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Hydroarylation of Alkenes by Protonation/Friedel−Crafts Trapping: HFIP-Mediated Access to Per-aryl Quaternary Stereocenters

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Supporting Information

ABSTRACT: Upon treatment with a combination of HFIP and an organic sulfonic acid, alkenes behave as Brønsted bases and protonate to give carbocations which can be trapped by electron-rich arenes. The reaction constitutes a Friedel−Crafts hydroarylation which proceeds with Markovnikov selectivity and is orthogonal to traditional metal-catalyzed processes. Intermolecular transfer hydrogenation and hydrothiolation under analogous conditions are also demonstrated.

Alkenes are a ubiquitous functional group (FG), the installation of which can be achieved using a suite of venerable methods including carbonyl alkenylation, alkene metathesis, C−C cross-coupling, alkyne reduction, and elimination reactions.[1] However, functionalization of alkenes, for example, via addition reactions, generally requires harsh conditions or the application of an organometallic species promoted by transition metals or Lewis acids (e.g., Scheme 1).[2] Exceptions are intramolecular reactions and/or reactions of alkenes polarized by conjugation to heteroatoms (e.g., Scheme 1c−e). This situation reflects the intrinsically strong and unpolarized nature of the C−C double bond. The ability to selectively functionalize alkenes by a hydroarylation protocol, which could operate under relatively mild conditions, in the absence of overt substrate bias and, moreover, tolerate preinstalled halide substituents for subsequent transition metal oxidative-addition-initiated coupling protocols, would constitute a useful addition to the synthetic chemist's reaction arsenal.

We recently reported the use of HFIP to stabilize benzylic carbocations in an oxonium-Prins approach to the synthesis of furanochromanes.[3] We considered applying similar reaction conditions to enable *inter*molecular alkene functionalization. More specifically, we reasoned that protonation of a styrenyl alkene to unveil an HFIP-stabilized benzylic carbocation could induce external trapping by an arene nucleophile. The result would be a Markovnikov-selective Friedel−Crafts (FC)-type hydroarylation. Although carbocations accessed from alcohols, epoxides, halides, and even by C−C bond cleavage are known to participate in FC reactions,[4−6] entry to this reaction manifold from alkenes is rare (see below) despite the aforementioned ready synthetic access to this structurally diverse FG. This situation reflects the two key challenges inherent in this reaction design: first, protonation of an intrinsically poorly Brønsted basic alkene, and second, trapping of the fleeting resultant carbocation with an external nucleophile before alternative pathways intervene, such as dimerization,[7,8] polymerization,[9] and degenerate collapse back to the alkene.

Alkene hydroarylation has been achieved using Pd(0) catalysis with aryl iodides and more recently using Ni(0) catalysis with organoboron derivatives.[10−12] A Ni/Fe radical approach has also been used to allow arylation (and even alkylation) with aryl (or alkyl) iodides.[13,14] However, alkene hydroarylation using non-prefunctionalized arenes (i.e., simple arenes without halogen or other reactive handles) has generally been achieved using metal-based Lewis acid promotors or metal-based C−H insertion/hydroarylation approaches (Scheme 1a).[15−24] Previous reports of Brønsted acid catalyzed intermolecular alkene hydroarylation fall into two categories. Monosubstituted styrenes can be arylated upon exposure to strong acids for extended periods at increased temperatures (e.g., refluxing TfOH, 20 h; Scheme 1b).[20,25−31] Alternatively, alkenes that are polarized by conjugation to heteroatoms and therefore readily protonate at carbon [e.g., enamines, enol ethers, *ortho*/*para*-quinone methide (imine)s (*o*/*p*QM(I)s)] may be arylated under milder conditions.[32] Pertinent recent (asymmetric) examples of this latter class include Sun's arylation of a *p*QM formed by chiral phosphoric acid (CPA)-catalyzed dehydration (Scheme 1c),[33] Tang's arylation of an *o*QMI formed by protonation (Scheme 1d),[34] and Liu's arylation of a styrene-derived *p*QM via benzylic radical formation/oxidation (Scheme 1e).[35] However, in all of these

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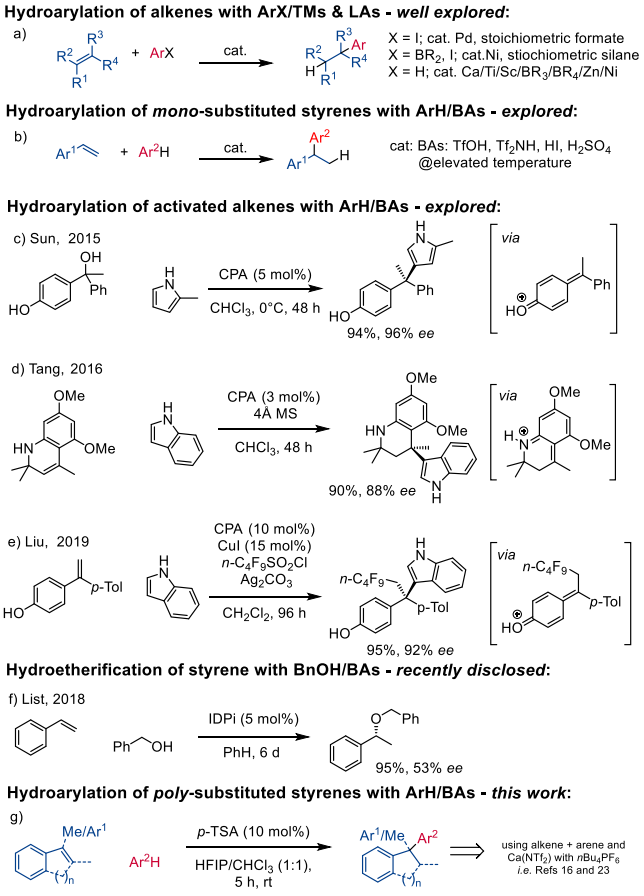
Scheme 1. Context of the Reaction[a]



[a]TM = transition metal complex catalyst, LA = Lewis acid catalyst, BA = Brønsted acid catalyst, CPA = chiral phosphoric acid, IDPi = imidodiphosphorimidate.

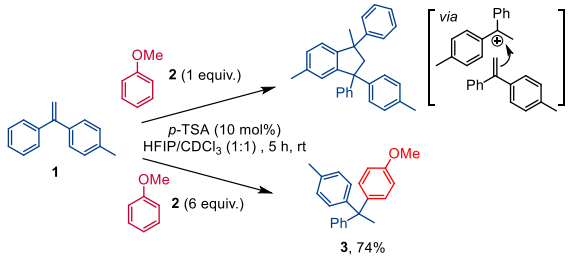
CPA-mediated transformations, the only arene nucleophiles able to successfully trap the cationic intermediates were indoles and pyrroles due to their ability to H bond with the CPA promotors.

Although not a hydroarylation, List has recently demonstrated that non-heteroatom-conjugated 1,1-disubstituted alkenes can undergo proton-induced intramolecular hydroetherification mediated by a highly acidic imidodiphosphorimidate (IDPi) catalyst to give tetrahydrofurans[36] and, tantalizingly, disclosed a single intermolecular variant—the coupling of benzyl alcohol with styrene (Scheme 1f).

Herein, we disclose a mild and operationally simple method to activate and intermolecularly arylate multiply substituted styrenyl alkenes using an aryl sulfonic acid catalyst (Scheme 1g). Key to this protocol is the use of HFIP to stabilize the intermediate carbocations.[37] The conditions contrast with the aforementioned previous Brønsted acid catalyzed protocols, which required harsh conditions and were only applicable to monosubstituted styrenes. The conditions also provide a straightforward and likely mechanistically distinct approach to this type of transformation relative to the Lewis acid/metal-catalyzed protocols of Niggemann[16] and Lebœuf.[23]

We initiated our investigation with 1-*para*-tolyl-1-phenylethylene **1** as the alkene (latent electrophile) and anisole **2** as the arene (nucleophile). To trigger protonation, we used *p*-TSA·H_2O as it is a cheap and easy to handle solid that is soluble in HFIP. We saw quantitative alkene dimerization when employing 1 equiv of anisole (Scheme 2).[7,8] No reaction was observed if isopropyl alcohol was exchanged for HFIP.

