:1; **29**: pale yellow solid, 3 mg (0.02 mmol, 5%); analytical data see below; **28**: colorless oil; 23 mg (0.07 mmol, 23%); eluent: pentane:diethyl ether = 5:1; ^1H NMR (500 MHz, $CDCl_3$) δ 7.49 (s, 1H), 7.10 (s, 1H), 5.49 (dd, J = 9.9, 4.5 Hz, 1H), 5.17 (s, 1H), 5.11 (s, 1H), 5.08 (s, 1H), 5.05 (s, 1H), 3.40 (dd, J = 15.5, 3.7 Hz, 1H), 3.34 (dd, J = 15.4, 4.0 Hz, 1H), 3.29 (dd, J = 13.6, 4.5 Hz, 1H), 3.18 (dd, J = 13.5, 5.4 Hz, 1H), 2.29 (s, 6H), 1.68 (s, 3H); $^{13}C\{^1H\}$ NMR (126 MHz, $CDCl_3$) δ 198.9, 198.8, 141.49, 141.47, 135.8, 135.7, 135.6, 134.71, 134.68, 132.71, 132.68, 131.12, 131.08, 108.0, 103.62, 103.60, 94.21, 94.19, 94.1, 48.59, 48.58, 36.7, 36.6, 22.23, 22.22, 19.9, 19.6; HRMS (ESI, m/z) calcd for $C_{16}H_{20}O_7+Na^+$ 347.1101, found 347.1104; IR (film, cm^{-1}) 2888, 1678, 1613, 1557, 1447, 1375, 1345, 1260, 1201, 1094, 1055, 970, 883, 804, 667.

*1-(1-Hydroxy-6,7-dimethylnaphthalin-2-yl)ethanone (**29**).* Pale yellow solid; 69 mg (0.32 mmol, 83%); eluent: pentane:diethyl ether = 50:1; mp = 100−103 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 14.00 (s, 1H), 8.18 (s, 1H), 7.54 (d, J = 8.9 Hz, 1H), 7.50 (s, 1H), 7.14 (d, J = 8.8 Hz, 1H), 2.67 (s, 3H), 2.44 (s, 3H), 2.43 (s, 3H); $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$) δ 204.2, 162.3, 140.6, 136.5, 135.9, 127.4, 124.3, 124.1, 123.8, 117.7, 112.9, 26.9, 20.5, 20.3; HRMS (ESI, m/z) calcd for $C_{14}H_{14}O_2+H^+$ 215.1067, found 215.1067; IR (film, cm^{-1}) 2965, 2919, 2856, 1625, 1568, 1465, 1419, 1371, 1325, 1253, 1191, 1146, 1057, 1025, 967.

*1-Hydroxy-6,7-dimethyl-2-naphthaldehyde (**31**).* Pale yellow solid; 51 mg (0.25 mmol, 64%); eluent: pentane:diethyl ether = 10:1; mp = 104−105 °C; ^1H NMR (300 MHz, $CDCl_3$) δ 12.54 (s, 1H), 9.81 (s, 1H), 8.05 (s, 1H), 7.42 (s, 1H), 7.27 (d, J = 8.3 Hz, 1H), 7.14 (d, J = 7.8 Hz, 1H), 2.34 (s, 6H); $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$) δ 196.2, 161.7, 141.3, 136.7, 136.1, 127.6, 125.8, 123.9, 123.1, 118.7, 114.0, 20.6, 20.3; HRMS (EI, m/z) calcd for $C_{13}H_{12}O_2$ 200.0837, found 200.0836; IR (film, cm^{-1}) 2978, 2920, 2858, 1627, 1570, 1497, 1465, 1422, 1369, 1320, 1261, 1212, 1145, 1089, 1023, 953, 880, 837, 771.

*Ozonides **32**, **33**, and **34**.* After ozonolysis of diene **20** (0.33 mmol) in dichloromethane (10 mL), following GP 1 for the ozonolysis reaction, triphenylphosphine (0.9 mmol) was added and

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the reaction mixture was warmed to room temperature over a period of an hour. Silica gel (1 g) was added and the reaction mixture was stirred for 3 d at room temperature. The solvent was removed under reduced pressure and the residue was purified by flash chromatography. Eluent: pentane:diethyl ether = 10:1 → diethyl ether.

