JOC Article

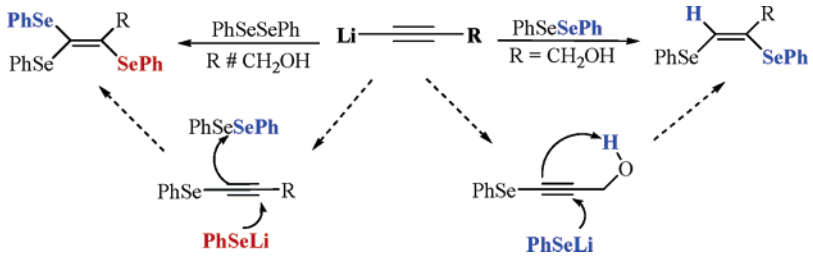
Highly Stereoselective One-Pot Procedure To Prepare Bis- and Tris-chalcogenide Alkenes via Addition of Disulfides and Diselenides to Terminal Alkynes

Angélica Venturini Moro,[†] Cristina W. Nogueira,[†] Nilda B. V. Barbosa,[†] Paulo Henrique Menezes,[‡] João Batista Teixeira da Rocha,[†] and Gilson Zeni*[,†]

Laboratório de Síntese, Reatividade, Avaliação Farmacológica e Toxicológica de Organocalcogênios, CCNE, UFSM, Santa Maria, Rio Grande do Sul, Brazil 97105-900, and Departamento de Química Fundamental, UFPE, Recife, PE, Brazil 50670-901

gzeni@quimica.ufsm.br

Received March 8, 2005



We present here the reaction of diorganoyl dichalcogenides with terminal alkynes under catalyst-free conditions, by a one-pot procedure, to prepare bis- and tris-chalcogenide alkenes selectively, avoiding the previous preparation of chalcogen alkynes. The reaction proceeded cleanly under mild reaction conditions, and the addition of dichalcogenides to alkynes occurred stereoselectively to give exclusively the corresponding *Z* isomers. We observed that the selectivity control was governed by the effective participation of the hydroxyl group from propargyl alcohols. In addition, the bis-chalcogenide alkenes were exclusively obtained with propargyl alcohol having the acidic hydroxyl group proton. Conversely, the alkynes with no potentially acidic hydroxyl group proton, at propargyl positons, gave exclusively the tris-chalcogenide alkenes.

Introduction

In view of the fact that many biologically active compounds have the structure of substituted alkenes, the stereoselective synthesis of multifunctional alkenes is an important goal in organic chemistry and is still being actively explored. In the last few decades, there has been remarkable interest in the synthesis of vinylic chalcogenides and their synthetic application in the development of methodologies for the synthesis of substituted alkenes.[1] There are several reasons for this, which include a widely varied synthetic organochemical potential and the fact that the chalcogen atom exercises a stabilizing effect on neighboring positive as well as negative charges. This makes the double bond in vinylic chalcogenides responsive toward both nucleophilic and electrophilic attack, an extremely useful feature for organic synthetic purposes.

Organoselenium chemistry is a very broad and exciting field, with many opportunities for research and development of applications. Organoselenium compounds have become attractive synthetic targets because of their chemo-, regio-, and stereoselective reactions and their useful biological activities.[2] Furthermore, organoselenium compounds can usually be used in a wide variety of functional groups, thus avoiding protection group chemistry.[3] Most organoselenium methodologies proceed stereo- and regioselectively in excellent yields. Although the

[†] UFSM.
[‡] UFPE.

(1) (a) Silveira, C. C.; Perin, G.; Braga, A. L. *Tetrahedron Lett.* **1995**, *36*, 7361−7362. (b) Denis, J. N.; Desauvage, S.; Hevesi, L.; Krief, A. *Tetrahedron Lett.* **1981**, *22*, 4009−4012. (c) Gerard, J.; Hevesi, L. *Tetrahedron* **2001**, *57*, 9109−9121. (d) Zeni, G.; Alves, D.; Braga, A. L.; Stefani, H. A.; Nogueira, C. W. *Tetrahedron Lett.* **2004**, *45*, 4823−4826. (e) Zeni, G.; Alves, D.; Pena, J. M.; Braga, A. L.; Stefani, H. A.; Nogueira, C. W. *Org. Biomol. Chem.* **2004**, *2*, 803−805. (f) Marino, J. P.; Nguyen, H. N. *J. Org. Chem.* **2002**, *67*, 6291−6296. (g) Zeni, G.; Stracke, M. P. Lissner, E.; Braga, A. L. *Synlett* **2003**, 1880−1882.