Scheme 2. Initial Attempts at Alkene Protonation and Arylation (Isolated Yield)

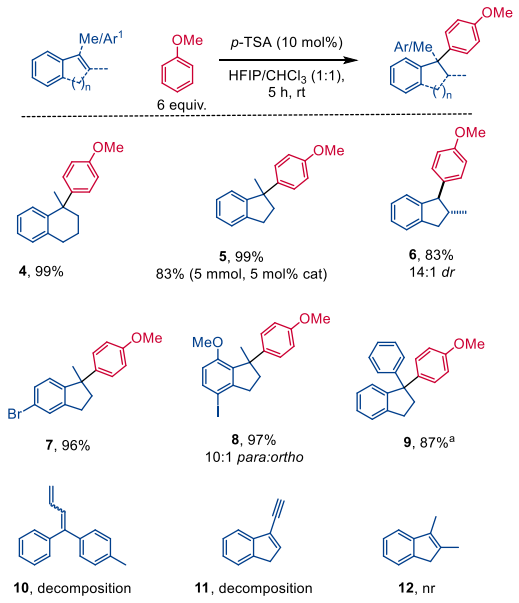


Undaunted, and drawing inspiration from the pioneering work of Jacobsen in which benzylic carbocations were successfully trapped by excess allyltrimethylsilane (6 equiv),[38] we increased the equivalents of anisole. Gratifyingly, this led to the formation of the desired triarylethane **3** in 74% yield when using 6 equiv of anisole; just trace amounts of the dimer were formed under these conditions (Scheme 2). We tested (*S*)-TRIP and a 3,5-$(CF_3)_2$-substituted IDP (imidophosphate) catalyst in an attempt to exert stereoselectivity, but no products of alkene protonation were observed.[39]

The reaction could be run open to air and did not require dried solvents. Use of $CDCl_3$ as cosolvent allowed reaction tracking by ^{1}H NMR. To explore the structural scope of this reaction, we tested a range of nonterminal styrenes (Scheme 3).

A range of substituted alkenes were found to be amenable to arylation, giving products **4**–**9**. Both indane and tetralin derivatives were hydroarylated in excellent yield. 1,2-Disubstituted indane **6** was formed with high stereo- and regioselectivity, as the result of *trans*-selective trapping following protonation to give the *sec*-benzylic carbocation as

Scheme 3. Reaction Scope with Respect to the Alkene (Isolated Yields)



[a]24 h.

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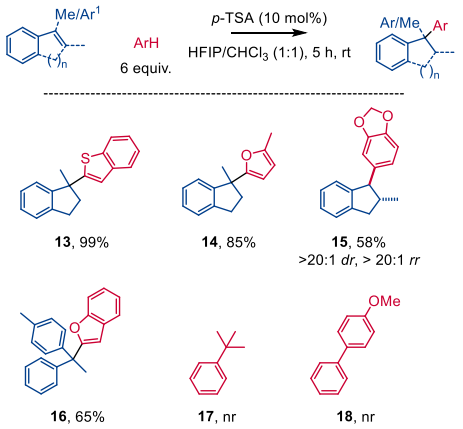
opposed to the alternative tertiary carbocation. The reaction was tolerant of a bromine substituent situated *para* to the incipient carbocation (→**7**) and an iodide substituent *meta* to the incipient carbocation (→**8**). The bromine and iodine functions in compounds **7** and **8** are of potential utility for further functionalization, and the syntheses of these compounds via the aforementioned metal-catalyzed hydroarylation protocols would be challenging by virtue of requiring chemoselective oxidative insertion into one halogenated substrate over the other. Compounds **3**–**7** were formed with complete *para* selectivity with respect to the anisole methoxy substituent, but for compound **8**, a small amount of the *ortho* isomer was also formed. Triaryl **9** was formed in good yield and with high *para* selectivity, albeit at extended reaction times (24 h). Neither 1,3-diene **10** nor enyne **11** was a competent substrate, affording just alkene decomposition. Attempted hydroarylation of tetrasubstituted alkene **12** was also unsuccessful, due to lack of any reaction under the standard or more forcing conditions.

Next, we explored variation of the nucleophilic arene component (Scheme 4).

Scheme 4. Reaction Scope with Respect to the Arene (Isolated Yields)

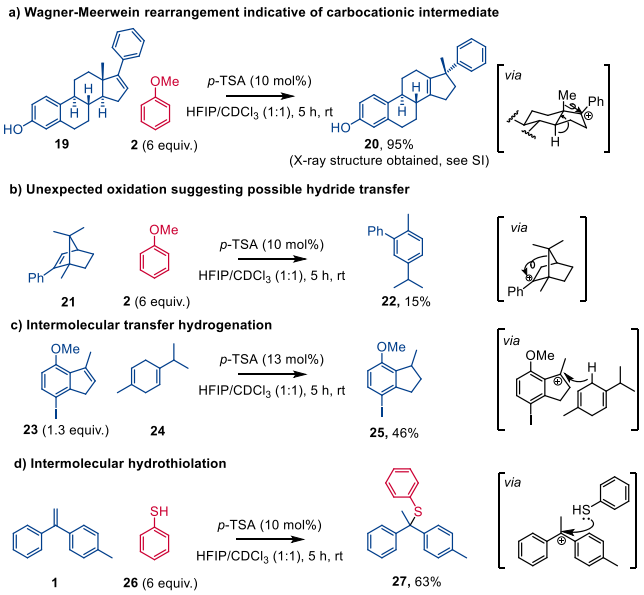


Benzothiophene was successfully installed to give compound **13** in near quantitative yield, which could potentially undergo further elaboration to difunctionalized benzothiophenes via interrupted Pummerer chemistry.[40] 2-Methylfuran, which is prone to polymerization, was successfully coupled with the 1-methylindene to give furan derivative **14**. 1,3-Benzodioxole, a common motif within natural products, could be installed with high stereo- and regioselectivity to give biaryl **15** as the single isolated product. Finally, benzofuran could be coupled with alkene **1** to yield the 1,1,1-triarylethane **16**. The C3 alkylation of both benzothiophene and benzofuran observed is in accordance with literature under such cationic conditions.[41]

Notable limitations of this method are the need to use an electron-rich aryl as the nucleophilic component—less electron-rich π-systems, such as *tert*-butylbenzene **17** and 4-methoxybiphenyl **18**, led to alkene decomposition or no reaction. Moreover, basic groups such as amides are generally not tolerated in the superstoichiometric arene nucleophile, presumably because they present lone pairs that can act as a kinetic dead end for preferential protonation over the alkene. Additionally, indoles were not suitable, making this method complementary to the previously described methods (Scheme 1c–e).

As a potential diagnostic test of the intermediacy of carbocations in these reactions, we sought to prepare a substrate for which a cationic intramolecular rearrangement could intercept the cation. As such, the estrone derivative **19** was prepared in which the adjacent quaternary center is primed for a 1,2-alkyl shift. Consistent with the formation of an intermediate carbocation, the tetrasubstituted alkene **20**, arising from subsequent migration and elimination, was obtained from this substrate upon subjection to the standard hydroarylation conditions using anisole as a potential trapping nucleophile (Scheme 5a).