35: pale yellow oil, 11 mg (0.05 mmol, 15%); analytical data see below.

32: yellow solid; 3 mg (0.01 mmol, 3%); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.04 (s, 1H), 6.89 (s, 1H), 5.24 (s, 1H), 5.07 (s, 1H), 3.22 (d, J = 17.0 Hz, 1H), 2.99 (d, J = 17.1 Hz, 1H), 2.88 (d, J = 15.6 Hz, 1H), 2.82 (d, J = 15.6 Hz, 1H), 2.24 (s, 3H), 2.22 (s, 3H), 1.74 (s, 3H), 1.70 (s, 3H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$) δ 137.8, 134.6, 133.1, 129.9, 128.9, 124.6, 109.2, 108.4, 105.9, 93.8, 39.2, 37.4, 22.6, 22.5, 19.8, 19.7; HRMS (ESI, m/z) calcd for $C_{16}H_{20}O_6$+Na^+ 331.1153, found 331.1153; IR (film, cm^{-1}) 2928, 2161, 2039, 1982, 1623, 1504, 1450, 1416, 1380, 1268, 1221, 1160, 1127, 1059, 968, 878, 798.

33: yellow oil; 11 mg (0.04 mmol, 13%); ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.94 (s, 1H), 6.92 (s, 1H), 3.42 (d, J = 15.2 Hz, 1H), 3.35 (d, J = 15.1 Hz, 1H), 3.24 (d, J = 17.1 Hz, 1H), 3.03 (d, J = 17.2 Hz, 1H), 2.30 (s, 3H), 2.22 (s, 6H), 1.73 (s, 3H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$) δ 203.2, 138.2, 134.9, 132.1, 130.0, 129.0, 124.4, 109.5, 105.7, 44.8, 39.3, 31.2, 22.4, 19.8, 19.7; HRMS (ESI, m/z) calcd for $C_{15}H_{18}O_4$+Na^+ 285.1097, found 285.1098; IR (film, cm^{-1}) 2926, 2860, 1713, 1621, 1574, 1504, 1449, 1417, 1360, 1333, 1293, 1257, 1216, 1158, 1099, 1022, 937, 875, 800, 747, 695, 639, 585.

34: yellow oil; 11 mg (0.04 mmol, 11%); ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.60 (s, 1H), 6.94 (s, 1H), 5.16 (s, 1H), 5.05 (s, 1H), 3.96 (d, J = 2.0 Hz, 2H), 3.42 (m, 2H), 2.31−2.26 (m, 9H), 1.63 (s, 3H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$) δ 206.3, 198.1, 142.0, 135.6, 134.7, 134.2, 133.3, 128.6, 108.1, 94.2, 49.3, 47.9, 30.2, 22.2, 20.0, 19.7; HRMS (ESI, m/z) calcd for $C_{16}H_{20}O_5$+H^+ 293.1384, found 293.1383; IR (film, cm^{-1}) 2922, 2889, 1717, 1679, 1613, 1557, 1503, 1449, 1439, 1416, 1374, 1352, 1322, 1258, 1219, 1200, 1160, 1119, 1106, 1090, 1056, 1024, 967, 939, 889, 852, 802, 774, 749, 722, 696, 640, 587, 513.