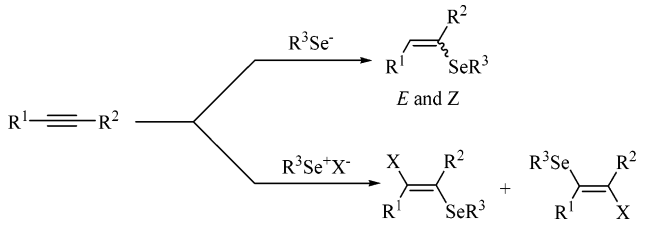
(2) (a) Nogueira, C. W.; Zeni, G.; Rocha, J. B. T. *Chem. Rev.* **2004**, *104*, 6255−6286. (b) Mugesh, G.; du Mont, W. W.; Sies, H. *Chem. Rev.* **2001**, *101*, 2125−2180. (c) Parnham, M. J.; Graf, E. *Prog. Drug Res.* **1991**, *36*, 9−47. (d) Nogueira, C. W.; Quinhones, E. B.; Jung, E. A. C.; Zeni, G.; Rocha, J. B. T. *Inflammation Res.* **2003**, *52*, 56−63.

10.1021/jo050448o CCC: $30.25
Published on Web 05/25/2005

first organoselenium compound was prepared by Wöhler in 1847,[4] only in the early 1970s did the chemistry of organoselenium become a versatile tool in organic chemistry.[5] Organoselenium chemistry developed rapidly, mainly in the area of selenocarbohydrates, selenoamino acids, and selenopeptides. The selenium group can be introduced in an organic substrate via both nucleophilic and electrophilic reagents. After being introduced in an organic substrate, the organoselenium group can easily be removed by selenoxide *syn* elimination[6] and [2,3] sigmatropic rearrangement.[7] In addition, the carbon−selenium bond can also be replaced by a carbon−hydrogen,[8] carbon−halogen,[9] carbon−lithium,[10] or carbon−carbon bond.[11]

Among organoselenium compounds, the vinylic selenides play an important role in organic synthesis. Although various methods are mentioned for the preparation of vinylic selenides, a more useful procedure has centered on the nucleophilic or electrophilic organoselenium addition to terminal or internal alkynes.[12] For example, the nucleophilic addition of selenophenol to alkynes affords, preferentially, the *Z*-vinylic selenides after longer reaction times at room temperature. The reaction is faster at a high temperature; however, the mixture of *Z* and *E* vinylic selenides was obtained in an almost 1:1 ratio (Scheme 1).[13] On the other hand, the eletrophilic addition of organoselenenyl halides to alkynes gave a mixture of Markownikov and anti-Markownikov adducts, depending on the nature of the substituents at the triple bond (Scheme 1).[14] Conversely, vinylic selenides can be prepared by palladium-catalyzed hydroselenation

SCHEME 1



of alkynes to afford the Markownikov adduct in good yields.[15]

In addition to organoselenium, the scope and application of organosulfur chemistry has increased tremendously since sulfur-containing groups serve an important auxiliary function in synthetic sequences. The application of organosulfur compounds in organic synthesis has become attractive because of their chemio-, regio-, and stereoselective reactions. Most of the synthetic transformations using organosulfur compounds have involved the use of vinylic sulfides.[16] Many procedures for the preparation of vinyl sulfides have been developed. Among them, the regioselective addition of hydrogen halide (HCl, HBr, HI) to acetylenic sulfides was the most simple and efficient.[17] Although the regioselectivity of the addition of hydrogen halide to acetylenic sulfides was excellent, it often resulted in the formation of both *Z*- and *E*-isomers due to use of excess aqueous hydrogen halide (37% HCl, 48% HBr, or 51% HI) or saturated gaseous HX in benzene. Moreover, the separation of the *Z*- and *E*-isomers was often quite difficult. Therefore, a new procedure is needed for the stereoselective synthesis of vinyl sulfides. In this way, both alkyl and aryl thiols have been shown to add regio- and stereoselectivity to alkynes to give vinyl sulfides. With activated alkynes such as acetylenic esters and ketones, the addition has been performed under basic conditions, using reagents such as KOH[18] and triethylamine.[19] However, for unactivated alkynes, the use of radical initiators,[20] transition-metal catalysts,[21] and high temperatures[22] has been required.

