chemistry proceedings

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Proceeding Paper

Au(I) as a π-Lewis Base Catalyst: Controlled Synthesis of Sterically Congested Bis(triflyl)enals from α-Allenols †

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† Presented at the 27th International Electronic Conference on Synthetic Organic Chemistry (ECSOC-27), 15–30 November 2023; Available online: https://ecsoc-27.sciforum.net/.

Abstract: We have recently achieved a gold-catalyzed bis[(trifluoromethyl)sulfonyl]ethylation of α-allenols, which allows the preparation of sterically congested bis(triflyl)enals. This sequence differs from the conventional reaction pathway of α-allenols under π-acid catalysis. In our case, Au(I) functions as a π-Lewis base catalyst rather than a π-Lewis acid to activate the allene.

Keywords: allenols; bis(triflyl)enals; gold

Citation: Toledano-Pinedo, M.; del Campo, T.M.; Yanai, H.; Almendros, P. Au(I) as a π-Lewis Base Catalyst: Controlled Synthesis of Sterically Congested Bis(triflyl)enals from α-Allenols. *Chem. Proc.* **2023**, *14*, x. https://doi.org/10.3390/xxxxx

Academic Editor(s): Name

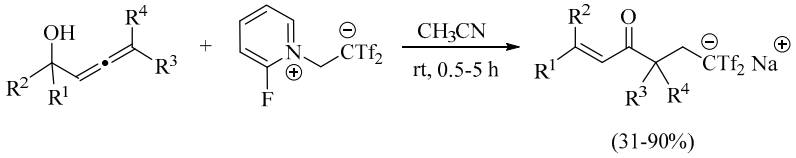
Published: 15 November 2023

1. Introduction

For many years, allenes have been considered very unstable molecules, which has caused a lack of knowledge of their chemical and synthetic applications in the scientific community [1]. However, in the last decades these compounds have experienced great growth in the field of organic synthesis due to their interesting reactivity that allows a great variety of possible transformations [2]. In particular, the allenol moiety is a special type of allene that exhibits a rich and fruitful reactivity [3].

Furthermore, metal catalysis allows the strict regulation of selectivity in chemical reactions which is crucial in organic synthesis because it enables the preparation of distinct molecules in a controlled manner [4]. In this context, gold catalysis has been used for the cycloisomerization or oxycyclization of α-allenols showing useful levels of chemo, regio, and/or stereoselectivity [5]. Specifically, gold catalysis has been widely used in the cycloisomerization or oxycyclization-functionalization of α-allenols [6].

Recently our research group has described that the reaction of metal-free allenols with the Yanai reagent selectively produces bis(triflyl)enones through the electrophilic attack of $Tf_2C{=}CH_2$ on the terminal sp^2-hybridized C4 atom of the allene rest (Scheme 1) [7]. In addition, it should be also noted that the strongly electron-withdrawing (trifluoromethyl)sulfonyl (triflyl, $Tf{=}SO_2CF_3$) group confers a positive effect on the metabolic stability and lipophilicity of potential drugs important to the field of medicinal chemistry [8].

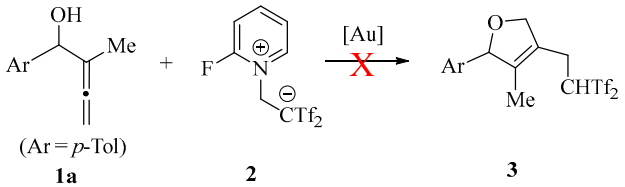


Scheme 1. The reaction of metal-free allenols with the Yanai reagent.

2. Results and Discussion

Due to the interest of our working group in the study of allenes and the Yanai reagent, which serves as a source of highly electrophilic $Tf_2C{=}CH_2$, we propose as the main objective of the work the study of the reactivity of α-allenols against Yanai salt, in the presence of a gold catalyst with the assumption of a cycloetherification (Scheme 2).

The reaction worked, however, the expected functionalized oxacycle **3** was not detected.

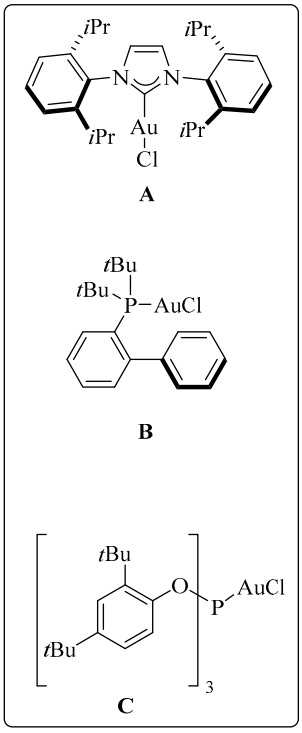


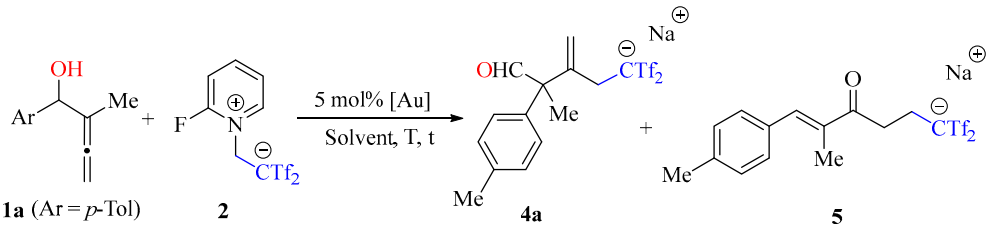
Scheme 2. Objective of work.