*1-(1-Hydroxy-3,6,7-trimethylnaphthalene-2-yl)ethanone (**35**).* After ozonolysis of diene **20** (0.25 mmol) in dichloromethane (12 mL), following the GP 6 for the ozonolysis reaction, triphenylphosphine (1.22 mmol) was added and the reaction mixture was warmed to room temperature over an hour and stirred for additional 16 h. The solvent was removed in vacuo and HOAc (3 mL) was added. After stirring for 20 h, the suspension was neutralized with saturated aqueous Na_2CO_3 solution and the product was extracted with diethyl ether (3×), washed with water and brine, and dried over anhydrous magnesium sulfate. Silica gel was added and after evaporation of the solvent the residue was purified by flash column chromatography. Pale yellow solid; 39 mg (0.17 mmol, 67%); eluent: pentane:diethyl ether = 10:1; mp = 167−170 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 14.73 (s, 1H), 8.13 (s, 1H), 7.36 (s, 1H), 6.95 (s, 1H), 2.72 (s, 3H), 2.67 (s, 3H), 2.42 (s, 3H), 2.41 (s, 3H); ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$) δ 205.5, 164.0, 140.8, 135.4, 135.1, 132.6, 126.4, 124.3, 123.0, 120.4, 115.1, 33.1, 25.5, 20.6, 20.3; HRMS (ESI, m/z) calcd for $C_{15}H_{16}O_2$-H^+ 227.1067, found 227.1079; IR (film, cm^{-1}) 2967, 2945, 2920, 1630, 1600, 1572, 1491, 1472, 1445, 1412, 1374, 1360, 1325, 1263, 1251, 1229, 1197, 1141, 1086, 1037, 1024, 1003, 980, 918, 888, 678, 641.

*1-Hydroxy-3,6,7-trimethyl-2-naphthaldehyde (**37**).* After ozonolysis of diene **17** (0.30 mmol) in dichloromethane (15 mL), following the GP 6 for the ozonolysis reaction, triphenylphosphine (1.20 mmol) was added and the reaction mixture was warmed to room temperature over an hour and stirred for additional 4 h. The solvent was removed in vacuo and the residue was purified by flash column chromatography. Pale yellow solid; 39 mg (0.18 mmol, 61%); eluent: pentane:ethyl acetate = 10:1; mp = 172−175 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 13.68 (s, 1H), 10.25 (s, 1H), 8.11 (s, 1H), 7.40 (s, 1H), 6.92 (s, 1H), 2.64 (s, 3H), 2.42 (s, 6H); ^{13}C{^{1}H} NMR (75 MHz, $CDCl_3$) δ 194.9, 163.8, 141.6, 137.1, 135.3, 133.7, 127.0, 124.1, 122.7, 119.0, 113.3, 120.7, 20.2, 19.0; HRMS (ESI, m/z) calcd for $C_{14}H_{14}O_2$+H^+ 215.1067, found 215.1070; IR (film, cm^{-1}) 2922, 2895, 2853, 1626, 1567, 1491, 1462, 1428, 1403, 1390, 1372, 1322, 1257, 1236, 1219, 1199, 1170, 1126, 1064, 1026, 1003, 944, 885, 813, 689.

*2-Hydroxy-2,5,8,9-tetramethyl-2H-benzo[h]chromen-4(3H)one (**39**) and 2,5,8,9-tetra-methyl-4H-benzo[h]chromen-4-one (**40**).* After ozonolysis of triene **22** (0.19 mmol) in dichloromethane (15 mL), following the GP 6 for the ozonolysis reaction, triphenylphosphine (1.40 mmol) was added and the reaction mixture was warmed to room temperature over a period of an hour and stirred for additional 16 h. The solvent was removed in vacuo and HOAc (3.0 mL) was added. After stirring for 18 h the suspension was neutralized with saturated aqueous Na_2CO_3 solution and the product was extracted with dichloromethane (3×), washed with water and brine, and dried over anhydrous magnesium sulfate. Silica gel was added and after evaporation of the solvent the residue was purified by flash column chromatography. **39**: pale yellow solid; 30 mg (0.11 mmol, 58%); eluent: pentane:diethyl ether = 1:1; mp = 160−164 °C (decomp.); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.98 (s, 1H), 7.41 (s, 1H), 7.06 (s, 1H), 3.16 (br s, 1H), 3.02 (d, J = 16.0 Hz, 1H), 2.93 (d, J = 16.0 Hz, 1H), 2.71 (s, 3H), 2.42 (s, 3H), 2.41 (s, 3H) 1.83 (s, 3H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$) δ 192.6, 157.2, 140.0, 135.9, 135.2, 134.7, 126.8, 123.1, 122.6, 121.9, 114.1, 101.3, 49.3, 28.3, 23.2, 20.5, 20.3; HRMS (ESI, m/z) calcd for $C_{17}H_{18}O_3$+H^+ 271.1329, found 271.1328; IR (film, cm^{-1}) 3362, 2970, 2923, 1658, 1602, 1565, 1444, 1403, 1323, 1265, 1234, 1179, 1154, 1057, 1026, 993, 881, 830, 735, 680, 613; **40**: pale yellow solid; 5 mg (0.02 mmol, 10%); eluent: pentane:diethyl ether = 1:1; mp = 138−141 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.13 (s, 1H), 7.52 (s, 1H), 7.32 (s, 1H), 6.21 (s, 1H), 2.90 (s, 3H), 2.48 (s, 3H), 2.47 (s, 3H), 2.46 (s, 3H); ^{13}C{^{1}H} NMR (101 MHz, $CDCl_3$) δ 180.5, 163.4, 155.1, 139.5, 135.9, 134.4, 134.1, 126.9, 125.0, 122.0, 121.6, 118.8, 113.2, 23.3, 20.51, 20.49, 20.1; MS (EI) m/z (%) 252 (100, M^+), 237 (7), 224 (12), 212 (34), 209 (12), 169 (10), 165 (15), 152 (16), 141 (28), 128 (14), 115 (27), 91 (7), 77 (10); HRMS (EI, m/z) calcd for $C_{17}H_{16}O_2$ 252.1150, found 252.1153; IR (film, cm^{-1}) 2962, 2921, 2856, 1654, 1617, 1496, 1449, 1401, 1358, 1319, 1260, 1203, 1169, 1094, 1046, 1025, 955, 909, 882, 847, 801, 697, 659, 613.

