JOC The Journal of Organic Chemistry

Note

pubs.acs.org/joc

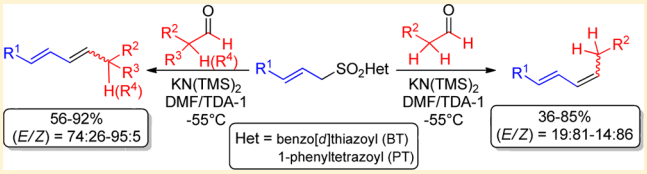
Julia–Kocienski Reaction-Based 1,3-Diene Synthesis: Aldehyde-Dependent (*E*,*E*/*E*,*Z*)-Selectivity

François Billard, Raphaël Robiette, and Jiří Pospíšil*

Institute of Condensed Matter and Nanosciences–Molecules, Solids and Reactivity (IMCN/MOST), Université Catholique de Louvain, Place Louis Pasteur 1, bte L4.01.02, 1348 Louvain-la-Neuve, Belgium

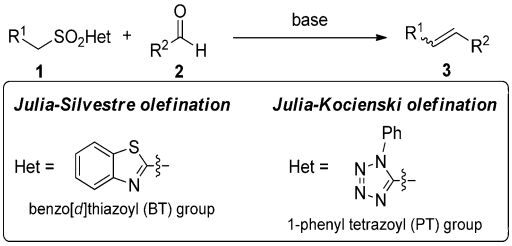
Supporting Information

ABSTRACT: A new modification of Julia–Kocienski olefination reaction based on the use of cation-specific chelating agents that yields 1,3-dienes with predictable (*E*/*Z*)-selectivity on newly created double bond was developed. The influence of the aldehyde structure on reaction (*E*/*Z*) selectivity is discussed and rationalized.



Over the past few decades, our synthetic tools were enriched by various novel and fundamentally different approaches to alkene synthesis. Unfortunately, none of the developed methods yet provided a universal solution in terms of yield, selectivity, and functional group tolerance. Since the mid-1990s, the second-generation Julia olefination reaction has become a privileged synthetic method when two complex molecular fragments should be connected (Scheme 1).[1] The

Scheme 1. Second-Generation Julia Olefination Reaction

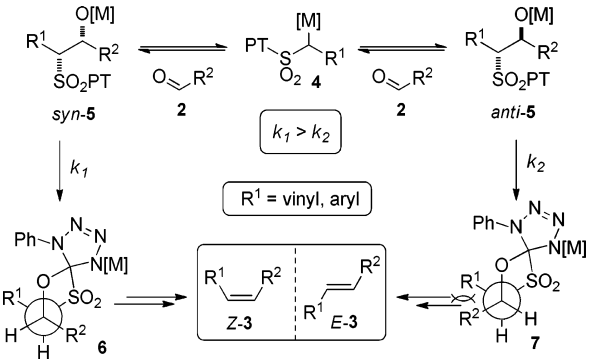


popularity of this synthetic method is based not only on its versatility, wide functional group tolerance and mild reaction conditions under which the reaction proceeds, but also on its generally high (*E*)-selectivity.

In our group, we are focused on the development of new more selective modifications of Julia–Kocienski olefination reaction.[2] After our recent success where we were able to increase the (*E*)-selectivity of this reaction,[2] we decided to focus our attention on the development of (*Z*)-selective modification of this reaction (Scheme 2). Taking into account the mechanism of the Julia–Kocienski reaction,[1] we reasoned that if the addition of sulfonyl anion **4** to aldehyde **2** was reversible,[3] reaction selectivity would be determined by the relative rate of Smiles rearrangement of *syn* and *anti* alkoxides **5**. It is known that for steric reasons the Smiles rearrangement of *syn*-**5** adduct that yields (*Z*)-olefins proceeds faster as compared to the rearrangement of *anti*-**5** adduct that yields (*E*)-olefins.[4]

In the literature, the addition of sulfonyl anion **4** to aldehyde **2** (R^1, R^2 = alkyl) is reported to be nonreversible.[1b,4] However,

Scheme 2. Proposed Equilibrium-Based Approach to (*Z*)-Olefins



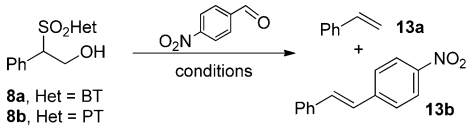
we assumed that if allylic or benzylic anions **4** (R^1 = alkyl or benzyl) would be reacted with aldehyde **2**, the addition reaction might be reversible.[5] To investigate this hypothesis, the reactivity and reaction selectivity of α-sulfonyl anions generated from allylic and benzylic sulfones[6] were studied in the context of 1,3-diene synthesis.[7]

Our study started with the investigation of the key step of our hypothesis, the reversibility of the addition of allylic and benzylic sulfonyl anions to aldehydes. Thus, hydroxy sulfones **8a** and **8b** were prepared[8] and reacted with $LiN(TMS)_2$ or $KN(TMS)_2$ in the presence of *p*-nitrobenzaldehyde **12b** (Table 1).[9] The goal of these experiments was to find suitable reaction conditions under which alcoholate **9** would not undergo Smiles rearrangement (transformation of alcoholate **9** to olefin **13a**) but rather retroaddition reaction (transformation of alcoholate **9** to benzylic anion **11** and aldehyde **12a**) (Scheme 3). The formation of the benzylic anion **11** would then be proved by its trapping with reactive aldehyde **12b** and the consecutive olefin **13b** formation.

Received: May 22, 2012
Published: July 5, 2012

   dx.doi.org/10.1021/jo300929a | J. Org. Chem. 2012, 77, 6358–6364

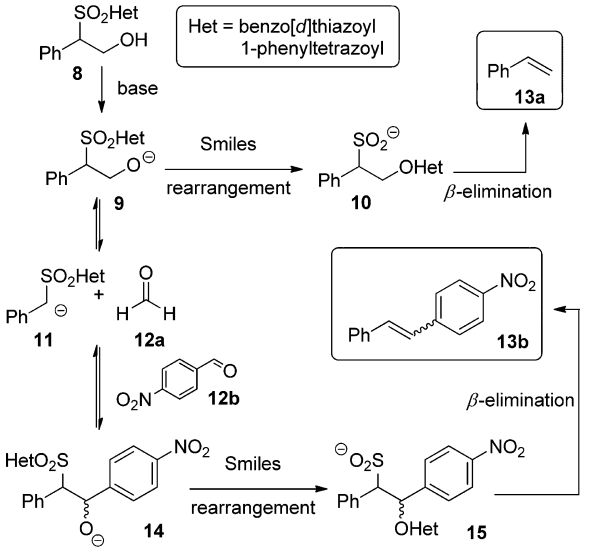
Table 1. Hydroxy Sulfone 8 Retroaddition Reaction Evaluation



entry	sulfone	conditions	13a:13b ratio[a]
1	8a	$LiN(TMS)_2$ (2.2 equiv),−60 °C, DMF/HMPA = 3:1	>98:<2
2	8a	$KN(TMS)_2$ (1.2 equiv), DMF, −55 °C	>98:<2
3	8a	$KN(TMS\}_2$ (1.2 equiv), 18-crown-6 (2.5 equiv), DMF, −55 °C	34:66
4	8a	$KN(TMS)_2$ (1.2 equiv), DMF/TDA-1 = 3:1,−60 °C	22:78 (72)[b]
5	8b	$KN(TMS)_2$ (1.2 equiv), −55 °C, 18-crown-6 (2.5 equiv), DMF	15:85 (65)[b]
6	8b	$KN(TMS)_2$ (1.2 equiv), DMF/TDA-1 = 3:1, −60 °C	<2:>98 (93)[b]

[a]Based on HPLC analysis. [b]Isolated yield of **13b** (in %).