Therefore, to study the reaction between an α-allenol and betaine **2**, we decided to optimize the reaction conditions. For this, different catalysts, solvents, temperature and reaction time were tested. By using [(PPh_3)AuCl]/AgOTf as a catalyst and carried out the reaction at room temperature, a separable mixture of the aldehyde **4a** together with the ketone **5** was obtained (Scheme 3, entry 1). In order to favor the formation of the new product **4a** compared to the enone **5**, we carried out the reaction but with the incorporation of 3 Å molecular sieves (MS) as a water trapping agent. In this case, aldehyde **4a** was achieved with a yield of 41% but from a more complex reaction in which the formation of ketone **5** was avoided (entry 2). Fortunately, the gold-catalyzed reaction carried out at 130 °C, in a sealed tube, gave a remarkable result, without detecting the formation of the enone **5**. In this case, product **4a**, containing a quaternary center, was selectively obtained in 61% yield (entry 3). Then, we next examined the reaction of **1a** with **2** by modifying the solvent, however, it was observed that in cyclohexane the desired aldehyde **4a** was generated in very low yield (6%) and in HFIP it was not formed (entries 4 and 5). An increase of the amount of betaine **2** did not contribute to the improvement of the performance of **4a** (entry 6).

Subsequently, we examined how the nature of the catalyst could affect the course of the reaction. In this way, the *N*-heterocyclic carbene (NHC) gold precatalyst [AuClIPr] (IPr = 1,3-bis(2,6-diisopropylphenyl)-imidazole-2-ylidene; A) led to higher yield of **4a** (entries 8 and 9), while only a slight enhancement was observed with biaryl phosphine gold(I) complex B (Buchwald-type ligand) (entries 10 and 11). However, the gold phosphite C salt generated decreased catalytic activity (entries 12 and 13). This fact can be justified considering that the NHC ligand with higher σ-donating capacity fits better in our gold-catalyzed transformation than the π-acidic phosphite ligand.

Also, the crucial role of both the gold complex and the silver salt, was demonstrated since in the absence of the previous metal salts, the synthesis of product **4a** was not achieved (entries 14 and 15). Furthermore, the use of the Gagosz catalyst [(Ph_3P)AuNTf_2] as a suitable promoter showed that it is not the silver salt that intervenes in the reaction but the cationic nature of the gold complex (entry 16).





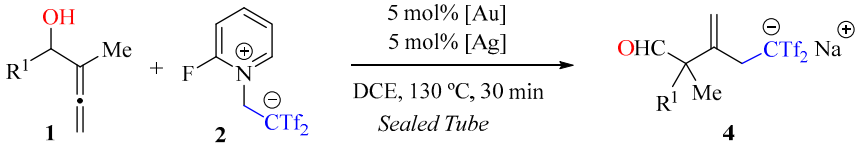
Entry 1	**1a**	**2** (1.1 equiv.)	[(PPh_3)AuCl]/AgOTf, DCE, rt, 2 h	**4a** (30%)	**5** (29%)
Entry 2	**1a**	**2** (1.1 equiv.)	[(PPh_3)AuCl]/AgOTf, MS 3 Å, DCE, rt, 2 h	**4a** (41%)	**5** (0%)
Entry 3	**1a**	**2** (1.1 equiv.)	[(PPh_3)AuCl]/AgOTf, DCE, 130 °C, 30 min	**4a** (61%)	**5** (0%)
Entry 4	**1a**	**2** (1.1 equiv.)	[(PPh_3)AuCl]/AgOTf, C_6H_{12}, 130 °C, 30 min	**4a** (6%)	**5** (0%)
Entry 5	**1a**	**2** (1.1 equiv.)	[(PPh_3)AuCl]/AgOTf, HFIP, 130 °C, 30 min	**4a** (0%)	**5** (0%)
Entry 6	**1a**	**2** (2.0 equiv.)	[(PPh_3)AuCl]/AgOTf, DCE, 130 °C, 30 min	**4a** (60%)	**5** (0%)
Entry 7	**1a**	**2** (1.1 equiv.)	[(PPh_3)AuCl]/$AgSbF_6$, DCE, 130 °C, 30 min	**4a** (55%)	**5** (0%)
Entry 8	**1a**	**2** (1.1 equiv.)	**A**/AgOTf, DCE, 130 °C, 30 min	**4a** (68%)	**5** (0%)
Entry 9	**1a**	**2** (1.1 equiv.)	**A**/$AgSbF_6$, DCE, 130 °C, 30 min	**4a** (74%)	**5** (0%)
Entry 10	**1a**	**2** (1.1 equiv.)	**B**/AgOTf, DCE, 130 °C, 30 min	**4a** (56%)	**5** (0%)
Entry 11	**1a**	**2** (1.1 equiv.)	**B**/$AgSbF_6$, DCE, 130 °C, 30 min	**4a** (62%)	**5** (0%)
Entry 12	**1a**	**2** (1.1 equiv.)	**C**/AgOTf, DCE, 130 °C, 30 min	**4a** (45%)	**5** (0%)
Entry 13	**1a**	**2** (1.1 equiv.)	**C**/$AgSbF_6$, DCE, 130 °C, 30 min	**4a** (40%)	**5** (0%)
Entry 14	**1a**	**2** (1.1 equiv.)	AgOTf, DCE, 130 °C, 30 min	**4a** (0%)	**5** (0%)
Entry 15	**1a**	**2** (1.1 equiv.)	[(PPh_3)AuCl], DCE, 130 °C, 30 min	**4a** (0%)	**5** (0%)
Entry 16	**1a**	**2** (1.1 equiv.)	[$(Ph_3P)AuNTf_2$], DCE, 130 °C, 30 min	**4a** (63%)	**5** (0%)

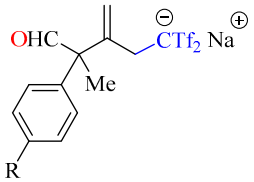
Scheme 3. Optimization of reaction conditions for the formation of β-methylene-δ,δ-bis(triflyl)pentanals **4**.

With these results in mind, we decided to test the reaction conditions corresponding to entry 3 (method I) and entry 9 (method II) (Scheme 3).

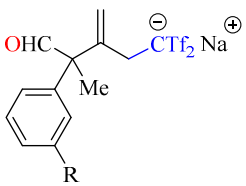
It is noteworthy that product **4a** was isolated as a sodium salt upon contact with glass material, manifesting the strongly acidic nature of the Tf_2CH moiety.