Scheme 5. Carbocation Rearrangements, Transfer Hydrogenation, and Hydrothiolation (Isolated Yields)



Intrigued by the potential of this tactic, we reasoned the camphor derivative **21** would also be prone to rearrangement. Indeed, upon subjection to our standard conditions, complete consumption of this substrate was observed with isolation of the rearranged and aromatized phenyl-substituted cymene derivative **22** (Scheme 5b). We postulated that alkene **21** was likely undergoing disproportionation, and that a suitable hydride source might also enable such reductive transformations, such as Brønsted acid mediated transfer hydrogenation. Such a transfer hydrogenation reaction would be orthogonal to known metal-catalyzed protocols.[42] Pleasingly, use of γ-terpinene **24** as the hydride source and iodoindane **23** as alkenyl substrate led to the desired alkane **25** with the sensitive aryl iodide moiety still intact (Scheme 5c). Intramolecular 1,5-hydride transfer has been achieved by Chiba and Xiao using Brønsted acid catalysis,[43−45] but to the best of our knowledge, this is the first example of a Brønsted acid catalyzed intermolecular transfer hydrogenation. Whereas there are a plethora of reports of intermolecular hydride transfer to carbonyls and imines from Hantzsch esters,[46] this HFIP-mediated reaction is notable because alkene **23** is a poor electrophile and skipped diene **24** is a poor hydride donor as judged by their respective Mayr coefficients.[47]

Finally, we considered the use of a thiol as a carbocation scavenger. Application of our standard reaction conditions

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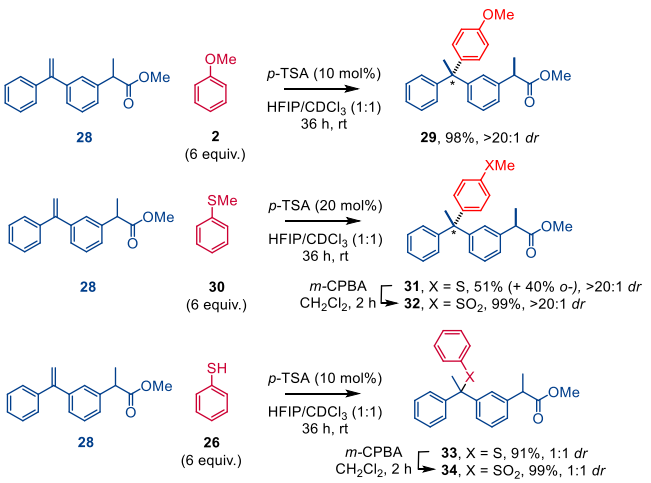
resulted in hydrothiolation of the alkene and formation of the C−S quaternary bond in **27** (Scheme 5d). It is noteworthy that organocatalytic C−S bond formation has previously been restricted to alkenes activated in an analogous manner to those for previous arylation strategies.[48,49] Indeed, the formation of such S-containing quaternary centers by nucleophilic addition has previously relied upon conjugate additions and Mannich-type reactions.[50]

To illustrate how this new hydroarylation procedure can be used to enable rapid access to more complex and synthetically useful structures, we prepared a triaryl analogue **29** from alkene **28**, which is a derivative of the nonsteroidal anti-inflammatory (NSAID) drug ketoprofen (Scheme 6).

Scheme 6. Functionalization of a Ketoprofen Derivative (Isolated Yields)[a]



[a]The asterisk (*) is undefined stereochemistry.

Surprisingly, the product was formed as a single diastereomer. Related remote induction C−C bond-forming reactions have been reported previously, particularly for reactions involving strongly polarized transition states.[51,52] Using thioansiole (**30**) as the nucleophile resulted in a similarly selective transformation to give thioether derivative **31**, but switching the nucleophile to thiophenol (**26**) delivered the expected hydrothiolated product **33** as a 1:1 mixture of diastereomers. Both thioether-containing products underwent smooth oxidation with excess *m*-CPBA to give the corresponding sulfones **32** and **34**, respectively.

It is evident that the described platform for alkene activation under Brønsted acid catalysis gives rapid access to a variety of ketoprofen analogues. This method could expedite investigations toward the effect of electronic and spatial geometry on the medicinal properties of profens.[53] It is noteworthy that this substrate-selective activation of the alkene was achieved in the presence of the ester moiety. This perhaps suggests that the ability of HFIP to stabilize carbocations renders the alkene more basic than the ester under these conditions. Although such selective activation is rare, List has reported an IDPi-mediated intramolecular cycloetherifcation reaction in the presence of a sulfonamide with no involvement of HFIP.[36]

We have described a facile method for the Brønsted acid catalyzed intermolecular hydroarylation of styrenes. The reaction exploits the ability of HFIP to enhance the Brønsted basicity of a styrene by stabilizing the benzylic carbocation. Friedel−Crafts trapping by electron-rich arenes occurs at room temperature, open to air, and with short reaction times employing a cheap sulfonic acid. Conceptually, this work lays a general platform for Brønsted acid activation of alkenes by protonation and subsequent intermolecular functionalization by a nucleophile.[54]

Future work toward enantioselectivity and alternative reactivity are underway within our laboratory.

EXPERIMENTAL SECTION

General Directions. All reactions were performed under nitrogen using oven-dried glassware unless stated otherwise. Yields refer to chromatographically and spectroscopically (^{1}H NMR) homogeneous materials unless otherwise indicated. MeCN, CH_2Cl_2, THF, Et_2O, DMF, and toluene were dried and deoxygenated with a Grubbs PureSolv 400 solvent purification system. The moisture content of the solvents was monitored by Karl Fischer coulometric titration (Mettler-Toledo DL39). Reagents were used as purchased from commercial sources unless otherwise stated and used according to COSHH regulations. Flash chromatography (FC) was performed on silica gel (Merck Kieselgel 60 F254 230−400 mesh) unless otherwise stated. Melting points were determined on a Stanford Research System OptiMelt. Thin layer chromatography (TLC) was performed on Merck aluminum-backed plates precoated with silica (0.2 mm, 60 F254) which were visualized either by quenching of ultraviolet fluorescence (λ_{max} = 254 and 366 nm) or staining with potassium permanganate/Δ, bromocresol green/Δ, or phosphomolybdic acid/Δ TLC dips prepared according to general procedures. ^{1}H NMR spectra were recorded on a 400 or 500 MHz Bruker AMX-400/500 instrument. Chemical shifts (δH) are quoted in parts per million (ppm), referenced to the appropriate residual solvent peak. ^{13}C NMR spectra were recorded at 101 or 125 MHz on a Bruker AMX-400/500 instrument. Chemical shifts (δC) are quoted in parts per million (ppm), referenced to the appropriate residual solvent peak. Mass spectra were obtained from the Imperial College Mass Spectrometry Service with the use of TOF and magnetic analyzers for ESI and EI techniques, respectively. High-resolution mass spectra (HRMS) were recorded on either a VG platform II or VG AutoSpec spectrometer, with only molecular ions ($[MH]^+$, $[MNa]^+$, $[MNH_4]^+$, $[MH_2O]^+$, $[MH]^-$) and major peaks being reported.