Our continuing interest in the synthesis[23] and application[24] of vinylic chalcogenides in organic synthesis prompted us to examine a one-pot procedure to prepare a series of bis-chalcogenide alkenes **2** and tris-chalcogenide alkenes **3** by the reaction of diorganoyl dichalco-

(3) (a) Nicolaou, K. C.; Petasis, N. A. *Selenium in Natural Products Synthesis*; CIS: Philadelphia, 1984. (b) Paulmier, C. *Selenium Reagents and Intermediates in Organic Synthesis*; Pergamon: Oxford, 1986. (c) Patai, S.; Rappoport, Z. *The Chemistry of Organic Selenium and Tellurium Compounds*; Wiley: New York, 1986; Vol 1. (d) Liotta, D. *Organoselenium Chemistry*; Wiley: New York, 1987. (e) Krief, A.; Hevesi, L. *Organoselenium Chemistry I*; Springer: Berlin, 1988. (f) Back, T. G. *Organoselenium Chemistry: A Pratical Approach*; Oxford University Press: Oxford, 1999. (g) Reich, H. J. *Acc. Chem. Res*. **1979**, *12*, 22−30. (h) Liotta, D. *Acc. Chem. Res*. **1984**, *17*, 28−34. (i) Wirth, T. Organoselenium Chemistry−Modern Developments in Organic Synthesis. *Top. Curr. Chem. 208*; Spring-Verlag: Heidelberg, 2000. (j) Mugesh, G.; Singh, H. B. *Acc. Chem. Res*. **2002**, *35*, 226−236.

(4) Wöhler, F.; Siemens, C. *Ann. Chem*. **1847**, *61*, 360−365.

(5) Sharpless, K. B.; Lauer, R. F. *J. Am. Chem. Soc*. **1973**, *95*, 2697−2699.

(6) (a) Huguet, J. L. *Adv. Chem. Ser.* **1967**, 345−348. (b) Sharpless, K. B.; Young, M. W.; Lauer, R. F. *Tetrahedron Lett.* **1973**, *22*, 1979−1982.

(7) (a) Reich, H. J. *J. Org. Chem*. **1975**, *40*, 2570−2572. (b) Sharpless, K. B.; Lauer, R. F. *J. Am. Chem. Soc.* **1972**, *94*, 7154−7155.

(8) Sevrin, M.; Vanende, D.; Krief, A. *Tetrahedron Lett*. **1976**, *30*, 2643−2646.

(9) Sevrin, M.; Dumont, W.; Hevesi, L. D.; Krief, A. *Tetrahedron Lett*. **1976**, *30*, 2647−2650.

(10) (a) Seebach, D.; Peleties, N. *Chem. Ber*. **1972**, *105*, 511−515. (b) Seebach, D.; Beck, A. K. *Angew. Chem., Int. Ed. Engl*. **1974**, *13*, 806−807. (c) Reich, H. J.; Shah, S. K. *J. Am. Chem. Soc*. **1975**, *97*, 3250−3252.

(11) Silveira, C. C.; Braga, A. L.; Vieira, A. S.; Zeni, G. *J. Org. Chem.* **2003**, *68*, 662−665.

(12) (a) Comasseto, J. V. *J. Organomet. Chem*. **1983**, *253*, 131−181. (b) Barros, O. S. D.; Lang, E. S.; de Oliveira, C. A. F.; Peppe, C.; Zeni, G. *Tetrahedron Lett*. **2002**, *43*, 7921−7923. (c) Dabdoub, M. J.; Dabdoub, V. B.; Pereira, M. A. *Tetrahedron Lett*. **2001**, *42*, 1595−1597. (d) Dabdoub, M. J.; Baroni, A. C. M.; Lenardão, E. J.; Gianeti, T. R.; Hurtado, G. R. *Tetrahedron* **2001**, *57*, 4271−4276. (e) Dabdoub, M. J.; Cassol, T. M.; Batista, A. C. F. *Tetrahedron Lett.* **1996**, *37*, 9005−9008.

(13) Comasseto, J. V.; Ferreira, J. T. B. *J. Organomet. Chem*. **1981**, *216*, 287−294.