Next, the scope of the methodology was explored using α-allenols **1** differently substituted in different positions of the aromatic ring by methyl, methoxyl and halogen groups, which led to the corresponding products **4** with good yields (Scheme 4). It is important to note that the described methodology is very robust, since both electron-donating groups and acceptor groups were tolerated. Furthermore, the reaction was shown to be chemo- and regioselective since α-allenol **1i**, substituted by an alkene moiety, also led to the desired aldehyde **4i** in reasonable yield (I: 41%; II: 49%).

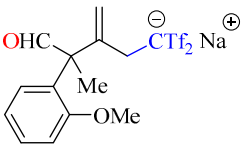




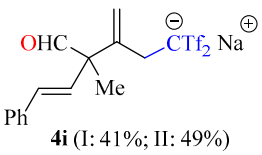
4a R = Me (I: 61%; II: 74%)
4b R = H (I: 57%; II: 64%)
4c R = Cl (I: 54%; II: 61%)
4d R = MeO (I: 74%; II: 85%)
4e R = Br (I: 50%; II: 58%)



4f R = Me (I: 52%; II: 60%)
4g R = MeO (I: 45%; II: 52%)



4h (I: 32%; II: 41%)

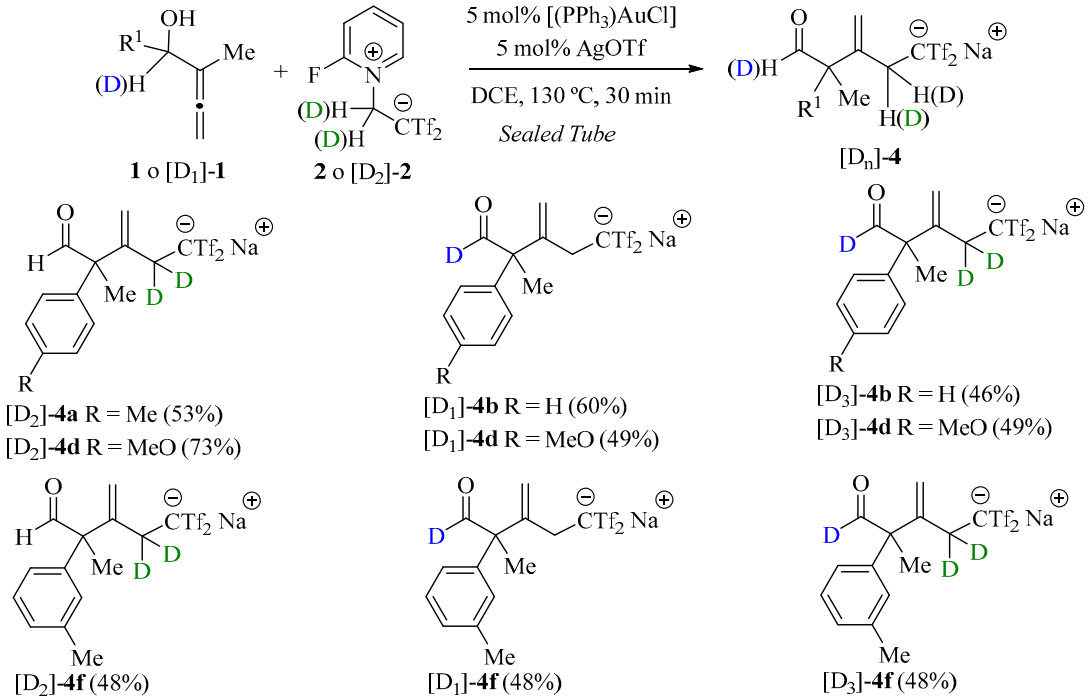


4i (I: 41%; II: 49%)

Method I: [Au] = [(PPh_3)AuCl], [Ag] = AgOTf; Method II: [Au] = [AuClIPr], [Ag] = $AgSbF_6$

Scheme 4. Study of the scope of the methodology.

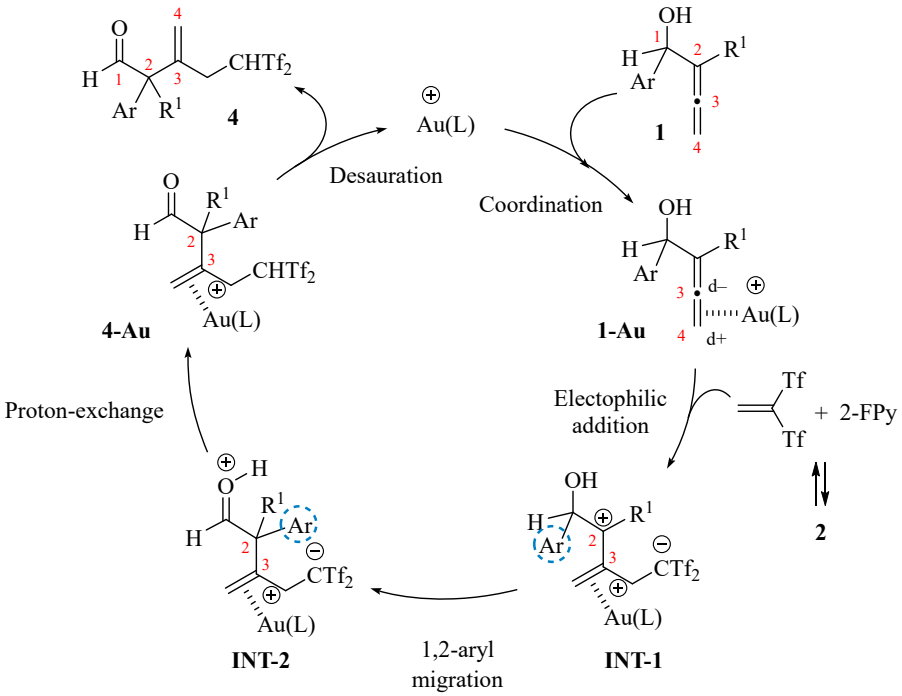
Subsequently, to explore the synthetic versatility, we decided to extend the methodology to obtain the desired aldehydes with deuterium atoms (Scheme 5). Thus, the reaction between α-allenol **1a** and $Tf_2C{=}CD_2$, generated in situ from the deuterated zwitterion [D₂]-**2**, in the presence of [(PPh₃)AuCl]/AgOTf and applying the conditions of method I, led to the aldehyde [D₂]-**4a** with reasonable yield (53%). Furthermore, the reaction between the deuterated α-allenols [D₁]-**1** with the non-deuterated zwitterion **2** led to the corresponding monodeuterated products [D₁]-**4**, with the CDO functionality. Likewise, the reaction between the deuterated α-allenols [D₁]-**1** with the deuterated zwitterion [D₂]-**2** provided the aldehydes [D₃]-**4**.