(8S,9S,13S,14S)-13-Methyl-17-phenyl-7,8,9,11,12,13,14,15-octahydro-6H-cyclopenta[a]phenanthren-3-ol[55] ***(19).*** Following conditions as reported by White: estrone was acylated and subsequently converted to the vinyl triflate.[56] Cross-coupling was carried out according to conditions as reported by Aubé.[57] Acetate deprotection was carried out following the procedure of Marcos.[58] To a dry microwave vial were added estrone (270 mg, 1 mmol, 1 equiv), 4-dimethylaminopyridine (12.2 mg, 0.1 mmol, 0.1 equiv), and a stirrer bar. The vial was then capped and put under an atmosphere of N_2; the solids dissolved were in CH_2Cl_2 (2 mL) and cooled to 0 °C. Pyridine (400 μL, 5 mmol, 5 equiv) was added in one portion followed by dropwise addition of acetic anhydride (280 μL, 3 mmol, 3 equiv) by a syringe. The reaction was then allowed to warm to room temperature and stirred at this temperature overnight. After this, the reaction was quenched by addition of 1 M HCl (5 mL). The organic layer was extracted with EtOAc, dried over $MgSO_4$, and concentrated to a white solid (311.2 mg), which was used in the following step without further purification. In a dry microwave vial, acylated estrone (311.2 mg, 1 mmol, 1 equiv), 2,6-di-*tert*-butyl-4-methylpyridine (220 mg, 1.07 mmol, 1.07 equiv), and a stirrer bar were added. The vial was then capped and put under an atmosphere of N_2. CH_2Cl_2 (2 mL) was added, and trifluoromethanesulfonic anhydride (200 μL, 1.19 mmol, 1.19 equiv) was added dropwise. After 6 h, the reaction was quenched by addition of saturated $NaHCO_3$ (aq) (5 mL). The organic was extracted with CH_2Cl_2 and dried over $MgSO_4$. Purification by flash column chromatography with EtOAc (5%) in hexane afforded the desired vinyl triflate estrone as a white solid (352.6 mg, 0.79 mmol, 79%). In an oven-dried microwave vial $Pd(PPh_3)_4$ (22.8 mg, 0.02 mmol, 0.025 equiv), $PhB(OH)_2$ (105.1 mg, 0.87 mmol, 1.1 equiv),

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and a stirrer bar were added, and the vial was put under N_2. To this was added vinyl triflate estrone (353 mg, 0.79 mmol, 1 equiv) dissolved in THF (6 mL) by a syringe followed by saturated $NaHCO_3$ (aq), which had been degassed for 15 min prior. The reaction was then stirred at rt overnight. After this, the reaction was extracted with EtOAc, dried over $MgSO_4$, concentrated in vacuo, and pushed through a short plug of silica. The subsequent white powder was dissolved in MeOH and K_2CO_3 (109.0 mg, 0.79 mmol, 1 equiv) and stirred for 30 min. After this, the reaction was concentrated and extracted with CH_2Cl_2 to yield estrone derivative **19** as a white solid (139 mg, 0.42 mmol, 53%): ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.43−7.38 (m, 2H), 7.34−7.23 (m, 3H), 6.87−6.82 (m, 1H), 6.81 (d, J = 2.5 Hz, 1H), 5.94 (dd, J = 3.3, 1.8 Hz, 1H), 2.97−2.88 (m, 3H), 2.42−2.31 (m, 3H), 2.24−2.19 (m, 1H), 2.17−2.07 (m, 1H), 2.01−1.94 (m, 1H), 1.84−1.77 (m, 1H), 1.73−1.63 (m, 3H), 1.50−1.43 (m, 1H), 1.06 (s, 3H). Data are in agreement with those in the literature (phenolic O−H not seen).[55]

(1R,4S)-1,7,7-Trimethyl-2-phenylbicyclo[2.2.1]hept-2-ene[59] ***(21)***. Prepared according to a modified procedure of Klankermayer (commercial Grignard reagent was used as opposed to employing in situ preparation).[59] In a dry flask under N_2, (*R*)-camphor (304.24 mg, 2 mmol, 1 equiv) was dissolved in THF (6 mL) and cooled to 0 °C. To this was added PhMgCl (2 M in Et_2O) (1.5 mL, 3 M, 1.5 equiv) dropwise by a syringe. This was allowed to come to rt and stirred overnight. After this time, the reaction was quenched by H_2O and extracted with CH_2Cl_2, dried over $MgSO_4$, and concentrated to a clear oil. Under an atmosphere of N_2, the oil was subsequently dissolved in dry pyridine (1.5 mL), and thionyl chloride (100 μL) was added dropwise. This was stirred for 1 h before addition of NH_4Cl and extracted with Et_2O. Flash column chromatography yielded the desired compound **21** as a colorless liquid (220 mg, 1.03 mmol, 52%): ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.26−7.10 (m, 5H), 5.91 (d, J = 3.3 Hz, 1H), 2.31 (t, J = 3.3 Hz, 1H), 1.87 (m, 1H), 1.60 (m, 1H), 1.25 (m, 1H), 1.07 (d, J = 6.0 Hz, 1H), 1.04 (s, 3H), 1.02−0.99 (m, 1H), 0.82 (s, 3H), 0.75 (s, 3H). Data are in agreement with those in the literature.[59]

Methyl 2-(3-(1-Phenylvinyl)phenyl)propanoate[60] ***(28)***. Prepared according to the method of Allegretti.[53] Ketoprofen (576 mg, 2.27 mmol, 1 equiv) was dissolved in MeOH (50 mL, excess) and added 0.2 mL of concentrated H_2SO_4. This was stirred at room temperature overnight, after which evaporation yielded a thick oil (610 mg) which was used without further purification and carried directly to the next step (Wittig olefination). In a dry flask under N_2, PPh_3MeBr (812 mg, 2.27 mmol, 1 equiv) was dissolved in dry THF (8 mL). To this was added *n*-BuLi (1.2 M in hexanes, 2 mL, 2.4 mmol, 1.05 equiv) dropwise by a syringe. An immediate color change from cream to red was observed. This was allowed to stir for 5 min before dropwise addition of the ketoprofen methyl ester (610 mg, 2.27 mmol, 1 equiv) in dry THF (8 mL) by syringe. This was allowed to stir overnight and quenched by addition of saturated NH_4Cl (aq) (20 mL). The mixture was extracted with EtOAc, dried over $MgSO_4$, concentrated in vacuo, and purified by flash column chromatography to yield the desired compound **28** as a colorless oil (453 mg, 1.70 mmol, 75% yield): ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.27−7.24 (m, 5H), 7.21 (d, J = 0.9 Hz, 1H), 7.19 (q, J = 1.4 Hz, 2H), 7.14 (dt, J = 6.9, 1.8 Hz, 1H), 5.39 (q, J = 1.2 Hz, 2H), 3.64 (q, J = 7.1 Hz, 1H), 3.58 (s, 3H), 1.41 (d, J = 7.1 Hz, 3H). Data are in agreement with those in the literature.[60]

General Procedure 1: Ketone to Alkene Conversion. To an oven-dried round-bottom flask, the required ketone (1 equiv) was dissolved in anhydrous THF (0.3 M). To the resultant cooled (0 °C) and stirred solution was added 3.0 M MeMgCl or 2.0 M PhMgCl dropwise (1.2 equiv). After addition was complete, the reaction was allowed to warm to rt and was stirred for 4 h. The reaction was recooled to 0 °C and quenched by slow addition of saturated aqueous NH_4Cl. Organics were extracted with CH_2Cl_2. Combined organics were washed with brine, dried over anhydrous Na_2SO_4, and concentrated on a rotary evaporator. The resultant material was then carried directly into dehydration. For this, a solution of *p*-TSA·H_2O (5 mol %) in MeOH (0.2 M) was added to the resultant alcohol (1 equiv) and refluxed for 4 h. After this time, the reaction was concentrated, quenched by addition of $NaHCO_3$, and extracted with Et_2O. Combined organics were washed, dried over anhydrous Na_2SO_4, and concentrated on a rotary evaporator. Flash column chromatography (1% Et_2O in petroleum ether) afforded the required alkenes.