Scheme 3. Competitive Experiment Designed To Determine if Hydroxy Sulfone 8 Can Undergo Retroaddition Reaction



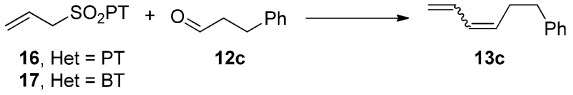
Our competitive experiments showed that the hydroxy sulfones **8** undergo retroaddition only when polar solvents and efficient cation-chelating agents (18-crown-6, TDA-1 for K^+) are used. Moreover, it was shown that BT-containing sulfone **8a** underwent retroaddition less readily as compared to sulfone **8b** (Table 1, entries 3 vs 5 and 4 vs 6). This observation could be explained by the difference in reactivity of the imine-like electrophilic centers present in BT- and PT-sulfones.[1,9,10]

Having established the conditions under which the addition of benzylic sulfones to aldehydes is reversible, we focused our attention on the (*E*/*Z*)-selectivity of the newly created olefin bond evaluation (Table 2).[9] Our goal was to find reaction conditions under which the transformation of *syn*-**5** adduct to spiro **6** (k_1, yields olefin (*Z*)-**3**) proceeds faster than the adduct *anti*-**5** to spiro **7** (k_2, yields olefin (*E*)-**3**) (Scheme 2).

First, the reaction of allyl PT-sulfone **16** and aldehyde **12c** was carried out using the standard Barbier-type[11] Julia olefination protocol (Table 1, entries 1 and 2). As expected, if THF was used as solvent, (*E*)-**13c** olefin was formed predominantly (entry 1). The use of "equilibrating" reaction conditions, DMF as a solvent and 18-crown-6 as cation scavenger, flipped the selectivity and yielded (*Z*)-**13c** olefin as the major product (entry 2). To increase further the (*Z*)-selectivity, we decided to premetalate sulfone **16** with $KN(TMS)_2$ and add aldehyde **12c** 30 min later (entry 3). Gratifyingly, olefin **13c** was formed in an increased 25:75 (*E*/*Z*) ratio. Addition of K^+-specific chelating agent, 18-crown-6, increased further the (*Z*)-selectivity of the olefin **3c** formation ((*E*/*Z*) = 16:84) but substantially diminished the reaction yield (entry 4).

It was found that prolonged premetalation reaction time carried out in the presence of cation scavenger led to rapid sulfone **16** degradation. Gratifyingly, the stirring of sulfone **16** with $KN(TMS)_2$ and 18-crown-6 for only 2 min prior to aldehyde **12c** addition yielded the targeted olefin **13c** with a 15:85 (*E*/*Z*) ratio and 74% yield (entry 6). If a shorter

Table 2. Reaction between Allyl Sulfones 16 and 17 and Dihydrocinnamaldehyde 12c



entry	conditions[a]	yield[b] (%)	*E*/*Z*[c]
1	$KN(TMS)_2$ added to a solution of **16** and **12c** in THF at −78 °C	nd	68:32
2	$KN(TMS)_2$ added to a solution of **16**, **12c** and 18-crown-6 in DMF at −55 °C	73	35:65
3	$KN(TMS)_2$ added to a solution of **16** in DMF at −55 °C, stirred for 30 min, aldehyde **12c** added at −55 °C	64	25:75
4	$KN(TMS)_2$ added to a solution of **16** and 18-crown-6 in DMF at −55 °C, stirred for 30 min, aldehyde **12c** added at −55 °C	17	16:84
5	$KN(TMS)_2$ added to a solution of **16** and 18-crown-6 in DMF at −55 °C, stirred for 1 min, aldehyde **12c** added at −55 °C	79	23:77
6	$KN(TMS)_2$ added to a solution of **16** in DMF/TDA-1 = 3:1 (v/v) at −60 °C, stirred for 2 min, aldehyde **12c** added at −60 °C	78	14:86
7	$KN(TMS)_2$ added to a solution of **17** in DMF/TDA-1 = 3:1 (v/v) at −60 °C, stirred for 2 min, aldehyde **12c** added at −60 °C	52	16:84

[a]The following quantities of given reagents were used: sulfone **16** or **17** (1.0 equiv), $KN(TMS)_2$ (1.1 equiv), aldehyde **12c** (1.1 equiv), and 18-crown-6 (2.3 equiv). [b]Average of two runs. Isolated yield. [c]Average of two runs. Based on GC analysis.

dx.doi.org/10.1021/jo300929a | J. Org. Chem. 2012, 77, 6358−6364

Table 3. Synthesis of Dienes 13 via Julia–Kocienski and Julia–Silvestre Reactions

entry	sulfone	aldehyde	product[a]	conditions[b]: yield[c] (*E*/*Z*)[d]
1	SO_2PT			**A:** 72% (63:37)
2				**B:** 65% (58:42)
3	**16**	**12c**	**13c**	**C:** 74% (15:85)
4		Ph	Ph	**D:** 78% (14:86)
5				**A:** 68% (79:21)
6				**B:** 47% (62:38)
7		**12d**	**13d**	**C:** 36% (15:85)
8		OBn	OBn	**D:** 48% (14:86)
9				**A:** 82% (66:34)
10				**B:** 67% (55:45)
11		**12e**		**C:** 63% (69:31)
12		OBn	BnO **13e**	**D:** 72% (72:28)
13				**A:** 65% (71:29)
14	SO_2PT			**B:** 58% (40:60)
15		**12c**		**C:** 50% (16:84)
16	C_3H_7 **18**	Ph	Ph **13f**	**D:** 40% (13:87)
17				**A:** 69% (55:45)
18				**B:** 59% (66:34)
19		**12e**		**C:** 55% (75:25)
20		OBn	BnO **13g**	**D:** 56% (74:26)
21				**A:** 82% (62:38)
22				**B:** 69% (54:46)
23				**C:** 50% (83:17)
24		TBDPSO **12g**	TBDPSO OBn **13h**	**D:** 62% (82:18)
25				**A:** 73% (65:35)
26				**B:** 63% (51:49)
27		**12h**	**13i**	**C:** 59% (77:23)
28				**D:** 68% (82:18)
29				**A:** 59% (61:39)
30				**B:** 65% (70:30)
31		TBSO **12i**	**13j**	**C:** 58% (94:6)
32			OTBS	**D:** 63% (96:4)
33				**A:** 64% (55:45)
34				**B:** 55% (51:49)
35		**12j**	**13k**	**C:** 51% (76:24)
36		Cl	Cl	**D:** 58% (74:26)
37				**A:** 70% (56:44)
38				**B:** 60% (48:52)
39		**12b**	**13l**	**C:** 65% (86:14)
40		O_2N	O_2N	**D:** 63% (89:11)
41				**A:** 68% (56:44)
42	SO_2PT			**B:** 69% (52:48)
43		**12c**		**C:** 59% (16:84)
44	Ph **19**	Ph	Ph **13m**	**D:** 60% (14:86)
45				**A:** 57% (65:35)
46				**B:** 53% (60:40)
47		**12n**	**13n**	**C:** 36% (15:85)
48		O		**D:** 48% (14:86)
49				**A:** 81% (42:58)
50				**B:** 63% (55:45)
51		**12e**		**C:** 55% (60:40)
52		OBn	BnO **13o**	**D:** 69% (56:44)
53				**A:** 81% (55:45)
54	SO_2PT			**B:** 75% (63:47)
55		BnO TBDPSO **12g**	TBDPSO OBn **13p**	**C:** 72% (88:12)
56	Ph **19**			**D:** 80% (82:18)
57				**A:** 66% (58:42)
58				**B:** 52% (69:21)
59		**12j**	**13q**	**C:** 45% (92:8)
60				**D:** 49% (95:5)
61				**A:** 68% (59:41)
62	SO_2BT			**B:** 53% (57:43)
63		**12c**	**13c**	**C:** 39% (30:70)
64	**17**	Ph	Ph	**D:** 42% (20:80)
65				**A:** 69% (65:35)
66				**B:** 65% (52:48)
67		**12d**	**13d**	**C:** 73% (20:80)
68		OBn	OBn	**D:** 74% (19:81)
69				**A:** 72% (56:44)
70				**B:** 66% (52:48)
71		**12e**		**C:** 70% (68:32)
72		OBn	BnO **13e**	**D:** 71% (70:30)
73				**A:** 75% (58:42)
74	SO_2BT			**B:** 72% (55:45)
75		**12c**		**C:** 69% (20:80)
76	C_3H_7 **20**	Ph	Ph **13f**	**D:** 73% (17:83)
77				**A:** 68% (55:45)
78				**B:** 69% (60:40)
79		TBSO **12i**	**13j**	**C:** 65% (90:10)
80			OTBS	**D:** 70% (91:9)
81				**A:** 56% (49:51)
82				**B:** 49% (45:55)
83		**12j**	**13k**	**C:** 53% (72:28)
84		Cl	Cl	**D:** 55% (78:22)
85	SO_2BT			**A:** 86% (57:43)
86				**B:** 79% (55:45)
87		**12c**		**C:** 82% (18:82)
88	**21** Ph	Ph	Ph **13m**	**D:** 85% (15:85)
89				**A:** 95% (48:52)
90	SO_2BT			**B:** 92% (42:58)
91		**12c**		**C:** 74% (15:85)
92	Ph **22**	Ph	Ph **13r**	**D:** 73% (14:86)
93				**A:** 85% (42:58)
94				**B:** 70% (32:68)
95		**12e**		**C:** 91% (81:19)
96		OBn	BnO **13s**	**D:** 92% (83:17)