Scheme 5. Extension of the methodology.

Next, two experiments were carried out in order to obtain more information about the reaction mechanism. An isotopic labeling test was carried out using anhydrous 1,2-dichloroethane and ^{18}O-labeled water, achieving the aldehyde **4a** with a lower yield (35%). As expected, its labeled analogue was not detected, so the participation of water in the reaction mechanism was ruled out. Additionally, another experiment was performed in the presence of TEMPO, a radical scavenger. In this case, the reaction progressed to aldehydes **4** with similar yields, demonstrating the non-participation of radicals in the reaction mechanism.

According to the results obtained, a possible mechanism that justifies the formation of bis(triflil)ethyl aldehydes **4** from α-allenols **1** through gold catalysis has been proposed in Scheme 6. Initially, the Au(I) catalyst through a π-type coordination with the terminal bond of the allene generates the **1**-Au complex. Next, in the presence of zwitterion **2**, source of $Tf_2C{=}CH_2$, the **1**-Au complex undergoes an electrophilic addition of the highly polarized olefin to give rise to the intermediate **INT-1**, with Au(I) acting as a Lewis base. The subsequent 1,2-migration of aryl favors the formation of the **INT-2** intermediate. Subsequently, the release of a proton and the protonolysis of the carbanion generates the **4**-Au gold complex. Finally, the species evolves through deauration to give access to the final products **4**, with simultaneous regeneration of the gold catalyst. This proposal is contrasted by DFT calculations carried out by Dr. Hikaru Yanai of the University of Tokyo.



Scheme 6. Catalytic Cycle for the formation of β-methylene-δ,δ-bis(triflyl)pentanals **4**.

3. Conclusions

The reactivity of α-allenols against the highly polarized molecule $Tf_2C{=}CH_2$, generated in situ from a Koshar-type zwitterion, has been studied. The novel transformation was carried out through a basic π-type catalysis based on a cationic gold complex, which led to the synthesis of different bis(triflil)enals [8].

4. Experimental Part

General procedure for the gold-catalyzed reaction of allenols 1 and [D_1]-1 with betaine 2 or deuterated betaine [D_2]-2: Betaine **2** or [D_2]-**2** (0.2 mmol), [Au] (0.01 mmol), and [Ag] (0.01 mmol) were sequentially added to a solution of the appropriate allenol **1** or [D_1]-**1** (0.2 mmol) in 1,2-dichloroethane (4 mL) at 130 °C. The reaction was heated at 130 °C in a sealed tube until disappearance of the starting material (TLC). The reaction mixture was allowed to cool to room temperature and then it was concentrated under reduced pressure. Chromatography of the residue eluting with toluene/ethyl acetate mixtures gave analytically pure compounds. Spectroscopic and analytical data for 3-methylene-5,5-bis(triflyl)pentanals **4** or [D_n]-**4** follow.

3-Methylene-5,5-bis(triflyl)pentanal 4a. From 25 mg (0.14 mmol) of allenol **1a**, and after flash chromatography of the residue using toluene/ethyl acetate (1:1) as eluent gave compound **4a** (41 mg, 61%) as a pale blue oil; ^{1}H NMR (300 MHz, CD_3CN): δ = 9.67 (s, 1H, CHO), 7.19 (m, 4H, ArH), 5.51 (m, 1H, C*H*H), 5.04 (t, 1H, *J* = 1.6 Hz, CH*H*), 2.84 (m, 2H, CH_2), 2.32 (s, 3H, CH_3), 1.51 (s, 3H, CH_3); ^{13}C NMR (75 MHz, CD_3CN): δ = 201.8 (CHO), 149.8, 137.9, 137.2, 130.3 (Ar, 2CH), 130.0, 128.9 (Ar, 2CH), 114.2 (CH_2), 60.3, 31.9 (CH_2), 21.0 (CH_3), 20.1 (CH_3); ^{19}F NMR (282 MHz, CD_3CN): δ = −79.5 (s, 6F, $2CF_3$); IR: ν = 1728, 1347, 1196 cm^{-1}; HRMS (ESI): calcd for $C_{16}H_{15}F_6O_5S_2$ [*M*]$^-$: 465.0271; found: 465.0278.

3-Methylene-5,5-bis(triflyl)pentanal 4b. From 25 mg (0.13 mmol) of allenol **1b**, and after flash chromatography of the residue using toluene/ethyl acetate (1:1) as eluent gave compound **4b** (47 mg, 74%) as a pale green oil; ^{1}H NMR (300 MHz, CD_3CN): δ = 9.65 (s, 1H, CHO), 7.21 (m, 2H, ArH), 6.93 (m, 2H, ArH), 5.52 (s, 1H, C*H*H), 5.02 (t, 1H, *J* = 1.6 Hz, CH*H*), 3.78 (s, 3H, OCH_3), 2.85 (m, 2H, CH_2), 1.50 (s, 3H, CH_3); ^{13}C NMR (75 MHz, CD_3CN): δ = 201.6 (CHO), 159.8, 150.0, 132.7, 131.9, 130.2 (Ar, 2CH), 115.0 (Ar, 2CH), 114.1 (CH_2),

59.9, 55.9, (OCH_3), 31.8 (CH_2), 20.1 (CH_3); ^{19}F NMR (282 MHz, CD_3CN): δ = −79.4 (s, 6F, $2CF_3$); IR: ν = 1717, 1336, 1097, 1180 cm^{-1}; HRMS (ESI): calcd for $C_{16}H_{16}F_6NaO_6S_2$ [*M* + Na]$^+$: 505.0185; found: 505.0163.