*1-(3-Acetyl-4-hydroxy-6,7-dimethylnaphthalene-2-yl)propan-2-one (**41**).* After ozonolysis of triene **21** (0.20 mmol) in dichloromethane (12 mL), following the GP 6 for the ozonolysis reaction, triphenylphosphine (1.50 mmol) was added and the reaction mixture was warmed to room temperature over an hour and stirred for additional 15 h. The solvent was removed in vacuo and HOAc (2.0 mL) was added. After stirring for 21 h, the suspension was neutralized with saturated aqueous Na_2CO_3 solution and the product was extracted with diethyl ether (3×), washed with water and brine, and dried over anhydrous magnesium sulfate. Silica gel was added and after evaporation of the solvent the residue was purified by flash column chromatography. Orange solid; 40 mg (0.15 mmol, 74%); eluent: pentane:ethyl acetate = 4:1; mp = 162−165 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 14.33 (s, 1H), 8.16 (s, 1H), 7.41 (s, 1H), 6.96 (s, 1H), 4.11 (s, 2H), 2.61 (s, 3H), 2.43 (s, 3H), 2.42 (s, 3H), 2.17 (s, 3H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$) δ 206.6, 204.6, 163.5, 141.0, 136.1, 135.0, 128.8, 126.9, 124.3, 123.7, 122.1, 115.0, 52.3, 32.0, 29.5, 20.5, 20.3; HRMS (ESI, m/z) calcd for $C_{17}H_{18}O_3$+Na^+ 293.1148, found 293.1155; IR (film, cm^{-1}) 3003, 2916, 2923, 1712, 1628, 1601, 1447, 1410, 1362, 1326, 1258, 1187, 1159, 1056, 1022, 973, 927, 888, 822, 660, 607, 542, 487, 449.

*1-Hydroxy-6,7-dimethyl-3-(2-oxopropyl)-2-naphthaldehyde (**42**).* After ozonolysis of triene **18** (0.22 mmol) in dichloromethane (8 mL), following the GP 6 for the ozonolysis reaction, triphenylphosphine (0.99 mmol) was added and the reaction mixture was warmed to room temperature over a period of an hour. The solvent was removed in vacuo and HOAc (5 mL) and Zn powder (2.20 mmol) were added. After stirring for 1 h, the suspension was neutralized with saturated aqueous Na_2CO_3 solution, the product was extracted with ethyl acetate (3×) and dried over anhydrous magnesium sulfate. Silica gel was added and after evaporation of the solvent the residue was purified by flash column chromatography. Yellow solid; 45 mg (0.18 mmol, 79%); eluent: pentane:ethyl acetate = 3:1; mp 180−185 °C (decomp.); ^{1}H NMR (500 MHz, DMSO-d^6) δ 13.38 (s, 1H), 10.00 (s, 1H), 8.05 (s, 1H), 7.58 (s, 1H), 7.08 (s, 1H), 4.27 (s, 2H), 2.41 (s, 3H), 2.40 (s, 3H), 2.25 (s, 3H); ^{13}C{^{1}H} NMR (126 MHz, DMSO-d^6) δ 206.4, 196.5, 161.7, 141.2, 135.9, 135.7, 131.7, 127.0, 122.9, 122.1, 120.2,