[a] Overall yields refer to pure, isolated products. [b] **Method A**: Sulfone (1.0 equiv), aldehyde (1.1 equiv), THF (-78°C) then $KN(TMS)_2$ (1.1 equiv). **Method B**: Sulfone (1.0 equiv), aldehyde (1.1 equiv), DMF (-55°C) then $KN(TMS)_2$ (1.1 equiv). **Method C**: Sulfone (1.0 equiv), 18-crown-6 (2.5 equiv), $KN(TMS)_2$ (1.1 equiv), DMF (-55°C), 2 min at -55°C then aldehyde (1.1 equiv). **Method D**: Sulfone (1.0 equiv), $KN(TMS)_2$ (1.1 equiv), DMF/TDA-1 = 3:1 (V/V) (-60°C), 2 min at -60°C then aldehyde (1.1 equiv). [c] (*E*/*Z*)-Ratio refers to newly created olefin bond. Based on crude ^{1}H-NMR analysis. [d] Color code indicates a substantial increase in (*E*) or (*Z*) selectivity in olefin **13** formation observed under our newly developed cation-free conditions.

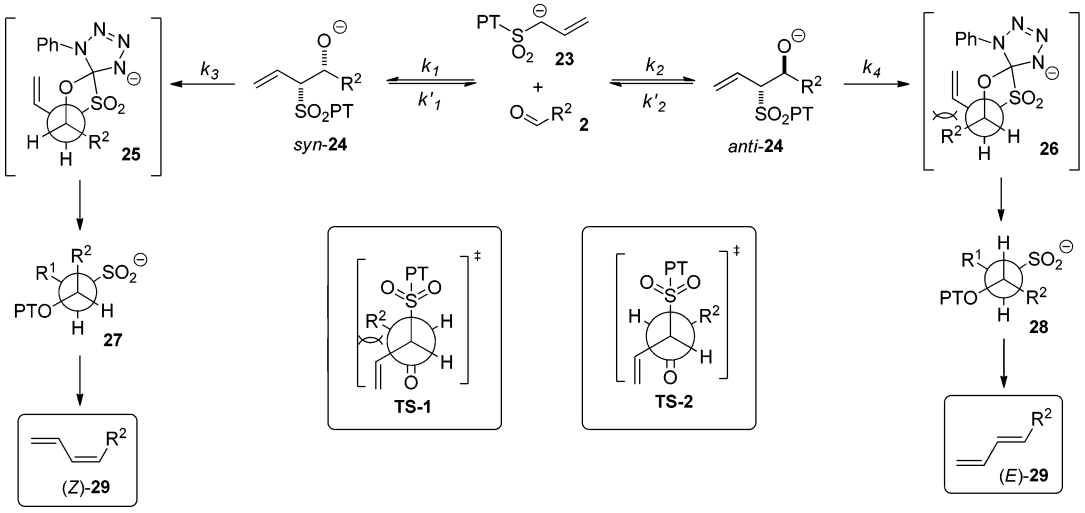
premetalation period (1 min) was employed, erosion of the (*Z*)-selectivity was observed (entry 5). To further increase the (*Z*)-**13c** formation, TDA-1[12] was used as cosolvent (entries 6 and 7). The use of DMF/TDA-1 = 3:1 (V/V) solvent mixture afforded olefin **13c** in the same (*E*/*Z*) ratio but slightly better yield (entry 6).

The selectivity of BT-containing sulfone **17** under the developed reaction conditions was also evaluated. Because of the results of our preliminary addition/retroaddition study (Table 1), we expected that the reaction of BT-sulfone **17** with aldehyde **12c** might proceed with lower (*Z*)-selectivity. However, under all tested reaction conditions, olefins **13c** were obtained with similar (*E*/Z)-selectivity, although in lower yield (see Table 2, entry 6 vs entry 7).[9]

Having established the optimal reaction conditions, the scope and limitations of this method (Table 3) were examined and the results were compared with reactions performed without the presence of chelating agents.[13]

dx.doi.org/10.1021/jo300929a | *J. Org. Chem.* 2012, 77, 6358–6364

Scheme 4. Proposed Mechanism of "Cation-Free" Julia–Kocienski Reaction of Allyl PT-sulfones



In general, reactions of PT-sulfones **16**, **18**, and **19** (Table 3, entries 1–60) were more stereoselective than those performed with BT-sulfones **17** and **20–22** (Table 3, entries 61–96). In both cases, the (*E*/*Z*)-selectivity of newly formed olefins **13** proved to be aldehyde dependent. When primary α-nonbranched aldehydes **12c,d** were used, the newly created olefins formed under "cation-free" conditions (methods C and D) were obtained with higher (*Z*)-selectivity as compared to standard conditions (methods A and B). The only exception was found when nonbranched α-alkoxy aldehyde **12e** was used (entries 9–12, 17–20, 49–52, 69–72, and 93–96). In these cases, the reactions yielded the corresponding olefins **13h–l,n,p,q** with moderate to good (*E*)-selectivity. The same trend was observed when α di- and trisubstituted or aromatic aldehydes **12g–j** and **n** were used (entries 21–40, 45–48, 53–60, and 77–80). In these cases, the (*E*)-olefins **13h–l,n,p,q** were formed as main products of the reaction. Interestingly, in these cases the obtained (*E*/*Z*) ratio was also superior to that obtained under the standard reaction conditions.

We believe that the stereochemical outcome of the 1,3-dienes **13** prepared by Julia–Kocienski and Julia–Silvestre reactions and presented in Table 3 can be easily rationalized (Scheme 4). If the olefination reactions were carried out under standard reaction conditions (methods A or B, addition step is not reversible ($k'_1,k'_2 \ll k_3,k_4$)), the (*E*/*Z*) ratio of **13** corresponds to the *syn*/*anti*-**24** adduct ratio.[1,2a] Thus, the Smiles rearrangement becomes the rate-determining step, but the addition step is the selectivity-determining step.

However, if chelating agents are employed (methods C and D), the addition step is reversible ($k'_1,k'_2 \ll k_3,k_4$) and the Smiles rearrangement becomes the rate and selectivity determination step. However, the final stereochemical outcome of the reaction ((*E*/*Z*) ratio) strongly depends on the aldehyde structure. If α-nonbranched aldehydes are employed, we expect that, for steric reasons, the Smiles rearrangement of adduct *syn*-**24** to intermediate **27** proceeds faster than the rearrangement of adduct *anti*-**24** to intermediate **28** ($k_3 > k_4$). (*Z*)-Olefins are thus preferentially formed.

However, the reaction becomes (*E*)-selective if the steric repulsion between R^2 and the vinyl group in TS-1 becomes important (α-branched and aromatic aldehydes). In this case, the relative rate of *syn* and *anti* addition starts to play a role in determining selectivity; *anti* addition is predicted to be preferred ($k_2 > k_1$).

In summary, we have developed a new modification of the Julia reaction that allows us to prepare 1,3-dienes, starting from PT- and BT-allyl sulfones, with high (*Z*) or (*E*) selectivity. It was shown that the olefin stereoselectivity is substrate (aldehyde) dependent. A rational explanation for observed (*E*,*Z*) selectivity is also proposed.