1-Methyl-4-(1-phenylvinyl)benzene[61] ***(1)***. Following the general procedure 1. Isolated as a colorless oil (82.6 mg, 0.425 mmol, 85%): ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.36−7.30 (m, 5H), 7.24 (d, J = 8.1 Hz, 2H), 7.18−7.11 (d, J = 8.1 Hz, 2H), 5.44 (d, J = 1.0 Hz, 1H), 5.41 (d, J = 1.0 Hz, 1H) 2.37 (s, 3H). Data are in agreement with those in the literature.[61]

4-Methyl-1,2-dihydronaphthalene.[62] Following the general procedure 1. Isolated as a colorless oil (52.6 mg, 0.365 mmol, 73%): ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.25−7.18 (m, 2H), 7.16−7.12 (m, 2H), 5.86 (ddt, J = 4.5, 3.0, 1.5 Hz, 1H), 2.77 (t, J = 8.2 Hz, 2H), 2.31−2.19 (m, 2H), 2.06 (q, J = 1.7 Hz, 3H). Data are in agreement with those in the literature.[62]

3-Methyl-1H-indene.[62] Following the general procedure 1. Isolated as a clear oil (127.6 mg, 0.98 mmol, 98%): ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.49−7.45 (m, 1H), 7.39−7.30 (m, 2H), 7.22 (tdd, J = 7.2, 2.8, 1.6 Hz, 1H), 6.22 (s, 1H), 3.44−3.15 (m, 2H), 2.28−2.04 (m, 2H). Data are in agreement with those in the literature.[62]

6-Bromo-3-methyl-1H-indene.[63] Following the general procedure 1. Isolated as a clear oil (82.6 mg, 0.395 mmol, 79%): ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.57 (d, J = 1.4 Hz, 1H), 7.46−7.39 (dd, J = 8.0, 1.4 Hz, 1H), 7.18 (d, J = 8.0 Hz, 1H), 6.19 (q, J = 2.0 Hz, 1H), 3.29 (t, J = 2.0, 2H), 2.14 (q, J = 2.0 Hz, 3H). Data are in agreement with those in the literature.[63]

7-Iodo-4-methoxy-3-methyl-1H-indene ***(23)***. Following the general procedure 1. Isolated as a white solid (118.7 mg, 0.415 mmol, 83%): mp 82 °C; ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.44 (d, J = 8.5 Hz, 1H), 6.58 (d, J = 8.5 Hz, 1H), 6.14−5.98 (d, J = 1.9 Hz, 1H), 3.83 (s, 3H), 3.23−3.11 (t, J = 2.1 Hz, 2H), 2.29 (app q, J = 1.9 Hz, 3H); ^{13}C{^{1}H} NMR (101 MHz, chloroform-*d*) δ 155.3, 151.0, 141.1, 134.7, 134.6, 127.8, 111.5, 82.3, 55.7, 43.5, 17.0; HRMS (EI) m/z $[M]^+$ calcd for $C_{11}H_{11}OI^+$ 285.9855; found 285.9862.

3-Phenyl-1H-indene.[64] Following the general procedure 1. Isolated as a clear oil (71 mg, 0.37 mmol, 74%): ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.64−7.59 (m, 3H), 7.55 (dt, J = 7.2, 1.0 Hz, 1H), 7.49−7.44 (m, 2H), 7.41−7.31 (m, 2H), 7.29−7.24 (m, 1H), 6.59 (t, J = 2.2 Hz, 1H), 3.52 (d, J = 2.2 Hz, 2H). Data are in agreement with those in the literature.[64]

General Procedure 2: Organocatalytic Hydroarylation. Alkene (0.1 mmol, 1 equiv) was weighed into a regular 2 mL glass vial. In a separate regular 2 mL glass vial, *p*-TSA·H_2O (1.9 mg, 0.01 mmol, 10 mol %) was weighed and solubilized in HFIP (0.2 mL), $CDCl_3$ (0.2 mL), and arene (0.6 mmol, 6 equiv) successively. This was then transferred to the vial containing alkene in one portion. The reaction was left to stand for 5 h before being quenched by addition of $NaHCO_3$ (0.5 mL), extracted with $CHCl_3$ (3×), and dried over Na_2SO_4. The titled compounds were isolated by flash column chromatography eluting 10−40% $CHCl_3$/hexane.

Procedure for Organocatalytic Transfer Hydrogenation. *4-Iodo-7-methoxy-1-methyl-2,3-dihydro-1H-indene* ***(25)***. 7-Iodo-4-methoxy-3-methyl-1*H*-indene (28.6 mg, 0.1 mmol, 1.3 equiv) was weighed into a regular 2 mL glass vial. In a separate regular 2 mL glass vial, *p*-TSA·H_2O (1.9 mg, 0.01 mmol, 13 mol %) was weighed and solubilized in HFIP (0.2 mL), $CDCl_3$ (0.2 mL), and γ-terpinene (12 μL, 0.075 mmol, 1 equiv) successively. This was then transferred to the vial containing the alkene in one portion. The reaction was left to stand for 5 h before being quenched by addition of $NaHCO_3$ (0.5 mL), extracted with $CHCl_3$ (3×), and dried over Na_2SO_4. The desired reduced compound was isolated by flash column chromatography eluting with 20% $CHCl_3$/hexane as a clear oil (10.1 mg, 0.0351 mmol, 47%): ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.47 (d, J = 8.5 Hz, 1H), 6.46 (d, J = 8.5 Hz, 1H), 3.79 (s, 3H), 3.55−3.47 (m, 1H), 3.00−2.91 (m, 1H), 2.87−2.69 (m, 1H), 2.30−2.20 (m, 1H), 1.73−1.65 (m, 1H), 1.21 (d, J = 7.0 Hz, 3H); ^{13}C{^{1}H} NMR (101 MHz, chloroform-*d*) δ 156.7, 149.2, 137.4, 136.6, 111.0, 82.9, 55.4, 39.5,

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37.0, 32.2, 20.0; HRMS (EI) m/z $[M]^+$ calcd for $C_{11}H_{13}IO^+$ 288.0011; found 288.0017.

General Procedure 3: Organocatalytic Hydrothiolation. Alkene (0.1 mmol, 1 equiv) was weighed into a regular 2 mL glass vial. In a separate regular 2 mL glass vial, *p*-TSA·H_2O (1.9 mg, 0.01 mmol, 10 mol %) was weighed and solubilized in HFIP (0.2 mL), $CDCl_3$ (0.2 mL), and thiol (0.6 mmol, 6 equiv) successively. This was then transferred to the vial containing alkene in one portion. The reaction was left to stand for 5 h (36 h for ketoprofen) before being quenched by addition of $NaHCO_3$ (0.5 mL), extracted with $CHCl_3$ (3×), and dried over Na_2SO_4. The titled compounds were isolated by flash column chromatography eluting 10−40% $CHCl_3$/hexane.

General Procedure 4: Oxidation of Thioethers. The thioether was dissolved in CH_2Cl_2 (concentration of 0.05 M), and *m*-CPBA was added (4 equiv). This was allowed to stir at rt for 2 h. The reaction was quenched by addition of saturated $Na_2S_2O_3$ and saturated $NaHCO_3$. The organic was extracted with CH_2Cl_2, dried over $MgSO_4$, and concentrated in vacuo. If necessary, flash column chromatography eluting 50% Et_2O/hexane afforded the desired compounds.

*1-Methoxy-4-(1-phenyl-1-(para-tolyl)ethyl)benzene (**3**).* Following the general procedure 2 for organocatalytic hydroarylation of alkene **1**. Isolated as a clear oil (22.3 mg, 0.0737 mmol, 74%): ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.28−7.24 (m, 2H), 7.22−7.17 (m, 1H), 7.11−6.97 (m, 8H), 6.82−6.78 (m, 2H), 3.79 (s, 3H), 2.33 (s, 3H), 2.15 (s, 3H); ^{13}C{^{1}H} NMR (101 MHz, chloroform-*d*) δ 157.7, 149.7, 146.5, 141.5, 135.5, 129.8, 128.8, 128.7, 128.7, 127.9, 126.0, 113.2, 55.3, 51.7, 30.7, 21.1.