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113.1, 46.5, 29.8, 20.0, 19.8; HRMS (ESI, m/z) calcd for $C_{16}H_{16}O_3$+Na^+ 279.0992, found 279.0989; IR (film, cm^{-1}) 2916, 1708, 1610, 1566, 1491, 1436, 1401, 1372, 1307, 1263, 1230, 1195, 1161, 1127, 1059, 1021, 944, 894, 867, 834, 809, 713, 690, 662, 613, 588, 553, 517.

*Trioxaadamantane **45** and **46**.* After ozonolysis of tetraene 7 (0.19 mmol) in dichloromethane (12 mL), following the GP 6 for the ozonolysis reaction, triphenylphosphine (2.00 mmol) was added and the reaction mixture was warmed to room temperature over an hour and was stirred for additional 16 h. The solvent was removed in vacuo and the residue was purified by flash column chromatography. **45**: Orange solid; 20 mg (0.06 mmol, 31%); eluent: pentane:ethyl acetate = 4:1 → 3:2; mp 138−140 °C (decomp.); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.78 (s, 1H), 7.31 (s, 1H,), 7.05 (s, 1H), 3.20 (d, J = 15.9 Hz, 1H), 2.93 (d, J = 16.0 Hz, 1H), 2.76 (d, J = 1.7 Hz, 1H), 2.31 (s, 3H), 2.28 (s, 3H), 1.94 (d, J = 12.2 Hz, 1H), 1.90 (d, J = 12.0 Hz, 1H), 1.60 (d, J = 12.9 Hz, 1H), 1.56 (dd, J = 12.9, 1.8 Hz, 1H), 1.45 (s, 3H), 1.37 (s, 3H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$) δ 198.6, 145.8, 137.0, 136.4, 131.1, 128.7, 128.3, 99.3, 98.6, 95.3, 75.6, 54.6, 43.6, 40.9, 36.9, 26.9, 26.8, 20.4, 19.5; HRMS (ESI, m/z) calcd for $C_{19}H_{22}O_5$+Na^+ 353.1359, found 353.1354; IR (film, cm^{-1}) 3406, 2991, 2939, 1665, 1609, 1416, 1386, 1349, 1323, 1258, 1210, 1181, 1123, 1031, 970, 892, 851, 833; **46**: orange solid; 6 mg (0.017 mmol, 9%); eluent: pentane:ethyl acetate = 4:1 → 3:2; mp 125−129 °C (decomp.); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.80 (s, 1H), 7.03 (s, 1H), 5.85 (s, 1H), 3.02 (s, 2H), 2.69 (d, J = 1.9 Hz, 1H), 2.31 (s, 3H), 2.29 (s, 3H), 1.92 (d, J = 12.3 Hz, 1H,), 1.85 (d, J = 12.3 Hz, 1H), 1.84 (dd, J = 12.3, 2.0 Hz, 1H), 1.71 (d, J = 12.3 Hz, 1H), 1.48 (s, 3H,), 1.28 (s, 3H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$) δ 197.7, 145.8, 137.6, 136.1, 130.8, 128.7, 128.2, 99.4, 98.9, 95.2, 75.3, 54.5, 42.5, 41.5, 39.3, 26.83, 26.79, 20.4, 19.5; HRMS (ESI, m/z) calcd for $C_{19}H_{22}O_5$+Na^+ 353.1359, found 353.1355; IR (film, cm^{-1}) 3415, 2991, 2934, 2859, 1658, 1607, 1492, 1448, 1387, 1343, 1306, 1274, 1218, 1187, 1157, 1114, 1045, 1014, 974, 951, 899, 864, 833, 797, 735, 710, 636, 603, 566.