EXPERIMENTAL SECTION

General Procedures for Olefination Reactions. *Method A.* A solution of aldehyde **12c** (131 μL, 1.1 mmol) and allyl sulfone **16** (250 mg, 1.0 mmol) in THF (10 mL, 0.1 M) was cooled to −78 °C, and $KN(TMS)_2$ (0.6 M solution in toluene) (1.83 mL, 1.1 mmol) was added over 2 min. The resulting mixture was stirred at −78 °C for 1 h before it was allowed to warm to rt. After being stirred at rt for 6 h, a saturated aqueous solution of NH_4Cl (10 mL) was added. The whole mixture was extracted with EtOAc (3 × 10 mL); the combined organic layers were washed with brine (10 mL), dried over $MgSO_4$, and filtered; the solvents were removed under reduced pressure. The residue was purified by flash column chromatography on SiO_2 (petroleum ether/EtOAc = 50:1), and the reaction yielded 114 mg (72%, *E*/*Z* = 63:37) of **13c** as a yellowish oil.

Method B. A solution of aldehyde **12c** (131 μL, 1.1 mmol) and allyl sulfone **16** (250 mg, 1.0 mmol) in DMF (10 mL, 0.1 M) was cooled to −55 °C, and $KN(TMS)_2$ (0.6 M solution in toluene) (1.83 mL, 1.1 mmol) was added over 2 min. The resulting mixture was stirred at −55 °C for 1 h before it was allowed to warm to rt. After 6 h at rt, the reaction was terminated and purified using the same protocol as mentioned in method A. The reaction yielded 103 mg (65%, *E*:*Z* = 58:42) of **13c** as a yellowish oil.

Method C. A solution of allyl sulfone **16** (250 mg, 1.0 mmol) and 18-crown-6 (661 mg, 2.5 mmol) in DMF (10 mL, 0.1 M) was cooled to −55 °C, and $KN(TMS)_2$ (0.6 M solution in toluene) (1.83 mL, 1.1 mmol) was added dropwise within 10 s. The resulting mixture was stirred at −55 °C for 2 min, and aldehyde **12c** (131 μL, 1.1 mmol) in DMF (0.2 mL) was added dropwise. The resulting mixture was stirred at −55 °C for 1 h before it was allowed to warm to rt. After 6 h at rt, the reaction was terminated and purified using the same protocol as mentioned in method A. The reaction yielded 117 mg (74%, *E*/*Z* = 15:85) of **13c** as a yellowish oil.

Method D. A solution of allyl sulfone **16** (250 mg, 1.0 mmol) in DMF/TDA-1 = 3:1 (v/v) (10 mL, 0.1 M) was cooled to −60 °C, and $KN(TMS)_2$ (0.6 M solution in toluene) (1.83 mL, 1.1 mmol) was added dropwise within 10 s. The resulting mixture was stirred at −60 °C for 2 min, and aldehyde **12c** (131 μL, 1.1 mmol) in DMF (0.2 mL)

dx.doi.org/10.1021/jo300929a | J. Org. Chem. 2012, 77, 6358–6364

was added dropwise. The resulting mixture was stirred at −60 °C for 1 h before it was allowed to warm to rt. After 6 h at rt, the reaction was terminated and purified using the same protocol as mentioned in method A. The reaction yielded 123 mg (78%, *E*/*Z* = 14:86) of **13c**[14] as a yellowish oil: ^{1}H NMR[15] (300 MHz, $CDCl_3$) δ 2.45 (dd, *J* = 15.1, 7.2 Hz, 2H*), 2.55 (dd, *J* = 15.3, 7.6 Hz, 2H), 2.67−2.80 (m, 2H), 5.01 (d, *J* = 9.7 Hz, 1H*), 5.12 (d, *J* = 10.0 Hz, 1H), 5.22 (dd, *J* = 16.9, 1.7 Hz, 1H), 5.53 (dt, *J* = 10.5, 7.7 Hz, 1H), 5.79 (dt, *J* = 15.1, 7.1 Hz, 1H*), 6.06 (t, *J* = 10.9 Hz, 1H), 6.15 (dd, *J* = 15.1, 10.4 Hz, 1H*), 6.35 (dt, *J* = 16.9, 10.2 Hz, 1H*), 6.65 (dtd, *J* = 16.9, 10.6, 1.0 Hz, 1H), 7.15−7.26 (m, 3H), 7.28−7.37 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 29.8, 34.6*, 35.8*, 36.0, 115.4*, 117.5, 126.1, 128.5, 128.6, 129.9, 131.6 (*E*), 131.8, 132.3, 134.5, 137.4, 141.9, 142.0*; IR (film) ν^{-1} 3031, 2956, 2887, 1524, 1487, 1334, 1001, 906, 800, 746, 702; MS (EI) *m*/*z* 158 (14) [M$^+$], 143 (6), 117 (32), 91 (100), 65 (12); HRMS (EI) *m*/*z* calcd for $C_{12}H_{14}$ 158.1090, found 158.1094.

Olefin 13d:.[15,16] yellow oil; ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.43 (q, *J* = 6.7 Hz, 2H*), 2.54 (dd, *J* = 14.2, 7.2 Hz, 2H), 3.54 (td, *J* = 6.8, 4.6 Hz, 2H), 4.53 (s, 2H*), 4.55 (s, 2H), 5.01 (d, *J* = 9.8 Hz, 1H*), 5.12 (d, *J* = 9.8 Hz, 1H), 5.15 (s, 1H*), 5.23 (d, *J* = 15.6 Hz, 1H), 5.51 (dt, *J* = 10.4, 7.7 Hz, 1H), 5.74 (dt, *J* = 15.3, 7.0 Hz), 6.06−6.19 (m, 1H), 6.33 (dt, *J* = 16.9, 10.3 Hz, 1H), 6.66 (dt, *J* = 17.2, 10.9 Hz, 1H), 7.47−7.16 (m, 5H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 28.7*, 33.2, 69.85, 69.88*, 73.1, 115.7, 117.8, 127.8, 127.86, 127.89*, 128.6, 131.1, 131.4*, 132.3, 132.9*, 137.3, 138.6*; IR (film) ν^{-1} 3031, 3024, 2986, 1604, 1582, 1463, 1132, 1041, 952, 863, 704; MS (CI) *m*/*z* 188 (100) [M]$^+$, 189 (35) [M + H]$^+$; HRMS (EI) *m*/*z* calcd for $C_{13}H_{16}O$ 188.1201, found 188.1203.

Olefin 13e:.[15,16] yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.09 (d, *J* = 6.3 Hz, 2H), 4.22 (dd, *J* = 6.7, 1.3 Hz, 2H*), 4.54 (s, 2H and 2H*), 5.08−5.44 (m, 2H and 2H*), 5.66 (dt, *J* = 11.8, 6.8 Hz, 1H*), 5.84 (dt, *J* = 14.4, 6.0 Hz, 1H), 6.19 (t, *J* = 11.1 Hz, 1H*), 6.26−6.45 (m, 2H), 6.60 (dt, *J* = 16.8, 10.6 Hz, 1H*), 7.27−7.42 (m, 5H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 66.0, 70.4, 72.3, 117.8, 119.4, 121.4, 122.5, 124.8, 125.1, 126.6, 128.0, 128.6, 130.3, 131.9, 132.3, 133.5, 136.5, 138.4; IR (film) ν^{-1} 3086, 3028, 2930, 2851, 1456, 1427, 1238, 1095, 1074, 1003, 910, 756, 727; MS (CI) *m*/*z* 174 (84) [M$^+$], 175 (20) [M$^+$+1], 149 (100), 145 (54), 133 (49), 118 (56), 117 (81), 115 (62), 105 (94); HRMS (EI) *m*/*z* calcd for $C_{12}H_{14}O$ 174.1039, found 174.1038.