(14) (a) Filer, C. N.; Ahern, D.; Fazio, R.; Shelton, E. J. *J. Org. Chem*. **1980**, *45*, 1313−1315. (b) Garratt, D. G.; Beaulieu, P. L.; Morisset, U. M. *Can. J. Chem.* **1981**, *59*, 927−934.

(15) Kuniyasu, H.; Ogawa, A.; Sato, K. I.; Ryu, I.; Sonoda, N. *Tetrahedron Lett*. **1992**, *33*, 5525−5528.

(16) For the synthetic utility of vinyl sulfides, see, for example: (a) Ager, D. J. *Chem. Soc. Rev.* **1982**, *11*, 493−522. (b) Takeda, T.; Furukawa, H.; Fujimori, M.; Suzuki, K.; Fujiwara, T. *Bull. Chem. Soc. Jpn.* **1984**, *57*, 1863−1869. (c) Gröbel, B.-T.; Seebach, D. *Synthesis* **1977**, 357−402. (d) Trost, B. M.; Lavoie, A. C. *J. Am. Chem. Soc*. **1983**, *105*, 5075−5090. (e) Magnus, P.; Quagliato, D. *J. Org. Chem.* **1985**, *50*, 0, 1621−1626. (f) Delucchi, O.; Pasquato, L. *Tetrahedron* **1988**, *44*, 6755−6794. (g) Pettit, G. R.; van Tamelen, E. E. *Org. React.* **1962**, *12*, 356−363. (h) Boar, R. B.; Hawkins, D. W.; McGhie, J. F.; Barton, D. H. R. *J. Chem. Soc., Perkin Trans. 1* **1973**, 654−657. (i) Trost, B. M.; Ornstein, P. L. *Tetrahedron Lett.* **1981**, *22*, 3463−3466. (j) Wenkert, E.; Ferreira, T. W. *J. Chem. Soc., Chem. Commun.* **1982**, 840−841. (k) Hojo, M.; Tanimoto, S. *J. Chem. Soc., Chem. Commun*. **1990**, 1284−1285. (l) Hojo, M.; Harada, H.; Yoshizawa, J.; Hosomi, A. *J. Org. Chem.* **1993**, *58*, 6541−6542.

(17) Comasseto, J. V.; Menezes, P. H.; Stefani, H. A.; Zeni, G.; Braga, A. L. *Tetrahedron* **1996**, *52*, 9687−9702.

(18) (a) Wadsworth, D. H.; Detty, M. R. *J. Org. Chem.* **1980**, *45*, 4611−4615. (b) Kobayashi, S.; Mukaiyama, T. *Chem. Lett.* **1974**, 705−708.

(19) Dieter, R. K.; Silks, L. A., III; Fishpaugh, J. R.; Kastner, M. E. *J. Am. Chem. Soc.* **1985**, *107*, 4679−4692.

SCHEME 2

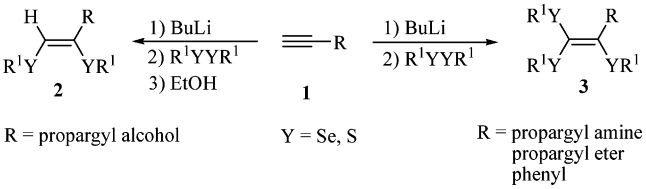
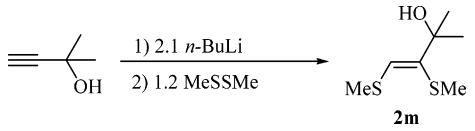


TABLE 1. Investigation of the Best Reaction Conditions



entry	cosolvent	*T* (°C)	time (h)	yield (%)
1		25	3	NR
2		74	3	20
3		74	12	31
4		74	36	48
5	EtOH	25	12	5
6	EtOH	74	3	54
7	EtOH	74	12	90
8	AcOH	74	12	13
9	H_2O	74	12	28

genides with terminal alkynes **1**, under catalyst-free conditions (Scheme 2).

Results and Discussion

Since our initial studies have focused on the development of an optimum set of reaction conditions, we have initially chosen 2-methylbut-3-yn-2-ol and dimethyl disulfide as standard starting materials. In this way, *n*-butyllithium (2.1 mmol) was added, at 0 °C, to a solution of the 2-methylbut-3-yn-2-ol (1 mmol) and THF (2 mL), and after 30 min, the dimethyl disulfide was added at 0 °C. The results of the reactions with a variety in temperature, time, and addition of a cosolvent are summarized in Table 1.