3-Methylene-5,5-bis(triflyl)pentanal 4c. From 25 mg (0.11 mmol) of allenol **1c**, and after flash chromatography of the residue using toluene/ethyl acetate (1:1) as eluent gave compound **4c** (28 mg, 50%) as a pale yellow oil; ^1H NMR (500 MHz, CD_3CN): δ = 9.65 (s, 1H, CHO), 7.53 (d, 2H, *J* = 8.7 Hz, ArH), 7.22 (d, 2H, *J* = 8.7 Hz, ArH), 5.57 (s, 1H, C*H*H), 5.07 (t, 1H, *J* = 1.6 Hz, CH*H*), 2.84 (m, 2H, CH_2), 1.52 (s, 3H, CH_3); ^{13}C NMR (125 MHz, CD_3CN): δ = 201.3 (CHO), 149.1, 140.0, 132.5 (Ar, 2CH), 131.2 (Ar, 2CH), 129.9, 121.7, 114.9 (CH_2), 60.3, 31.9 (CH_2), 20.2 (CH_3); ^{19}F NMR (282 MHz, CD_3CN): δ = −79.5 (s, 6F, $2CF_3$); IR: ν = 1717, 1424, 1196, 1265, 738 cm^{-1}; HRMS (ESI): calcd for $C_{15}H_{12}BrF_6O_5S_2$ [*M*]$^-$: 528.9219; found: 528.9214.

3-Methylene-5,5-bis(triflyl)pentanal 4d. From 40 mg (0.21 mmol) of allenol **2d**, and after flash chromatography of the residue using toluene/ethyl acetate (2:1) as eluent gave compound **4d** (54 mg, 54%) as a pale green oil; ^1H NMR (300 MHz, CD_3CN): δ = 9.66 (s, 1H, CHO), 7.38 (m, 2H, ArH), 7.29 (m, 2H, ArH), 5.56 (m, 1H, C*H*H), 5.07 (t, 1H, *J* = 1.6 Hz, CH*H*), 2.78 (m, 2H, CH_2), 1.53 (s, 3H, CH_3); ^{13}C NMR (75 MHz, CD_3CN): δ = 201.4 (CHO), 139.5, 133.5, 130.9 (Ar, 2CH), 129.5 (Ar, 2CH), 124.7, 120.3, 114.9 (CH_2), 60.3, 31.9 (CH_2), 20.2 (CH_3); ^{19}F NMR (282 MHz, CD_3CN): δ = −79.5 (s, 6F, $2CF_3$); IR ($CHCl_3$): ν = 1720, 1373, 1142, 1200 cm^{-1}; HRMS (ESI): calcd for $C_{15}H_{12}ClF_6O_5S_2$ [*M*]$^-$: 484.9724; found: 484.9727.

3-Methylene-5,5-bis(triflyl)pentanal 4e. From 40 mg (0.23 mmol) of allenol **1e**, and after flash chromatography of the residue using toluene/ethyl acetate (1:1) as eluent gave compound **4e** (56 mg, 52%) as a pale green oil; ^1H NMR (300 MHz, CD_3CN): δ = 9.69 (s, 1H, CHO), 7.63 (m, 1H, ArH), 7.53 (m, 1H, ArH), 7.25 (m, 1H, ArH), 7.12 (m, 1H, ArH), 5.54 (m, 1H, C*H*H), 5.04 (t, 1H, *J* = 1.6 Hz, CH*H*), 2.87 (m, 2H, CH_2), 2.32 (s, 3H, CH_3), 1.51 (s, 3H, CH_3); ^{13}C NMR (75 MHz, CD_3CN): δ = 201.8 (CHO), 149.8, 140.3, 139.4, 132.8 (Ar, CH), 132.0 (Ar, CH), 129.8 (Ar, CH), 128.7 (Ar, CH), 126.0, 114.3 (CH_2), 60.5, 31.9 (CH_3), 21.5 (CH_2), 20.1 (CH_3); ^{19}F NMR (282 MHz, $CHCl_3$): δ = −79.5 (s, 6F, $2CF_3$); IR: ν = 1712, 1434, 1262 cm^{-1}; HRMS (ESI): calcd for $C_{16}H_{15}F_6O_5S_2$ [*M*]$^-$: 465.0271; found: 465.0261.

3-Methylene-5,5-bis(triflyl)pentanal 4f. From 50 mg (0.30 mmol) of allenol **2f**, and after flash chromatography of the residue using toluene/ethyl acetate (2:1) as eluent gave compound **4f** (35 mg, 45%) as a pale green oil; ^1H NMR (500 MHz, CD_3CN): δ = 9.69 (s, 1H, CHO), 7.29 (m, 1H, ArH), 6.86 (m, 3H, ArH), 5.55 (m, 1H, C*H*H), 5.06 (t, 1H, *J* = 1.7 Hz, CH*H*), 3.77 (s, 3H, OCH_3), 2.88 (m, 2H, CH_2), 1.52 (s, 3H, CH_3); ^{13}C NMR (125 MHz, CD_3CN): δ = 201.6 (CHO), 161.0, 149.7, 142.0, 130.6 (Ar, CH), 121.8 121.0 (Ar, CH), 114.6 (Ar, CH), 114.3 (CH_2), 113.9 (Ar, CH), 60.6, 55.8 (OCH_3), 31.9 (CH_2), 20.2 (CH_3); ^{19}F NMR (282 MHz, CD_3CN): δ = −79.5 (s, 6F, $2CF_3$); IR: ν = 1717, 1336, 1114, 1193 cm^{-1}; HRMS (ESI): calcd for $C_{16}H_{15}F_6O_6S_2$ [*M*]$^-$: 481.0214; found: 481.0220.