Olefin 13f:[15] yellow oil; ^{1}H NMR (500 MHz, $CDCl_3$) δ 0.93 (t, *J* = 7.3 Hz, 3H), 0.94 (t, *J* = 7.3 Hz, 3H*), 1.39−1.47 (m, 2H), 2.02−2.19 (m, 2H), 2.37−2.57 (m, 2H), 2.72 (dd, *J* = 8.9, 6.7 Hz, 2H,), 5.37 (dt, *J* = 10.8, 7.5 Hz, 1H), 5.50 (td, *J* = 15.8, 7.6 Hz, 1H), 5.59−5.78 (m, 2H), 5.98−6.14 (m, 2H), 6.30 (dd, *J* = 15.2, 10.9, 1H), 6.39 (dd, *J* = 15.1, 11.1 Hz, 1H), 7.19−7.34 (m, 5H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 13.95, 13.99*, 22.72, 22.76*, 29.8, 34.7*, 34.9*, 35.2, 36.11*, 36.16; 123.8, 124.4, 125.8, 126.0, 126.5, 128.5, 129.4, 130.5, 131.1, 132.6, 133.5, 135.2, 142.2; IR (film) ν^{-1} 3086, 3028, 2930, 2851, 1456, 1427, 1238, 1095, 1074, 1003, 910, 756, 727; MS (EI) *m*/*z* 200 (13) [M$^+$], 201 (2) [M$^+$+1], 143 (12), 129 (13), 117 (15), 109 (68), 91 (100); HRMS (EI) *m*/*z* calcd for $C_{15}H_{20}$ 200.1560, found 200.1560.

Olefin 13g:[15] yellowish oil; ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.93 (t, *J* = 6.1 Hz, 3H), 0.96 (t, *J* = 5.2 Hz, 3H*), 1.39−1.51 (m, 2H), 2.10 (q, *J* = 7.1 Hz, 2H), 2.20 (q, *J* = 7.5 Hz, 2H*), 4.08 (d, *J* = 6.3 Hz, 2H), 4.12 (d, *J* = 6.2 Hz, 1H*), 4.21 (d, *J* = 6.8 Hz, 1H*), 4.54 (s, 2H), 4.56 (s, 2H*), 5.50 (dt, *J* = 15.1, 7.6 Hz, 1H), 5.64−5.78 (m, 2H and 1H*), 6.09 (dd, *J* = 14.7, 10.5 Hz, 1H), 6.27 (dd, *J* = 15.2, 10.3 Hz, 1H), 6.59 (ddd, *J* = 15.2, 11.0, 1.1 Hz, 1H*), 7.27−7.47 (m, 5H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.88, 22.6, 23.0*, 30.0*, 34.9, 35.0*, 66.0*, 70.8, 72.1, 72.3*, 125.0, 125.5, 127.5, 127.7, 127.8, 128.3, 130.2, 130.4, 132.3, 133.1, 135.4, 138.4; IR (film) ν^{-1} 3063, 3026, 2957, 2927, 2858, 1659, 1497, 1454, 1362, 1099, 1070, 989, 734, 696; MS (CI) *m*/*z* 216 (64) [M]$^+$, 217 (12) [M + H]$^+$, 159 (100), 134 (78), 125 (52), 91 (82); HRMS (CI) *m*/*z* calcd for $C_{15}H_{20}O$ 216.1514, found 216.1521.

Olefin 13h:[15] yellowish oil; ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.93 (t, *J* = 7.4 Hz, 3H, H-1), 1.06 (s, *J* = 9.8 Hz, 9H), 1.44 (dq, *J* = 14.6, 7.3 Hz, 2H), 2.02−2.17 (m, 2H), 2.13−2.24 (m, 2H*), 3.65 (dd, *J* = 10.5, 4.8 Hz, 1H), 3.81 (dd, *J* = 10.5, 6.6 Hz, 1H), 4.01 (dt, *J* = 12.1, 6.9 Hz, 2H*), 4.45 (d, *J* = 10.0 Hz, 1H*), 4.46 (d, *J* = 12.1 Hz, 1H), 4.49 (d, *J* = 9.9 Hz, 1H*), 4.65 (d, *J* = 12.1 Hz, 1H), 5.18 (dd, *J* = 10.0, 9.6 Hz, 1H*), 5.46 (dd, *J* = 15.2, 7.6 Hz, 1H), 5.54 (dd, *J* = 15.4, 7.4 Hz, 1H*), 5.71 (dt, *J* = 15.0, 7.2 Hz, 1H), 6.05 (dd, *J* = 14.9, 10.5 Hz, 1H), 6.21 (dd, *J* = 15.3, 10.4 Hz, 1H), 6.52 (dd, *J* = 11.1, 9.3 Hz, 1H*), 7.28−7.48 (m, 11H), 7.61−7.74 (m, 4H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.7, 15.0*, 19.3, 22.4, 22.8*, 24.4*, 26.8, 34.7, 34.9, 66.7*, 67.0, 70.4, 70.5*, 80.6*, 80.7, 127.3, 127.58, 127.64, 127.9*, 128.3, 128.4*, 129.6, 129.7*, 133,4*, 133.9, 135.5*, 135.7, 137.2, 138.8*, 138.9; IR (film) ν^{-1} 3069, 3031, 2986, 2928, 2852, 1470, 1431, 1103, 1089, 989, 702; MS (FAB) *m*/*z* 507 (65) [M + Na]$^+$, 271 (56), 249 (42), 198 (100); HRMS (FAB) *m*/*z* calcd for $C_{32}H_{40}O_2SiNa$ 507.2695, found 507.2698.

Olefin 13i:.[15,17] yellowish oil; ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.91 (t, *J* = 5.9 Hz, 3H), 0.99−1.50 (m, 10H), 1.50−1.88 (m, 3H), 1.90−2.11 (m, 2H), 2.15 (dd, *J* = 13.9, 6.4 Hz, 2H*), 5.16 (t, *J* = 10.1 Hz, 1H*), 5.32 (dt, *J* = 15.5, 6.2 Hz, 1H*), 5.49−5.73 (m, 2H), 5.91−6.09 (m, 2H), 6.23−6.37 (m, 2H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 14.0, 22.8, 23.1*, 26.1*, 26.3, 26.4, 30.0*, 33.2, 33.5*, 35.0, 35.2*, 37.0*, 40.9, 41.2*, 127.0*, 128.0, 131.0, 132.6, 134.7*, 136.3*, 138.5, 140.7*; IR (film) ν^{-1} 3016, 2957, 2921, 2851, 1448, 1377, 986; MS (EI) *m*/*z* 178 (56) [M]$^+$, 170 (11), 135 (28), 121 (28), 112 (33), 96 (54), 93 (42), 86 (100); HRMS (EI) *m*/*z* calcd for $C_{13}H_{22}$ 178.1716, found 178.1715.

Olefin 13j:.[15,18] colorless oil; ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.062 (s, 3H), 0.067 (s, 3H), 0.88−0.95 (s, 12H), 1.22 (d, *J* = 6.3 Hz, 3H), 1.31−1.58 (m, 2H), 2.06 (dd, *J* = 14.4, 7.1 Hz, 2H), 4.33 (p, *J* = 6.2 Hz, 1H), 5.57 (dd, *J* = 14.6, 5.7 Hz, 1H), 5.66 (dd, *J* = 14.5, 7.0 Hz, 1H), 5.94−6.17 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ −4.61, −4.42, 14.0, 18.51, 22.7, 25.9*, 26.1, 35.0, 65.5*, 69.3, 128.7, 130.1, 134.4, 135.6; IR (film) ν^{-1} 2957, 2927, 2891, 2858, 1550, 1504, 1462, 1252, 1089, 987, 832; MS (CI) *m*/*z* 254 (100) [M]$^+$, 255 (35) [M + H]$^+$, 139 (43), 115 (65); HRMS (CI) *m*/*z* calcd for $C_{15}H_{30}OSi$ 254.2066, found 254.2068.