*2,8,9-Trimethyl-5-(2-oxopropyl)-4H-benzo[h]chromen-4-one (**48**).* After ozonolysis of tetraene 7 (0.16 mmol) in dichloromethane (15 mL), following the GP 6 for the ozonolysis reaction, triphenylphosphine (1.56 mmol) was added, and the reaction mixture was warmed to room temperature over a period of an hour and stirred for additional 14 h. The solvent was removed in vacuo; HOAc (4 mL) was added and stirred for 4 d. The suspension was neutralized with saturated aqueous Na_2CO_3 solution; the product was extracted with dichloromethane (3×) and dried over anhydrous magnesium sulfate. Silica gel was added and after evaporation of the solvent, the residue was purified by flash column chromatography. Pale yellow solid; 15 mg (0.05 mmol, 32%); eluent: pentane:ethyl acetate = 4:1 → ethyl acetate; mp = 138−141 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.16 (s, 1H), 7.56 (s, 1H), 7.28 (s, 1H), 6.17 (d, J = 0.6 Hz, 1H), 4.30 (s, 2H), 2.49 (s, 3H,), 2.47 (d, J = 0.6 Hz, 3H), 2.46 (s, 3H), 2.39 (s, 3H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$) δ 206.3, 179.7, 164.0, 155.3, 139.8, 136.8, 134.0, 130.0, 127.3, 127.2, 122.4, 122.1, 117.8, 112.8, 50.2, 30.1, 20.54, 20.50, 20.1; MS (EI) m/z (%) 294 (23, M^+), 277 (20), 252 (100), 212 (11), 165 (9), 152 (13), 141 (7), 128 (7), 115 (9), 77 (7); HRMS (EI, m/z) calcd for $C_{19}H_{18}O_3$ 294.1256, found 294.1263; IR (film, cm^{-1}) 21, 1719, 1654, 1621, 1455, 1389, 1361, 1322, 1203, 1164, 1146, 1049, 1024, 1002, 980, 900, 850, 733, 708, 693, 628, 618, 546.

*3,3′-Diacetyl-4,4′-dihydroxy-2,2′,6,6′,7,7′-hexamethyl-9,9′-bianthracen-10,10′(9H,9′H)-dione (**47**).* After ozonolysis of tetrane 7 (0.20 mmol) in dichloromethane (12 mL), following the GP 6 for the ozonolysis reaction, triphenylphosphine (2.00 mmol) was added and the reaction mixture was warmed to room temperature over an hour and stirred for additional 16 h. The solvent was removed in vacuo and the residue was dissolved in methanol (10 mL), $Ca(OAc)_2$ (0.90 mmol) was added and the reaction mixture was stirred for 4 d. The suspension was acidified with 2 M HCl and the product was extracted with dichloromethane (2×) and dried over anhydrous magnesium sulfate. Silica gel was added and, after evaporation of the solvent, the residue was purified by flash column chromatography. Orange solid; 23 mg (0.04 mmol, 40%); eluent: pentane:ethyl acetate = 4:1; mp = 168−170 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 13.01 (s, 1H), 12.95 (s, 1H), 7.74 (s, 2H,), 6.80 (s, 1H), 6.53 (s, 1H), 6.20 (s, 1H), 5.89 (s, 1H), 4.41 (s, 2H), 2.60 (s, 3H), 2.59 (s, 3H), 2.35 (s, 6H), 2.33 (s, 3H) 2.27 (s, 3H), 2.26 (s, 3H) 2.17 (s, 3H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$) δ 203.9, 203.8, 187.8, 187.7, 160.1, 159.9, 143.6, 143.3, 143.2, 143.1, 142.2, 141.7, 137.8, 137.6, 137.3, 137.1, 130.7, 130.3, 129.84, 129.77, 129.15, 129.08, 126.9, 126.7, 121.9, 115.7, 115.1, 54.9, 54.8, 32.29, 32.25, 20.4, 20.31, 20.26, 19.7, 19.6; HRMS (ESI, m/z) calcd for $C_{38}H_{34}O_6$−H^+ 585.2283, found 585.2284; IR (film, cm^{-1}) 2923, 2853, 1697, 1630, 1603, 1561, 1485, 1453, 1387, 1348, 1315, 1289, 1259, 1220, 1202, 1185, 1148, 1078, 1023, 959, 945, 895, 823, 739, 600, 545.