*1-(4-Methoxyphenyl)-1-methyl-1,2,3,4-tetrahydronaphthalene (**4**).* Following the general procedure 2 for organocatalytic hydroarylation of 4-methyl-1,2-dihydronaphthalene. Isolated as a clear oil (25.0 mg, 0.0991 mmol, 99%): ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.12−6.99 (m, 6H), 6.78 (d, J = 8.9 Hz), 3.77 (s, 3H), 2.83 (t, J = 6.5 Hz, 2H), 2.02 (ddd, J = 13.2, 8.2, 3.2 Hz, 1H), 1.86 (ddd, J = 13.2, 9.1, 3.0 Hz, 1H), 1.81−1.72 (m, 1H), 1.70 (s, 3H), 1.69−1.61 (m, 1H); ^{13}C{^{1}H} NMR (101 MHz, chloroform-*d*) δ 157.4, 144.7, 143.9, 137.1, 129.2, 129.1, 128.5, 125.9, 125.8, 113.2, 55.3, 42.4, 41.6, 30.4, 30.3, 19.7; HRMS (EI) m/z $[M + H]^+$ calcd for $C_{18}H_{21}O^+$ 253.1587; found 253.1588.

*1-(4-Methoxyphenyl)-1-methyl-2,3-dihydro-1H-indene (**5**).* Following the general procedure 2 for organocatalytic hydroarylation of 3-methyl-1*H*-indene. Isolated as a clear oil (23.6 mg, 0.0990 mmol, 99%): ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.29 (ddd, J = 5.5, 2.8, 0.9 Hz, 1H), 7.24−7.18 (m, 2H), 7.12 (d, J = 8.9 Hz, 2H), 7.09−7.06 (m, 1H), 6.82 (d, J = 8.9 Hz, 1H), 3.79 (s, 3H), 2.97−2.86 (m, 2H), 2.38 (ddd, J = 12.5, 7.6, 6.6 Hz, 1H), 2.20 (ddd, J = 12.5, 7.6, 6.6 Hz, 1H), 1.67 (s, 3H); ^{13}C{^{1}H} NMR (101 MHz, chloroform-*d*) δ 157.7, 151.4, 143.7, 141.3, 127.8, 126.7, 126.6, 124.6, 124.2, 113.4, 55.3, 51.6, 44.3, 30.5, 27.7; HRMS (CI) m/z $[M + H]^+$ calcd for $C_{17}H_{19}O^+$ 239.1430; found 239.1429. On 5 mmol scale following a modified general procedure 2 for organocatalytic hydroarylation. To 3-methyl-1*H*-indene (651 mg, 5.0 mmol, 1 equiv) was added *p*-TSA·H_2O (47.5 mg, 0.25 mmol, 5 mol %) dissolved in a solution of anisole (3.26 mL, 30 mmol, 6 equiv), 10 mL of $CHCl_3$, and 10 mL of HFIP. This was allowed to stir, and after 5 h was quenched by addition of $NaHCO_3$ (25 mL), extracted with $CHCl_3$ (3×), and dried over Na_2SO_4. The titled compound was isolated by flash column chromatography eluting 10−40% $CHCl_3$/hexane, isolated as a clear oil (989 mg, 4.15 mmol, 83%) in agreement with the small-scale characterization.

*(1RS,2RS)-1-(4-Methoxyphenyl)-2-methyl-2,3-dihydro-1H-indene (**6**).* Following the general procedure 2 for organocatalytic hydroarylation of commercially available 2-methylindene. Isolated as a clear oil (19.7 mg, 0.0827 mmol, 83%); stereochemistry assigned by NOE analysis. For major diastereomer: ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.24 (app. s, 1H), 7.21−7.09 (m, 4H), 6.94−6.79 (m, 3H), 3.82 (s, 3H), 3.75 (d, J = 10.0 Hz, 1H), 3.13 (dd, J = 15.3, 7.5 Hz, 1H), 2.64 (dd, J = 15.3, 10.0 Hz, 1H), 2.49−2.35 (m, 1H), 1.18 (d, J = 6.6 Hz, 3H); ^{13}C{^{1}H} NMR (101 MHz, chloroform-*d*) δ 158.4, 147.5, 143.8, 136.1, 129.7, 126.6, 126.4, 124.8, 124.2, 113.9, 59.0, 55.4, 46.5, 40.4, 18.3. HRMS (CI) m/z $[M + H]^+$ calcd for $C_{17}H_{19}O^+$ 239.1430; found 239.1430.

*5-Bromo-1-(4-methoxyphenyl)-1-methyl-2,3-dihydro-1H-indene (**7**).* Following the general procedure 2 for organocatalytic hydroarylation of 6-bromo-3-methyl-1*H*-indene. Isolated as a clear oil (30.5 mg, 0.0961 mmol, 96%): ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.41 (s, 1H), 7.32 (d, J = 8.1 Hz, 1H), 7.10 (d, J = 8.8 Hz, 2H), 6.92 (d, J = 8.1 Hz, 1H), 6.81 (d, J = 8.8 Hz, 2H), 3.79 (s, 2H), 2.89 (m, 2H), 2.37 (ddd, J = 12.5, 7.8, 6.5 Hz, 1H), 2.19 (ddd, J = 12.5, 7.8, 7.5 Hz, 1H), 1.63 (s, 3H); ^{13}C{^{1}H} NMR (101 MHz, chloroform-*d*) δ 157.8, 150.5, 146.1, 140.6, 129.7, 127.8, 127.7, 125.8, 120.4, 113.5, 55.4, 51.3, 44.3, 30.4, 27.6; HRMS (EI) m/z [M+]$^+$ calcd for $C_{17}H_{17}OBr^+$ 316.0457; found 316.0454.

*4-Iodo-7-methoxy-1-(4-methoxyphenyl)-1-methyl-2,3-dihydro-1H-indene (**8**).* Following the general procedure 2 for organocatalytic hydroarylation of alkene **23**. Isolated as a clear oil (38.2 mg, 0.0969 mmol, 97%): ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.56 (d, J = 8.5 Hz, 1H), 7.06 (d, J = 8.8 Hz, 2H), 6.78 (d, J = 8.8 Hz, 2H), 6.51 (d, J = 8.5 Hz, 1H), 3.78 (s, 3H), 3.62 (s, 3H), 2.92−2.80 (m, 2H), 2.2−2.23 (m, 1H), 2.21−2.12 (m, 1H), 1.74 (s, 3H); ^{13}C{^{1}H} NMR (101 MHz, chloroform-*d*) δ 157.6, 157.2, 149.6, 140.9, 138.6, 137.4, 127.0, 113.4, 112.2, 83.3, 55.5, 55.3, 53.8, 43.5, 36.6, 26.7; HRMS (EI) m/z $[M]^+$ calcd for $C_{18}H_{19}IO_2^+$ 394.0424; found 394.0416.

*1-(4-Methoxyphenyl)-1-phenyl-2,3-dihydro-1H-indene (**9**).* Following the general procedure 2 for organocatalytic hydroarylation of 3-phenyl-1*H*-indene. Isolated as a pale-yellow oil (26.0 mg, 0.0865 mmol, 87%): ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.28−7.16 (m, 8H), 7.10−7.04 (m, 3H), 6.81 (d, J = 8.8 Hz, 2H), 3.79 (s, 3H), 2.90−2.87 (m, 2H), 2.82−2.79 (m, 2H); ^{13}C{^{1}H} NMR (101 MHz, chloroform-*d*) δ 157.73, 149.63, 147.51, 143.75, 139.26, 129.51, 128.47, 127.88, 126.78, 126.25, 126.04, 125.96, 124.63, 113.20, 61.20, 55.22, 43.66, 30.61; HRMS (CI) m/z $[M + H]^+$ calcd for $C_{22}H_{21}O^+$ 301.1587; found 301.1578.