Olefin 13k:[15] yellowish oil; ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.94 (t, *J* = 7.3 Hz, 3H*), 0.96 (t, *J* = 7.4 Hz, 3H), 1.32−1.61 (m, 2H), 2.14 (p, *J* = 6.9 Hz, 2H), 2.28 (dt, *J* = 14.9, 7.4 Hz, 2H*), 5.47−5.73 (m. 1H*), 5.76−60.2 (m, 2H), 6.40 (d, *J* = 15.7 Hz, 1H), 6.51 (d, *J* = 10.1 Hz, 1H*), 6.75 (dd, *J* = 15.6, 10.4 Hz, 1H), 7.06 (dt, *J* = 11.1, 9.2 Hz, 1H*), 7.22−7.45 (m, 4H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.94, 14.01*, 22.6, 23.1*, 30.3*, 35.2, 124.6*, 125.3*, 126.4, 127.5, 127.7*, 128.6, 128.8*, 128.9, 130.6, 130.8*, 131.4, 132.7*, 136.4*, 136.5*, 136.7, 138.9; IR (film) ν^{-1} 3012, 2959, 2928, 2872, 1641, 1489, 1456, 1091, 1012, 986, 845, 820, 798, 735; MS (EI) *m*/*z* 206 (68) [M]$^+$, 207 (18) [M + 1]$^+$, 208 (33) [M + 2]$^+$, 209 (6) [M + 3]$^+$, 205 (11), 179 (37), 177 (100), 167 (37), 165 (87), 163 (46), 141 (49); HRMS (EI) *m*/*z* calcd for $C_{13}H_{15}Cl$ 206.0857, found 206.0857.

Olefin 13l:[15] yellowish solid; mp = 32−33 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.95 (t, *J* = 7.8 Hz, 3H), 1.42−1.53 (m, 2H), 2.16 (dt, *J* = 14.2, 6.8 Hz, 2H), 2.31 (dt, *J* = 13.1, 6.6 Hz, 2H*), 5.68 (dt, *J* = 15.6, 8.6 Hz, 1H*), 5.76−6.02 (m, 2H), 6.19 (dt, *J* = 15.4, 9.4 Hz, 1H*), 6.47 (d, *J* = 15.5 Hz, 1H), 6.53 (d, *J* = 10.6 Hz, 1H*), 6.88 (dd, *J* = 15.7, 10.4 Hz, 1H), 7.19 (dt, *J* = 11.2, 9.3 Hz, 1H*), 7.46 (t, *J* = 8.1 Hz, 2H), 7.51 (t, *J* = 7.8 Hz, 2H*), 8.03 (d, *J* = 8.7 Hz, 2H), 8.09 (d, *J* = 8.2 Hz, 2H*); ^{13}C NMR (75 MHz, $CDCl_3$) δ 13.9, 22.5, 35.2, 124.9, 125.6, 127.4, 129.3, 129.6, 130.1, 132.0, 132.7, 133.3, 135.0, 138.7, 139.8, 140.7, 141.6, 148.9; IR (film) ν^{-1} 3062, 2983, 2945, 2875, 1523, 1346, 995, 825, 864, 723; MS (EI) *m*/*z* 217 (75) [M]$^+$, 218 (11) [M + 1]$^+$, 188 (67), 158 (34), 142 (81), 141 (100), 128 (58), 115 (46); HRMS (EI) *m*/*z* calcd for $C_{13}H_{15}O_2N$ 217.1097, found 217.1093.

Olefin 13m:[15] yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.49 (dd, *J* = 14.9, 7.1 Hz, 2H*), 2.64 (dd, *J* = 14.6, 7.3 Hz, 2H), 2.75−2.86 (m, 2H), 5.59 (dt, *J* = 10.7, 7.6 Hz, 1H), 5.88 (dt, *J* = 15.2, 7.1 Hz, 1H*), 6.20 (t, *J* = 10.9 Hz, 1H), 6.27 (dd, *J* = 15.0, 10.0 Hz, 1H*), 6.47 (d, *J* = 15.8 Hz, 1H*), 6.54 (d, *J* = 15.5 Hz, 1H), 6.77 (dd, *J* = 15.6, 10.4 Hz, 1H*), 7.03 (ddd, *J* = 15.4, 11.3 Hz, 1H), 7.19−7.42 (m, 10H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 30.1, 34.9*, 36.0*, 36.1, 124.5, 126.2, 126.4*, 126.6, 127.4*, 127.6, 128.6, 128.7, 128.8, 129.5, 130.7*, 131.3*, 132.0, 132.6, 134.8*, 137.8, 141.9; IR (film) ν^{-1} 3071, 3024, 2924, 2870, 1495, 1452, 1074, 986, 945, 748, 729; MS (EI) *m*/*z* 234 (18) [M], 235 (3) [M + H]$^+$, 143 (100), 128 (47), 91 (54), 84 (41); HRMS (EI) *m*/*z* calcd for $C_{18}H_{18}$ 234.1403, found 234.1400.

dx.doi.org/10.1021/jo300929a | *J. Org. Chem.* 2012, 77, 6358−6364

Olefin **13n**:[15] slightly yellow oil; ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.96 (d, J = 6.6 Hz, 3H), 1.11−1.34 (m, 1H), 1.34−1.52 (m, 1H), 1.52−1.62 (m, 1H), 1.64 (s, 3H), 1.72 (s, 3H), 2.04 (dq, J = 14.3, 7.3 Hz, 2H), 2.11−2.26 (m, 1H), 2.32 (dt, J = 13.5, 6.7 Hz, 1H), 5.14 (t, J = 7.0 Hz, 1H), 5.57 (dt, J = 10.5, 8.0 Hz, 1H), 5.84 (dt, J = 15.0, 7.4 Hz, 1H*), 6.24 (t, J = 10.9, 1H), 6.47 (d, J = 15.7 Hz, 1H*), 6.55 (d, J = 15.6 Hz, 1H), 6.80 (dd, J = 15.6, 10.3 Hz, 1H*), 7.09 (dd, J = 15.5, 11.1 Hz, 1H), 7.18−7.48 (m, 5H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 17.9, 19.8, 25.9, 26.0, 29.9, 33.1*, 33.4, 35.4, 37.0, 40.6*, 124.8, 125.0, 126.3*, 126.5, 127.3*, 127.5, 128.8, 129.7, 130.1*, 131.4, 131.9*, 132.2, 132.2, 134.7*, 137.9; IR (film) ν^{-1} 3078, 3058, 2926, 2908, 2870, 1595, 1493, 1448, 1377, 984, 945, 908; MS (CI) m/z 254 (100) $[M]^+$, 255 (31) $[M + 1]^+$, 211 (23), 163 (11), 143 (16); HRMS (CI) m/z calcd for $C_{19}H_{26}$ 254.2035, found 254.2027.

Olefin **13o**:[15] yellow viscous oil; ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.19 (d, J = 6.1 Hz, 2H), 4.36 (d, J = 6.8 Hz, 2H*), 4.63 (d, J = 6.0 Hz, 2H), 5.77 (dt, J = 11.1, 6.8 Hz, 1H*), 6.00 (dt, J = 15.1, 6.1 Hz, 1H), 6.41 (t, J = 11.0 Hz, 1H*), 6.51 (dd, J = 15.2, 10.5 Hz, 1H), 6.62 (d, J = 15.7 Hz, 1H), 6.65 (d, J = 15.5 Hz, 1H*), 6.87 (dd, J = 15.6, 10.5 Hz, 1H), 7.07 (dd, J = 15.5, 11.2 Hz, 1H*), 7.24−7.54 (m, 10H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 65.9*, 70.5, 72.1*, 72.2, 123.8, 126.5, 126.6*, 127.66, 127.70, 127.74, 127.8, 128.0, 128.3*, 128.48, 128.50, 128.7, 130.2, 132.0, 132.8, 133.0, 134.3, 137.1*, 137.2, 138.3*, 138.4; IR (film) ν^{-1} 3080, 3059, 3026, 2920, 2850, 1597, 1494, 1450, 1360, 1097, 1070, 989, 732, 692; MS (EI) m/z 250 (8) $[M]^+$, 159 (22), 131 (53), 117 (56), 115 (75); HRMS (CI) m/z calcd for $C_{18}H_{18}O$ 250.1352, found 250.1346.