General Procedure 8 for the Synthesis of Anthraquinones (GP 8). After ozonolysis of the tetraene (0.20 mmol) in dichloromethane (15 mL), following the GP 6 for the ozonolysis reaction, triphenylphosphine (2.00 mmol) was added and the reaction mixture was warmed to room temperature over an hour and additionally stirred for 20 h. The solvent was removed in vacuo and the residue was dissolved in *i*PrOH (12.0 mL) and dichloromethane (2.0 mL), K_2CO_3 (2.00 mmol) was added and the reaction mixture was stirred for 18 h at room temperature. The suspension was acidified with 2 M HCl and the product was extracted with dichloromethane (2×) and dried over anhydrous magnesium sulfate. Silica gel was added and after evaporation of the solvent the residue was purified by flash column chromatography.

*2-Acetyl-1-hydroxy-3,6,7-trimethylanthracen-9,10-dione (**9**).* Orange solid; 18 mg (0.06 mmol, 29%); eluent: pentane:ethyl acetate = 10:1 → 5:1; mp = 171−173 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 12.99 (s, 1H), 8.01 (s, 1H), 8.00 (s, 1H), 7.63 (s, 1H), 2.61 (s, 3H), 2.43 (s, 6H), 2.39 (s, 3H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$) δ 203.4, 188.8, 182.5, 159.8, 145.3, 144.9, 144.7, 136.0, 133.4, 131.7, 131.3, 128.8, 128.1, 121.7, 114.7, 32.1, 20.6, 20.52, 20.47; HRMS (ESI, m/z) calcd for $C_{19}H_{16}O_4$+Na^+ 331.0941, found 331.0943; IR (film, cm^{-1}) 2923, 2854, 1681, 1631, 1594, 1561, 1477, 1442, 1384, 1346, 1285, 1251, 1226, 1156, 1097, 1031, 969, 909, 832, 805, 766, 740, 556.

*2-Acetyl-1-hydroxy-3,6-dimethylanthracen-9,10-dione (Kwanzoquinone A) (**44**).* Orange solid; 18 mg (0.06 mmol, 33%); eluent: pentane:ethyl acetate = 4:1 → ethyl acetate; mp = 182−185 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 12.99 (s, 1H), 8.18 (d, J = 7.9 Hz, 1H), 8.07 (s, 1H), 7.64 (s, 1H), 7.60 (d, J = 7.9 Hz, 1H), 2.61 (s, 3H), 2.54 (s, 3H), 2.39 (s, 3H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$) δ 203.2, 188.3, 182.5, 159.8, 146.4, 144.9, 136.0, 135.3, 133.5, 133.2, 131.0, 128.0, 127.3, 121.7, 114.5, 32.0, 22.1, 20.4; MS (EI) m/z (%) 294 (39, M^+), 279 (100), 195 (6), 165 (9), 152 (13); HRMS (ESI, m/z) calcd for $C_{18}H_{14}O_4$+Na^+ 317.0784, found 317.0781; IR (film, cm^{-1}) 2921, 1688, 1670, 1634, 1602, 1561, 1477, 1358, 1321, 1300, 1268, 1243, 1222, 1199, 1143, 1050, 960, 884, 853, 817, 768, 736, 602.

The analytical data for the compound are in accordance with the literature.[24]

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

^{1}H and ^{13}C{^{1}H} NMR spectra for selected compounds and crystallographic data. This material is available free of charge via the Internet at http://pubs.acs.org. The crystal structures have been deposited at the Cambridge Crystallographic Data Centre and allocated the deposition number CCDC 1027957 and CCDC 1027958.

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Notes

The authors declare no competing financial interest.

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