3-Methylene-5,5-bis(triflyl)pentanal 4g. From 40 mg (0.23 mmol) of allenol **2g**, and after flash chromatography of the residue using toluene/ethyl acetate (1:1) as eluent gave compound **4g** (24 mg, 32%) as a pale green oil; ^1H NMR (300 MHz, CD_3CN): δ = 9.79 (s, 1H, CHO), 7.26 (m, 2H, ArH), 6.98 (m, 2H, ArH), 5.54 (m, 1H, C*H*H), 5.13 (t, 1H, *J* = 1.7 Hz, CH*H*), 3.73 (s, 3H, OCH_3), 2.97 (m, 2H, CH_2), 1.43 (s, 3H, CH_3); ^{13}C NMR (75 MHz, CD_3CN): δ = 202.0 (CHO), 157.9, 149.0, 132.0, 130.2 (Ar, CH), 129.7 (Ar, CH), 122.1 (Ar, CH), 114.7 (CH_2), 112.8 (Ar, CH), 58.9, 56.1 (OCH_3), 32.6 (CH_2), 21.3 (CH_3); ^{19}F NMR (282 MHz, CD_3CN): δ = −79.4 (s, 6F, $2CF_3$); IR: ν = 1701, 1421, 1119, 1262 cm^{-1}; HRMS (ESI): calcd for $C_{16}H_{15}F_6O_6S_2$ [*M*]$^-$: 481.0214; found: 481.0220.

3-Methylene-5,5-bis(triflyl)pentanal 4h. From 40 mg (0.22 mmol) of allenol **2h**, and after flash chromatography of the residue using hexanes/*i*-propanol (4:1) as eluent gave compound **4h** (32 mg, 41%) as a pale brown oil; ^1H NMR (500 MHz, CD_3CN): δ = 9.46 (s, 1H, CHO), 7.45 (m, 1H, ArH), 7.33 (m, 3H, ArH), 7.26 (m, 1H, ArH), 6.44 (m, 2H, CH=CH),

5.51 (s, 1H, C*H*H), 5.11 (s, 1H, CH*H*), 3.02 (s, 2H, CH_2), 1.37 (s, 3H, CH_3); ^{13}C NMR (125 MHz, CD_3CN): δ = 201.3 (CHO), 148.5, 138.2, 132.6 (CH), 130.3 (CH), 129.6 (Ar, 2CH), 128.7 (Ar, CH), 127.3 (Ar, 2CH), 121.2, 114.5 (CH_2), 59.0, 31.9 (CH_2), 19.1 (CH_3); ^{19}F NMR (282 MHz, CD_3CN): δ = −79.4 (s, 6F, $2CF_3$); IR: ν = 1715, 1346, 1141, 1182 cm^{-1}; HRMS (ESI): calcd for $C_{17}H_{15}F_6O_5S_2$ [*M*]$^-$: 477.0265; found: 477.0271.

3-Methylene-5,5-bis(triflyl)pentanal 4i. From 15 mg (0.09 mmol) of allenol **2i**, and after flash chromatography of the residue using toluene/ethyl acetate (3:1) as eluent gave compound **4i** (20 mg, 57%) as a pale yellow oil; ^1H NMR (500 MHz, acetone-d_6): δ = 9.70 (s, 1H, CHO), 7.35 (m, 5H, ArH), 5.65 (s, 1H, C*H*H), 5.03 (t, 1H, *J* = 1.6 Hz, CH*H*), 2.94 (m, 2H, CH_2), 1.54 (s, 3H, CH_3); ^{13}C NMR (125 MHz, acetone-d_6): δ = 200.7 (CHO), 149.8, 140.4, 133.2, 129.5 (Ar, 2CH), 128.9 (Ar, 2CH), 127.8 (Ar, CH), 122.6 (q, *J* = 329.3 Hz, $2CF_3$), 114.3 (CH_2), 60.6, 32.1 (CH_2), 20.0 (CH_3); ^{19}F NMR (282 MHz, acetone-d_6): δ = −80.2 (s, 6F, $2CF_3$); IR: ν = 1720, 1334, 1123, 1193 cm^{-1}; HRMS (ESI): calcd for $C_{15}H_{14}F_6O_5S_2$ [*M*]$^-$: 451.0114; found: 451.0185.

3-Methylene-5,5-bis(triflyl)pentanal [D_2]-4a. From 30 mg (0.17 mmol) of allenol **1a**, and after flash chromatography of the residue using toluene/ethyl acetate (3:1) as eluent gave compound [D_2]-**4a** (42 mg, 53%) as a pale green oil; ^1H NMR (400 MHz, acetone-d_6): δ = 9.67 (s, 1H, CHO), 7.19 (m, 4H, ArH), 5.62 (s, 1H, C*H*H), 5.01 (s, 1H, CH*H*), 2.30 (s, 3H, CH_3), 1.51 (s, 3H, CH_3); ^{13}C NMR (101 MHz, acetone-d_6): δ = 200.7 (CHO), 149.9, 137.4, 130.2 (Ar, 2CH), 129.8, 129.5, 128.8 (Ar, 2CH), 122.5 (q, *J* = 329.5 Hz, $2CF_3$), 114.2 (CH_2), 60.2, 20.9 (CH_3), 19.9 (CH_3); ^{19}F NMR (376 MHz, acetone-d_6): δ = −79.2 (s, 6F, $2CF_3$); IR: ν = 1720, 1338, 1054, 1187 cm^{-1}; HRMS (ESI): calcd for $C_{16}H_{14}D_2F_6O_5S_2$ [*M*]$^-$: 467.0396; found: 467.0413.