*2-(1-Methyl-2,3-dihydro-1H-inden-1-yl)benzo[b]thiophene (**13**).* Following the general procedure 2 for organocatalytic hydroarylation of 3-methyl-1*H*-indene. Isolated as a colorless oil (26.3 mg, 0.0994 mmol, 99%): ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.75 (dd, J = 7.4, 1.2 Hz, 1H), 7.64 (dd, J = 7.4, 1.2 Hz, 1H), 7.33−7.26 (m, 4H), 7.26−7.23 (m, 2H), 6.89 (d, J = 0.6 Hz, 1H), 3.15−2.91 (m, 2H), 2.59 (ddd, J = 12.8, 7.8, 5.1 Hz, 1H), 2.32 (dt, J = 12.8, 7.8 Hz, 1H), 1.82 (s, 3H); ^{13}C{^{1}H} NMR (101 MHz, chloroform-*d*) δ 155.6, 149.9, 143.2, 140.0, 139.5, 127.4, 126.8, 124.9, 124.2, 123.9, 123.7, 123.1, 122.2, 119.8, 51.0, 44.2, 30.5, 28.6; HRMS (EI) m/z $[M]^+$ calcd for $C_{18}H_{16}S^+$ 264.0967; found 264.0961.

*2-Methyl-5-(1-methyl-2,3-dihydro-1H-inden-1-yl)furan (**14**).* Following the general procedure 2 for organocatalytic hydroarylation of 3-methyl-1*H*-indene. Isolated as a colorless oil (18.0 mg, 0.0849 mmol, 85%): ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.26−7.13 (m, 4H), 5.84−5.82 (m, 1H), 5.80 (d, J = 3.0 Hz, 1H), 3.04−2.91 (m, 2H), 2.61−2.54 (m, 1H), 2.24 (d, J = 0.9 Hz, 3H), 2.14−2.01 (m, 1H), 1.59 (s, 3H); ^{13}C{^{1}H} NMR (101 MHz, chloroform-*d*) δ 159.4, 151.0, 149.1, 143.2, 126.9, 126.5, 124.7, 123.6, 105.7, 104.9, 48.7, 39.8, 30.4, 26.0, 13.8. HRMS (CI) m/z $[M + H]^+$ calcd for $C_{15}H_{17}O^+$ 213.1274; found 213.1275.

*5-((1RS,2RS)-2-Methyl-2,3-dihydro-1H-inden-1-yl)benzo[d][1,3]-dioxole (**15**).* Following the general procedure 2 for organocatalytic hydroarylation of commercially available 2-methylindene. Isolated as a colorless oil (14.6 mg, 0.0578 mmol, 58%). Crude ^{1}H NMR analysis suggested 5:3 dr, but a single diastereomer was isolated clean. Stereochemistry assigned by analogy with compound **6**: ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.23 (d, J = 7.4 Hz, 1H), 7.19−7.07 (m, 2H), 6.88 (d, J = 7.4 Hz, 1H), 6.78 (d, J = 7.9 Hz, 1H), 6.72−6.62 (m, 2H), 5.96−5.93 (m, 2H), 3.72 (d, J = 9.5 Hz, 1H), 3.12 (dd, J = 15.4, 7.6 Hz, 1H), 2.71−2.54 (m, 1H), 2.46−2.31 (m, 1H), 1.17 (d, J = 6.6 Hz, 3H); ^{13}C{^{1}H} NMR (101 MHz, chloroform-*d*) δ 147.7, 147.1, 146.1, 143.6, 137.9, 126.6, 126.3, 124.7, 124.1, 121.9, 108.7, 108.0, 100.9, 59.4, 46.3, 40.2, 18.2; HRMS (EI) m/z $[M]^+$ calcd for $C_{17}H_{16}O_2^+$ 252.1150; found 252.1147.

*2-(1-Phenyl-1-(para-tolyl)ethyl)benzofuran (**16**).* Following the general procedure 2 for organocatalytic hydroarylation of alkene **1**. Isolated as a colorless oil (20.3 mg, 0.0649 mmol, 65%): ^{1}H NMR (400 MHz, chloroform-*d*) δ 7.51−7.45 (m, 1H), 7.43 (d, J = 8.1 Hz,

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1H), 7.29 (q, J = 6.7 Hz, 2H), 7.26−7.15 (m, 5H), 7.15−7.06 (m, 4H), 6.32−6.21 (m, 1H), 2.35 (s, 3H), 2.19 (s, 3H); $^{13}C\{^1H\}$ NMR (101 MHz, chloroform-d) δ 163.8, 155.0, 146.6, 143.4, 136.2, 128.8, 128.4, 128.1 (2C), 128.0, 126.5, 123.6, 122.6, 120.7, 111.3, 104.9, 49.6, 27.7, 21.0; HRMS (CI) m/z $[M + H]^+$ calcd for $C_{23}H_{21}O^+$ 313.1587; found 313.1584.

(8R,9S,17S)-17-Methyl-17-phenyl-7,8,9,11,12,15,16,17-octahydro-6H-cyclopenta[a]phenanthren-3-ol (**20**). Following the general procedure 2 for organocatalytic hydroarylation of alkene **19**. Isolated as an off-white solid (31.4 mg, 0.0950 mmol, 95%): mp 147 °C; $[\alpha]_D^{23}$ = −13.5 (c = 0.33, $CHCl_3$); ^1H NMR (400 MHz, chloroform-d) δ 7.33−7.29 (m, 4H), 7.21−7.16 (m, 2H), 6.66−6.61 (m, 2H), 2.99−2.87 (m, 2H), 2.57−2.45 (m, 3H), 2.36−2.27 (m, 1H), 2.27−2.21 (m, 1H), 2.15 (t, J = 10.7 Hz, 1H), 2.09−1.96 (m, 3H), 1.93−1.81 (m, 1H), 1.65−1.58 (m, 1H), 1.48 (s, 3H), 1.47−1.42 (m, 1H); $^{13}C\{^1H\}$ NMR (101 MHz, chloroform-d) δ 153.5, 148.8, 141.3, 138.7, 138.5, 133.0, 128.2, 126.3, 126.2, 125.6, 115.5, 112.6, 53.4, 42.6, 41.4, 40.3, 30.8, 30.1, 27.4, 27.0, 24.3, 22.8; HRMS (EI) m/z $[M + H]^+$ calcd for $C_{24}H_{27}O^+$ 331.2056; found 331.2053. Crystals suitable for single X-ray analysis were grown by slow evaporation from Et_2O/hexane. For details, see the Supporting Information.

5-Isopropyl-2-methyl-1,1′-biphenyl[65] (**22**). Following the general procedure 2 for organocatalytic hydroarylation of alkene **21**. Isolated as a clear oil (3.2 mg, 0.0152 mmol, 15%): ^1H NMR (500 MHz, chloroform-d) δ 7.44−7.39 (m, 2H), 7.36−7.32 (m, 3H), 7.20 (dt, J = 7.8, 0.7 Hz, 1H), 7.16−7.09 (m, 2H), 2.91 (spt, J = 6.9 Hz, 1H), 2.24 (s, 3H), 1.27 (d, J = 6.9 Hz, 6H). Data are in agreement with those in the literature.[65]

Phenyl(1-phenyl-1-(para-tolyl)ethyl)sulfane (**27**). Following the general procedure 3 for organocatalytic hydrothiolation of alkene **1**. Isolated as a clear oil (19.2 mg, 0.063 mmol, 63%): ^1H NMR (400 MHz, chloroform-d) δ 7.44−7.38 (m, 2H), 7.35−7.21 (m, 6H), 7.16−7.05 (m, 6H), 2.35 (s, 3H), 1.94 (s, 3H); $^{13}C\{^1H\}$ NMR (101 MHz, chloroform-d) δ 146.5, 143.5, 136.6, 136.4, 132.8, 128.7, 128.6, 128.5, 128.3 (2C), 127.9, 126.7, 59.5, 30.4, 21.1; HRMS (EI) m/z $[M(-SC_6H_5)]^+$ calcd for $C_{15}H_{15}^+$ 195.1174; found 195.1175.