Olefin **13p**:[15] yellowish syrup; ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.06 (s, 9H*), 1.07 (s, 9H), 3.70 (dd, J = 10.6, 5.0 Hz, 1H and 1H*), 3.86 (dd, J = 10.7, 6.4 Hz, 1H and 1H*), 3.89 (dd, J = 11.4, 6.8 Hz, 1H*), 4.06 (dd, J = 11.9, 6.7 Hz, 1H), 4.49 (dd, J = 12.1, 6.3 Hz, 1H and 1H*), 4.68 (dd, J = 12.2, 3.8 Hz, 1H and 1H*), 5.41 (dd, J = 10.1, 9.8 Hz, 1H*), 5.71 (dd, J = 15.4, 7.5 Hz, 1H), 6.39 (dd, J = 15.5, 10.5 Hz, 1H, H-1), 6.45 (dd, J = 10.8, 6.2 Hz, 1H*), 6.56 (d, J = 15.7 Hz, 1H, H-1), 6.57 (d, J = 15.4 Hz, 1H*), 6.78 (dd, J = 15.5, 10.2 Hz, 1H), 6.87 (dd, J = 14.9, 10.5 Hz, 1H*), 7.28−7.52 (m, 15), 7.58−7.80 (m, 5H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 19.5, 26.9*, 27.1, 66.9*, 67.1, 70.4*, 70.9, 75.4, 80.6, 124.3, 126.6, 126.8, 127.7, 128.1, 128.5, 128.76, 128.85, 129.5, 129.8, 132.0, 132.8, 135.1, 135.9, 137.4, 138.8, 138.9; IR (film) ν^{-1} 3068, 3028, 2957, 2929, 2856, 1471, 1427, 1110, 1083, 991, 700; MS (FAB) m/z 541 (85) $[M + Na]^+$, 411 (24), 271 (68), 249 (32), 197 (100); HRMS (FAB) m/z calcd for $C_{35}H_{38}O_2SiNa$ 541.2539, found 541.2543.

Olefin **13q**:.[15,18] yellowish oil; ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.25 (s, 9H*), 1.27 (s, 9H), 5.51 (d, J = 11.9 Hz, 1H*), 5.88 (d, J = 15.5 Hz, 1H), 6.02 (t, J = 11.8 Hz, 1H*), 6.17 (dd, J = 15.5, 10.2 Hz, 1H), 6.46 (d, J = 15.4 Hz, 1H*), 6.49 (d, J = 15.7 Hz, 1H), 6.77 (dd, J = 15.6, 10.2 Hz, 1H), 7.18−7.40 (m, 5H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 22.9, 29.6*, 29.8, 124.1*, 125.6, 126.3, 126.6*, 127.2, 127.6*, 128.8, 130.1, 130.4, 131.9*, 137.9, 147.0; IR (film) ν^{-1} 3024, 2958, 2916, 2849, 1595, 1488, 1462, 1361, 1232, 987, 910, 744; MS (EI) m/z 186 (27) $[M]^+$, 187 (2) $[M + H]^+$, 171 (26), 86 (66), 84 (100), 57 (14); HRMS (EI) m/z calcd for $C_{14}H_{18}$ 186.1403, found 186.1399.

Olefin **13r**:.[15,19] yellowish oil; ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.62 (dd, J = 15.0, 7.0 Hz, 2H*), 2.69−2.80 (m, 2H), 2.80−3.01 (m, 2H and 2H*), 5.79 (dt, J = 11.6, 6.9 Hz, 1H), 6.35 (dt, J = 15.8, 6.7 Hz, 1H*), 6.51 (d, J = 15.9 Hz, 1H*), 6.54 (d, J = 11.6 Hz, 1H), 7.21−7.49 (m, 10H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 30.6, 35.1*, 36.1*, 36.3, 126.1*, 126.2, 126.8, 127.1*, 128.3, 128.5, 128.7, 128.9, 129.6, 130.1*, 130.5*, 132.0, 137.7, 137.9*, 141.8, 141.9*; IR (film) ν^{-1} 3061, 3024, 2922, 2854, 1601, 1495, 1452, 1074, 1030, 964, 908, 735, 696; MS (EI) m/z 208 (7) $[M]^+$, 209 (2) $[M + 1]^+$, 129 (12), 117 (100), 115 (66), 91 (86); HRMS (EI) m/z calcd for $C_{16}H_{16}$ 208.1247, found 208.1248.

Olefin **13s**:.[15,20] yellowish oil; ^{1}H NMR (300 MHz, $CDCl_3$) δ 4.25 (d, J = 6.0 Hz, 2H), 4.36 (dd, J = 6.4, 1.1 Hz, 2H*), 4.58 (s, 2H*), 4.63 (s, 2H), 5.97 (dt, J = 12.4, 6.3 Hz, 1H*), 6.39 (dt, J = 15.9, 6.0 Hz, 1H), 6.67 (d, J = 11.2 Hz, 1H*), 6.69 (d, J = 16.0 Hz, 1H), 7.21−7.53 (m, 10H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 67.1*, 70.9, 72.3, 72.6*, 126.2, 126.7, 127.3*, 127.8, 127.98, 128.04*, 128.4*, 128.6, 128.7, 129.0, 129.1*, 132.0*, 132.7, 136.7*, 136.9, 138.3*, 138.4; IR (film) ν^{-1} 3061, 3026, 2922, 2848, 1494, 1452, 1360, 1112, 1072, 966, 732, 692; MS (FAB) m/z 295 (15) $[M + Na]^+$, 281 (61), 263 (20), 247 (100), 237 (35), 221 (56), 199 (42), 180 (65); HRMS (FAB) m/z calcd for $C_{16}H_{16}ONa$ 247.1099, found 247.1097.

Hydroxysulfone 8 Synthesis. *Epoxide Opening.*[8] A solution of styrene oxide (690 μL, 6.07 mmol) and BT-SH (1.12 g, 6.68 mmol) in CH_2Cl_2 (66.8 mL, 0.1 M) was cooled to 0 °C, and $Sm(OTf)_3$ (36 mg, 0.06 mmol) was added in one portion. The resulting mixture was allowed to warm to rt and stirred for 8 h. After the mixture was stirred at rt for 8 h, a saturated aqueous solution of $NaHCO_3$ (50 mL) was added. The resulting layers were separated, and the aqueous layer was extracted with CH_2Cl_2 (3 × 70 mL); the combined organic layers were washed with brine (50 mL), dried over $MgSO_4$, and filtered; and the solvents were removed under reduced pressure. The residue was purified by flash column chromatography on SiO_2 (petroleum ether/EtOAc = 4:1 → 2:1), and the reaction yielded 1.70 g (98%) of **hydroxy BT-sulfide** as a colorless viscous oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.97 (broad s, 1H), 4.17−4.35 (m, 2H), 5.16 (dd, J = 7.2, 5.6 Hz, 1H), 7.29−7.48 (m, 7H), 7.75 (d, J = 8.0 Hz, 1H), 7.90 (d, J = 8.1 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 55.4, 67.5, 121.3, 121.8, 124.9, 126.5, 128.1, 128.6, 129.3, 135.7, 137.7, 152.8, 166.7; MS (CI) m/z 288 (100) $[M + 1]^+$, 289 (19) $[M + 2]^+$, 290 (11) $[M + 2]^+$, 151 (8), 149 (25); HRMS (CI) m/z calcd for $C_{15}H_{14}ONS_2$ 288.0517, found 288.0515. **Hydroxy PT-sulfide:** colorless viscous oil; ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.06 (broad s, 1H), 4.24 (d, J = 6.1 Hz, 2H), 5.19 (t, J = 6.3 Hz, 1H), 7.28−7.44 (m, 5H), 7.53 (broad s, 5H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 55.5, 67.5, 121.3, 121.8, 124.9, 126.5, 128.1, 128.6, 129.3, 135.7, 137.7, 152.8, 166.7; MS (ESI) m/z 299 (100) $[M + 1]^+$, 300 (21) $[M + 2]^+$, 301 (8) $[M + 3]^+$, 239 (30), 151 (20); HRMS (ESI) m/z calcd for $C_{15}H_{15}ON_4S$ 299.0961, found 299.0964.