3-Methylene-5,5-bis(triflyl)pentanal [D_2]-4b. From 30 mg (0.16 mmol) of allenol **1b**, and after flash chromatography of the residue using toluene/ethyl acetate (3:1) as eluent gave compound [D_2]-**4b** (55 mg, 73%) as a pale green oil; ^1H NMR (400 MHz, acetone-d_6): δ = 9.65 (s, 1H, CHO), 7.24 (d, 2H, *J* = 8.9 Hz, ArH), 6.93 (d, 2H, *J* = 8.9 Hz, ArH), 5.61 (s, 1H, C*H*H), 5.00 (s, 1H, CH*H*), 3.79 (s, 3H, OCH_3), 1.51 (s, 3H, CH_3); ^{13}C NMR (101 MHz, acetone-d_6): δ = 200.5 (CHO), 159.7, 150.0, 132.6, 131.8, 130.1 (Ar, 2CH), 122.6 (q, *J* = 329.0 Hz, $2CF_3$), 114.9 (Ar, 2CH), 114.0 (CH_2), 59.8, 55.5 (OCH_3), 20.0 (CH_3); ^{19}F NMR (376 MHz, acetone-d_6): δ = −80.2 (s, 6F, $2CF_3$); IR: ν = 1717, 1338, 1053, 1182 cm^{-1}; HRMS (ESI): calcd for $C_{16}H_{14}D_2F_6O_6S_2$ [*M*]$^-$: 483.0345; found: 483.0351.

3-Methylene-5,5-bis(triflyl)pentanal [D_2]-4e. From 10 mg (0.06 mmol) of allenol **1e**, and after flash chromatography of the residue using toluene/ethyl acetate (3:1) as eluent gave compound [D_2]-**4e** (13 mg, 48%) as a colorless oil; ^1H NMR (300 MHz, acetone-d_6): δ = 9.68 (s, 1H, CHO), 7.25 (t, 1H, *J* = 7.6 Hz, ArH), 7.18 (m, 1H, ArH), 7.10 (m, 2H, ArH), 5.64 (s, 1H, C*H*H), 5.02 (s, 1H, CH*H*), 2.32 (s, 3H, CH_3), 1.52 (s, 3H, CH_3); ^{13}C NMR (75 MHz, acetone-d_6): δ = 200.7 (CHO), 149.9, 139.1, 133.8, 129.8 (Ar, CH), 129.3 (Ar, CH), 128.5 (Ar, CH), 126.5, 125.9 (Ar, CH), 122.6 (q, *J* = 329.1 Hz, $2CF_3$), 114.2 (CH_2), 60.5, 21.5 (CH_3), 20.0 (CH_3); ^{19}F NMR (376 MHz, acetone-d_6): δ = −80.2 (s, 6F, $2CF_3$); IR: ν = 1718, 1338, 1182 cm^{-1}; HRMS (ESI): calcd for $C_{16}H_{13}D_2F_6O_5S_2$ [*M*]$^-$: 467.0396; found: 467.0420.

3-Methylene-5,5-bis(triflyl)pentanal [D_1]-4b. From 25 mg (0.13 mmol) of allenol [D_1]-**1b**, and after flash chromatography of the residue using toluene/ethyl acetate (3:1) as eluent gave compound [D_1]-**4b** (31 mg, 49%) as a pale yellow oil; ^1H NMR (400 MHz, acetone-d_6): δ = 7.24 (m, 2H, ArH), 6.93 (m, 2H, ArH), 5.61 (t, 1H, *J* = 2.0 Hz, C*H*H), 4.99 (t, 1H, *J* = 1.6 Hz, CH*H*), 3.79 (s, 3H, OCH_3), 2.92 (m, 2H, CH_2), 1.51 (s, 3H, CH_3); ^{13}C NMR (101 MHz, acetone-d_6): δ = 200.1 (t, *J* = 27.5 Hz, CDO), 159.7, 150.1, 131.7, 130.1 (Ar, 2CH), 122.5 (q, *J* = 329.0 Hz, $2CF_3$), 114.9 (Ar, 2CH), 113.9 (CH_2), 62.6, 59.7, 55.5 (OCH_3), 31.9 (CH_2), 19.9 (CH_3); ^{19}F NMR (376 MHz, acetone-d_6): δ = −80.2 (s, 6F, $2CF_3$); ^{23}Na NMR (132 MHz, acetone-d_6): δ = −8.3 (s, 1Na, Na); IR: ν = 1716, 1334, 1039, 1182 cm^{-1}; HRMS (ESI): calcd for $C_{16}H_{14}DF_6O_6S_2$ [*M*]$^-$: 482.0283; found: 482.0317.

3-Methylene-5,5-bis(triflyl)pentanal [D_1]-4i. From 25 mg (0.16 mmol) of allenol [D_1]-**1i**, and after flash chromatography of the residue using toluene/ethyl acetate (3:1) as eluent gave compound [D_1]-**4i** (42 mg, 60%) as a pale yellow oil; ^{1}H NMR (400 MHz, acetone-d_6): δ = 7.36 (m, 4H, ArH), 7.28 (m, 1H, ArH), 5.64 (t, 1H, *J* = 1.9 Hz, C*H*H), 5.03 (t, 1H, *J* = 1.6 Hz, CH*H*), 2.93 (m, 2H, CH_2), 1.54 (s, 3H, CH_3); ^{13}C NMR (101 MHz, acetone-d_6): δ = 200.6 (t, *J* = 27.5 Hz, CDO), 149.8, 140.4, 138.0, 133.2, 129.5 (Ar, 2CH), 128.9 (Ar, 2CH), 127.9 (Ar, CH), 122.6 (q, *J* = 329.0 Hz, $2CF_3$), 114.3 (CH_2), 60.5, 32.0 (CH_2), 20.0 (CH_3); ^{19}F NMR (376 MHz, acetone-d_6): δ = −80.2 (s, 6F, $2CF_3$); IR: ν = 1715, 1334, 1040, 1175 cm^{-1}; HRMS (ESI): calcd for $C_{15}H_{13}DF_6O_5S_2$ [*M*]$^-$: 452.0177; found: 452.0178.