Methyl 2-(3-(1-(4-Methoxyphenyl)-1-phenylethyl)phenyl)propanoate (**29**). Following the general procedure 2 for organocatalytic hydroarylation of alkene **28**. Isolated as a clear oil (36.7 mg, 0.0980 mmol, 98%): IR ν_{max} (CH_2Cl_2) 1737, 1510, 1249, 1182 cm^{-1}; ^1H NMR (400 MHz, chloroform-d) δ 7.31−7.19 (m, 4H), 7.16 (d, J = 7.7 Hz, 1H), 7.12−7.08 (m, 2H), 7.06 (t, J = 1.5 Hz, 1H), 7.02 (d, J = 8.8 Hz, 2H), 6.97 (d, J = 7.8 Hz, 1H), 6.82 (d, J = 8.8 Hz, 2H), 3.81 (s, 3H), 3.66 (q, J = 7.2 Hz, 1H), 3.64 (s, 3H), 2.18 (s, 3H), 1.45 (d, J = 7.2 Hz, 3H); added 0.1 mL of benzene-d_6 to resolve 2C at 52.1 in pure $CDCl_3$; $^{13}C\{^1H\}$ NMR (101 MHz, chloroform-d) δ 175.1, 157.7, 149.8, 149.4, 141.2, 140.2, 129.8, 128.8, 128.3, 128.1, 127.9, 127.6, 126.0, 124.9, 113.2, 55.3, 52.1, 52.0, 45.6, 30.7, 18.8; HRMS (ES) m/z $[M + Na]^+$ calcd for $C_{25}H_{26}O_3Na^+$ 397.1780; found 397.1769.

Methyl 2-(3-(1-(4-(Methylthio)phenyl)-1-phenylethyl)phenyl)propanoate (**31**). Following the general procedure 2 for organocatalytic hydroarylation of alkene **28**. Isolated as a single diastereomer in the form of a colorless oil (19.9 mg, 0.0510 mmol, 51%): IR ν_{max} (CH_2Cl_2) 1733, 1238, 1044 cm^{-1}; ^1H NMR (400 MHz, chloroform-d) δ 7.28 (dd, J = 3.0, 1.6 Hz, 1H), 7.25−7.17 (m, 3H), 7.17−7.13 (m, 3H), 7.09−7.05 (m, 2H), 7.05−6.97 (m, 3H), 6.94 (dt, J = 7.7, 1.6 Hz, 1H), 3.67−3.63 (q, 7.1 Hz, 1H), 3.62 (s, 3H), 2.47 (s, 3H), 2.15 (s, 3H), 1.43 (d, J = 7.1 Hz, 3H); $^{13}C\{^1H\}$ NMR (101 MHz, chloroform-d) δ 175.0, 149.2, 148.8, 146.0, 140.1, 135.8, 129.2, 128.6, 128.1, 128.1, 127.9 (2C), 127.5, 126.0, 124.9, 52.2, 52.0, 45.5, 30.4, 18.6, 15.8; HRMS (ES) m/z $[M + OH]^+$ calcd for $C_{25}H_{27}O_3S^+$ 4071681; found 407.1676.

Methyl 2-(3-(1-(4-(Methylsulfonyl)phenyl)-1-phenylethyl)phenyl)propanoate (**32**). Following the general procedure 4 for oxidation of thioether **31**. Isolated as a single diastereomer in the form of a colorless oil (6.9 mg, 0.016 mmol, 99%): IR ν_{max} (CH_2Cl_2) 1737, 1316, 1152 cm^{-1}; ^1H NMR (400 MHz, chloroform-d) δ 7.86−7.80 (m, 2H), 7.34−7.26 (m, 5H), 7.26−7.21 (m, 1H), 7.19 (dt, J = 7.6, 1.4 Hz, 1H), 7.06 (m, 2H), 7.01 (t, J = 1.9 Hz, 1H), 6.91 (dtd, J = 7.7, 2.0, 1.4 Hz, 1H), 3.66 (q, J = 7.2 Hz, 1H), 3.62 (s, 3H), 3.07 (s, 3H), 2.19 (s, 3H), 1.43 (d, J = 7.2, 3H); $^{13}C\{^1H\}$ NMR (101 MHz, chloroform-d) δ 175.0, 155.7, 148.1, 147.7, 140.6, 138.3, 129.9, 128.7, 128.6, 128.3, 128.1, 127.6, 127.1, 126.7, 125.6, 53.0, 52.2, 45.6, 44.7, 30.5, 18.8; HRMS (EI) m/z $[M + H]^+$ calcd for $C_{25}H_{27}O_4S^+$ 423.1625; found 423.1617.

Methyl 2-(3-(1-Phenyl-1-(phenylthio)ethyl)phenyl)propanoate (**33**). Following the general procedure 3 for organocatalytic hydrothiolation of alkene **28**. Isolated as an inseparable 1:1 mixture of diastereomers in the form of a colorless oil (34.2 mg, 0.0908 mmol, 91%): IR ν_{max} (CH_2Cl_2) 1730, 1439, 1282 cm^{-1}; ^1H NMR (400 MHz, chloroform-d) δ 7.41−7.38 (m, 2H), 7.33−7.28 (m, 3H), 7.25−7.20 (m, 4H), 7.17−7.15 (m, H), 7.13−7.09 (t, J = 7.7 Hz, 2H), 7.04−7.02 (m, 2H), 3.67 (q, J = 3.1 Hz), 3.64 (s, 3H), 1.93 (s, 3H), 1.45 (d, J = 3.1 Hz, 3H- one diastereomer), 1.43 (d, J = 3.1 Hz, 3H-one diastereomer); $^{13}C\{^1H\}$ NMR (101 MHz, chloroform-d) δ 175.1, 175.0, 146.7, 146.6, 146.3, 140.2, 140.1, 136.8, 132.5, 128.7, 128.4, 128.3, 128.2, 128.1, 128.0, 127.8, 127.4, 126.8, 125.7, 125.5, 59.8, 52.1, 45.6, 45.6, 30.5, 18.8; HRMS (EI) m/z $M(-SC_6H_5)]^+$ calcd for $C_{18}H_{19}O_2^+$ 267.1385; found 267.1376.

Methyl 2-(3-(1-Phenyl-1-(phenylsulfonyl)ethyl)phenyl)propanoate (**34**). Following the general procedure 4 for oxidation of thioether **33**. Isolated as an inseparable 1:1 mixture of diastereomers in the form of a colorless oil (16.5 mg, (0.040 mmol, 99%): IR ν_{max} (CH_2Cl_2) 1731, 1299, 1265, 1141 cm^{-1}. ^1H NMR (400 MHz, chloroform-d) δ 7.53−7.50 (m, 2H), 7.47−7.35 (m, 3H), 7.33−7.28 (m, 5H), 7.25−7.21 (m, 4H), 3.68−3.61 (m, 1H), 3.64 (s, 3H- one diastereomer), 3.63 (s, 3H- one diastereomer), 2.09 (s, 3H), 1.41 (d, J = 7.2 Hz, 3H- one diastereomer), 1.37 (d, J = 7.2 Hz, 3H-one diastereomer); $^{13}C\{^1H\}$ NMR (101 MHz, chloroform-d) δ 174.7, 140.3, 139.3, 139.2, 136.7, 136.6, 133.1, 130.3, 129.5, 129.3, 128.9, 128.6, 128.6, 128.3, 128.3, 128.1, 128.0, 127.2, 126.8, 75.2, 75.2, 52.1, 45.4, 26.1, 18.7, 18.6; HRMS (EI) m/z $[M + H]^+$ calcd for $C_{24}H_{24}O_4S^+$ 409.1474; found 409.1483.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.9b02393.

^1H and ^{13}C NMR spectra of compounds and single-crystal X-ray structure determination for compound **20** (PDF)

Crystallography data for **20** (CIF)

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Notes

The authors declare no competing financial interest.

A version of this manuscript was filed on the preprint server ChemRxiv.[66] Raw ^1H and ^{13}C NMR spectra of new compounds (online at 10.14469/hpc/5091).

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