Sulfide Oxidation. A solution of hydroxy BT-sulfide (500 mg, 1.74 mmol) in EtOH (17.4 mL, 0.2 M) was cooled to 0 °C, and a cold (0 °C) yellow solution of molybdate (108 mg, 87 μmol) in 35% aqueous H_2O_2 (2 mL, 17.5 mmol) was added dropwise. The resulting mixture was allowed to warm to rt and stirred for an additional 18 h. The resulting slightly yellow milky solution was cooled to 0 °C, and aqueous saturated $Na_2S_2O_3$ (10 mL) was added dropwise. Water (10 mL) was added, and the whole mixture was extracted with EtOAc (3 × 25 mL). The combined organic layers were washed with brine (10 mL), dried over $MgSO_4$, and filtered, and the solvents were removed under reduced pressure. The residue was purified by flash column chromatography on SiO_2 (petroleum ether/EtOAc = 2:1 → 1:1 → 0:100), and the reaction yielded 410 mg (74%) of **8a** as a colorless solid: mp = 161−162 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.60 (broad s, 2H), 4.30 (dd, J = 12.4, 4.9 Hz, 1H), 4.78 (dd, J = 12.4, 7.5 Hz, 1H), 4.93 (dd, J = 7.4, 4.9 Hz, 1H), 7.21−7.35 (m, 5H), 7.58 (dd, J = 11.2, 4.1 Hz, 1H), 7.92 (d, J = 8.1 Hz, 1H), 4.64 (dt, J = 7.7, 1.0 Hz, 1H), 8.24 (d, J = 8.3 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 61.5, 72.6, 111.6, 122.4, 125.7, 127.9, 128.3, 129.2, 129.8, 130.1, 137.3, 152.7, 165.3; MS (ESI) m/z 342 (100) $[M + Na]^+$, 301 (64), 214 (17), 121 (8); HRMS (ESI) m/z calcd for $C_{15}H_{14}O_3NS_2$ 320.0410, found 320.0412.

Sulfone **8b**: colorless viscous syrup; ^{1}H NMR (300 MHz, $CDCl_3$) δ ^{1}H NMR (300 MHz, $CDCl_3$) δ 3.09 (broad s, 1H), 4.20 (dd, J = 12.3, 4.8 Hz, 1H), 4.64 (dd, J = 12.3, 8.5 Hz, 1H), 5.02 (dd, J = 8.4, 4.8 Hz, 1H), 7.21−7.43 (m, 7H), 7.45−7.63 (m, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 61.4, 73.8, 126.2, 127.6, 129.4, 130.3, 130.5, 131.6, 132.9, 153.7; MS (ESI) m/z 353 (100) $[M + Na]^+$, 331 (15) $[M + 1]^+$, 267 (8), 119 (10); HRMS (ESI) m/z calcd for $C_{15}H_{15}O_3N_4S$ 331.0859, found 331.0863.

■ ASSOCIATED CONTENT

Supporting Information

Optimization tables, additional information, and ^{1}H and ^{13}C NMR spectra for all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

dx.doi.org/10.1021/jo300929a | J. Org. Chem. 2012, 77, 6358−6364

AUTHOR INFORMATION

Corresponding Author

*E-mail: jiri.pospisil@uclouvain.be.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

Fabio Lucaccioni (U.C.L) is gratefully acknowledged for his help with GC and HPLC separation method development. J.P. is grateful to Prof. István E. Markó (U.C.L.) for his continuous support. The Université Catholique de Louvain and the Fond de la Recherche Scientific (Chargé de Recherche F.R.S.-FNRS to J.P., Chercheur Qualifié F.R.S.-FNRS to R.R.) are gratefully acknowledged for financial support.

REFERENCES

(1) (a) Blakemore, P. R. *J. Chem. Soc., Perkin Trans. 1* **2002**, 2563−2585. (b) Aïssa, C. *Eur. J. Org. Chem.* **2009**, 1831−1844. (c) Markó, I. E.; Pospíšil, J. In *Science of Synthesis*; de Meijere, A., Ed.; Georg Thieme Verlag: Stuttgart, 2009; Vol. *47a*, pp105−160 and references cited therein.

(2) (a) Pospíšil, J. *Tetrahedron Lett.* **2011**, *52*, 2348−2352. (b) Pospíšil, J.; Markó, I. E. *Org. Lett.* **2006**, *8*, 5983−5986.

(3) The addition/retroaddition process was already proposed previously as a possible explanation of unusual high (*Z*)-selectivity of newly created olefin; see: Kikuchi, R.; Fujii, M.; Akita, H. *Tetrahedron: Asymmetry* **2009**, *20*, 1975−1983.

(4) Baudin, B. D.; Hareau, G.; Julia, S. A.; Ruel, O. *Bull. Soc. Chim. Fr.* **1993**, *130*, 336−357.

(5) This assumption was based on analogy with the olefination reaction of 2-pyridyl sulfones with various aldehydes; see refs 1b, 4, and: Charette, A. B.; Berthelette, C.; St-Martin, D. *Tetrahedron Lett.* **2001**, *42*, 5149−5153.

(6) Allyl and benzyl BT- and PT-sulfones were prepared in two steps from the corresponding allylic or benzylic alcohols; see: Pospíšil, J.; Sato, H. *J. Org. Chem.* **2011**, *76*, 2269−2272.

(7) The stereoselective synthesis of 1,3-dienes is very important since they are highly versatile synthetic building blocks; see, e.g. (a) Oppolzer, W. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon Press: Oxford, 1991; Vol. *5*, pp 315−377. (b) Roush, W. R. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon Press: Oxford, 1991; Vol. *5*, pp 513−546. (c) Weinreb, S. M. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Eds.; Pergamon Press: Oxford, 1991; Vol. *5*, pp 401−444. (d) Clennan, E. L. *Tetrahedron* **1991**, *47*, 1343−01382.

(8) Sulfones **14** were prepared in two steps starting from styryl oxide; see: Vougioukas, A. E.; Kagan, H. B. *Tetrahedron Lett.* **1987**, *28*, 6065−6068.

(9) For more details, see the Supporting Information.

(10) (a) Kocienski, P. J.; Bell, A. G.; Blakemore, P. R. *Synlett* **2000**, 365−367. (b) Pospíšil, J.; Robiette, R.; Sato, H.; Debrus, K. *Org. Biomol. Chem.* **2012**, *10*, 1225−1234.

(11) Barbier-like reaction conditions: the base is added to the reaction mixture containing sulfone **16** and aldehyde **12c** in appropriate solvent.

(12) TDA-1 = tris[2-(2-methoxy)ethyl]amine; selective K^+-specific chelating agent, see, e.g., ref 2 or Tamao, K.; Nakagawa, Y.; Ito, Y. *Org. Synth.* **1996**, *73*, 1035−1042.

(13) The same substrates (sulfone and aldehyde) were reacted with KHMDS using THF (method A) and DMF (method B) as solvents. Selectivity of the reaction was then compared with the reactions carried out under our optimized reaction conditions using 18-crown-6/DMF (method C) or DMF/TDA-1 = 3:1 (v/v) (method D) systems.

(14) Habrant, D.; Stengel, B.; Meunier, S.; Mioskowski, C. *Chem.—Eur. J.* **2007**, *13*, 5433−5440.

(15) Characterization data corresponds to (*E*/*Z*)-mixtures of olefins. Characteristic peaks for minor isomer obtained using method D reaction protocol are marked with an asterisk.

(16) Borg, T; Tuzina, P; Somfai, P. *J. Org. Chem.* **2011**, *76*, 8070−8075.

(17) Ikeda, Y.; Ukai, J.; Ikeda, N.; Yamamoto, H. *Tetrahedron* **1987**, *43*, 731−742.

(18) Gallagher, W. P.; Terstiege, I.; Maleczka, R. E. *J. Am. Chem. Soc.* **2001**, 3194−3204.

(19) Irfan, M.; Fuchs, M.; Glasnov, T. N.; Kappe, C. O. *Chem.—Eur. J.* **2009**, 11608−11618.

(20) Parrish, J. P.; Jung, Y. C.; Shin, S. I.; Jung, K. W. *J. Org. Chem.* **2002**, 7127−7130.