3-Methylene-5,5-bis(triflyl)pentanal [D_1]-4e. From 25 mg (0.14 mmol) of allenol [D_1]-**1e**, and after flash chromatography of the residue using toluene/ethyl acetate (3:1) as eluent gave compound [D_1]-**4e** (32 mg, 48%) as a pale yellow oil; ^{1}H NMR (400 MHz, acetone-d_6): δ = 7.25 (t, 1H, *J* = 7.6 Hz, ArH), 7.18 (m, 1H, ArH), 7.10 (m, 2H, ArH), 5.64 (t, 1H, *J* = 2.0 Hz, C*H*H), 5.02 (t, 1H, *J* = 1.6 Hz, CH*H*), 2.94 (m, 2H, CH_2), 2.32 (s, 3H, CH_3), 1.52 (s, 3H, CH_3); ^{13}C NMR (101 MHz, acetone-d_6): δ = 200.6 (t, *J* = 27.8 Hz, CDO), 150.0, 140.2, 139.1, 133.8, 129.8 (Ar, CH), 129.3 (Ar, CH), 128.5 (Ar, CH), 125.9 (Ar, CH), 122.6 (q, *J* = 329.6 Hz, $2CF_3$), 114.1 (CH_2), 60.4, 32.1 (CH_2), 21.5 (CH_3), 20.0 (CH_3); ^{19}F NMR (376 MHz, acetone-d_6): δ = −80.2 (s, 6F, $2CF_3$); IR: ν = 1715, 1335, 1041, 1187 cm^{-1}; HRMS (ESI): calcd for $C_{16}H_{14}DF_6O_5S_2$ [*M*]$^-$: 466.0333; found: 466.0355.

3-Methylene-5,5-bis(triflyl)pentanal [D_3]-4b. From 25 mg (0.13 mmol) of allenol [D_1]-**1b**, and after flash chromatography of the residue using toluene/ethyl acetate (3:1) as eluent gave compound [D_3]-**4b** (31 mg, 49%) as a pale yellow oil; ^{1}H NMR (400 MHz, acetone-d_6): δ = 7.24 (m, 2H, ArH), 6.93 (m, 2H, ArH), 5.61 (s, 1H, C*H*H), 4.99 (s, 1H, CH*H*), 3.79 (s, 3H, OCH_3), 1.51 (s, 3H, CH_3); ^{13}C NMR (101 MHz, acetone-d_6): δ = 200.1 (t, *J* = 27.2 Hz, CDO), 159.7, 150.1, 132.6, 131.7, 130.1 (Ar, 2CH), 122.6 (q, *J* = 329.4 Hz, $2CF_3$), 114.9 (Ar, 2CH), 113.9 (CH_2), 59.7, 55.5 (OCH_3), 19.9 (CH_3); ^{19}F NMR (376 MHz, acetone-d_6): δ = −79.1 (s, 6F, $2CF_3$); ^{23}Na NMR (132 MHz, acetone-d_6): δ = −8.3 (s, 1Na, Na); IR: ν = 1712, 1338, 1184 cm^{-1}; HRMS (ESI): calcd for $C_{16}H_{12}D_3F_6O_6S_2$ [*M*]$^-$: 484.0408; found: 484.0445.

3-Methylene-5,5-bis(triflyl)pentanal [D_3]-4i. From 30 mg (0.19 mmol) of allenol [D_1]-**1i**, and after flash chromatography of the residue using toluene/ethyl acetate (3:1) as eluent gave compound [D_3]-**4i** (39 mg, 46%) as a pale yellow oil; ^{1}H NMR (400 MHz, acetone-d_6): δ = 7.33 (m, 5H, ArH), 5.65 (s, 1H, C*H*H), 5.03 (s, 1H, CH*H*), 1.54 (s, 3H, CH_3); ^{13}C NMR (101 MHz, acetone-d_6): δ = 200.5 (t, *J* = 27.5 Hz, CDO), 149.8, 140.4, 133.2, 129.5 (Ar, 2CH), 128.9 (Ar, 2CH), 127.8 (Ar, CH), 122.6 (q, *J* = 329.1 Hz, $2CF_3$), 114.4 (CH_2), 60.5, 20.0 (CH_3); ^{19}F NMR (376 MHz, acetone-d_6): δ = −80.2 (s, 6F, $2CF_3$); IR: ν = 1713, 1337, 1187 cm^{-1}; HRMS (ESI): calcd for $C_{15}H_{11}D_3F_6O_5S_2$ [*M*]$^-$: 454.0302; found: 454.0301.

3-Methylene-5,5-bis(triflyl)pentanal [D_3]-4e. From 25 mg (0.14 mmol) of allenol [D_1]-**1e**, and after flash chromatography of the residue using toluene/ethyl acetate (3:1) as eluent gave compound [D_3]-**4e** (32 mg, 48%) as a pale yellow oil; ^{1}H NMR (400 MHz, acetone-d_6): δ = 7.25 (t, 1H, *J* = 7.6 Hz, ArH), 7.18 (m, 1H, ArH), 7.10 (m, 2H, ArH), 5.64 (s, 1H, C*H*H), 5.02 (s, 1H, CH*H*), 2.32 (s, 3H, CH_3), 1.52 (s, 3H, CH_3); ^{13}C NMR (101 MHz, acetone-d_6): δ = 200.3 (t, *J* = 27.5 Hz, CDO), 149.9, 140.2, 139.1, 133.8, 129.8 (Ar, CH), 129.3 (Ar, CH), 128.5 (Ar, CH), 125.9 (Ar, CH), 122.6 (q, *J* = 328.9 Hz, $2CF_3$), 114.2 (CH_2), 60.4, 21.5 (CH_3), 20.0 (CH_3); ^{19}F NMR (376 MHz, acetone-d_6): δ = −80.2 (s, 6F, $2CF_3$); IR: ν = 1706, 1340, 1190 cm^{-1}; HRMS (ESI): calcd for $C_{16}H_{12}D_3F_6O_5S_2$ [*M*]$^-$: 468.0459; found: 468.0489.

Author Contributions: M.T.-P. planned and conducted experiments. M.T.-P. analyzed the data for the compounds and compiled most of the Supplementary Information. T.M.d.C. analyzed data to support the mechanistic proposal. H.Y. carried out DFT calculations. P.A. designed and directed the project. M.T.-P. wrote the manuscript. T.M.d.C., H.Y. and P.A. contributed to discussion. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by AEI (MICIU), FEDER (Project PGC2018-095025-B-I00) and KAKENHI (20K06947).

Acknowledgments: We are grateful to Beatriz Peñín for preliminary studies.

Conflicts of Interest: The authors declare no conflict of interest.

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