As shown in Table 1, the reaction of 2-methylbut-3-yn-2-ol with dimethyl disulfide at room temperature for 3 h did not afford the desired vinyl sulfide **2m** (Table 1, entry 1). When the temperature is changed to 74 °C, the reaction resulted in a low yield after 3 h (Table 1, entry 2). Furthermore, if the heating (74 °C) was continued for 12 h, vinyl sulfide **2m** was obtained in 31% yield (Table 1, entry 3). We also observed that a higher reaction time (36 h) did not significantly improve the yield (Table 1, entry 4). Taken in analogy with the hydrotelluration reactions, which lead to a *Z*-alkene exclusively, in which the tellurolate anion and the hydrogen are known to add to the alkyne in a *trans*-fashion and the proton is believed to come from the hydroxyl group of ethanol,[23a,b] we applied this finding by choosing EtOH as a proton source. Nonetheless, performing the reaction in the presence of EtOH at room temperature for 12 h and 74 °C for 3 h gave unsatisfactory results (Table 1, entries 5 and 6), whereas the use of 74 °C for 12 h increased the yield to 90% (Table 1, entry 7). Replacement of EtOH with H_2O or AcOH was inefficient to obtain better results, even under conditions of high temperature and a long reaction time (Table 1, entries 8 and 9). Thus, careful analysis of the optimized reactions revealed that the optimum conditions for this one- pot procedure were the addition of *n*-butyllithium (2.1 mmol) to a solution of 2-methylbut-3-yn-2-ol (1 mmol) and THF (2 mL), at 0 °C. Then, after 30 min at room temperature, dimethyl disulfide (1.2 mmol) was added. The reaction was stirred for 3 h; after that, EtOH (0.5 mL) was added. The mixture was heated at 74 °C for 12 h. Using these reaction conditions, we were able to prepare *Z*-vinylic sulfide **2m** in 90% yield. To demonstrate the efficiency of this reaction, we explored the generality of our method extending the conditions to various propargyl alcohols as well as other aromatic and aliphatic disulfides, and the results are summarized in Table 2.

Inspection of Table 2 shows that the reaction worked well for a variety of propargylic alcohols. Both hindered and nonhindered propargyl alcohols gave the desired sulfide in good yields. A closer inspection of the results revealed that the reaction is sensitive to the position of substituents in aromatic disulfides. For example, diphenyl disulfides with a Cl substituent at the meta position gave a worse yield than at the ortho and para positions (Table 2, entries 4−6). Diphenyl disulfides with a NO_2 or NH_2 group at the para position did not react under our standard conditions, even after many modifications (change in the base, amount of disulfide, solvent, cosolvents, temperature, and time) (Table 2, entries 7 and 8). These results demonstrated that the efficiency of the vinyl sulfide formations could significantly depend on the electronic effects of the substituents in the aromatic ring. The vinyl sulfide formation was low in the cases where benzylic and long-chain aliphatic disulfide were employed (Table 2, entries 9 and 10), probably due to the steric effect of these groups. Based on the above results, it is noteworthy that the vinyl sulfide formation was not sensitive to the structure of propargyl alcohols; however, it was dependent on the nature of disulfides.

In an attempt to broaden the scope of our methodology, the possibility of performing the reaction with diselenides instead of disulfides was also investigated. Thus, the standard reaction condition applied to prepare the vinyl sulfides was also tested for diselenides. In this way, *n*-butyllithium (2.1 mmol) was added to a solution of propargyl alcohol (1 mmol) and THF (2 mL), at 0 °C, and after 30 min at room temperature, diselenide (1.2 mmol) was added at 0 °C. The reaction was stirred for 3 h, after which time EtOH (0.5 mL) was added. The mixture was heated at 74 °C at 12 h. The scope and limitations of the diselenide addition to propargyl alcohol are summarized in Table 3.

(20) (a) Galambos, G.; Csokasi, P.; Szantay, C. J.; Czira, G.; Szantay, C. *Heterocycles* **1994**, *38*, 1459−1464. (b) Montevecchi, P. C.; Navacchia, M. L. *Tetrahedron Lett.* **1998**, *39*, 9077−9080.

(21) (a) Kuniyasu, H.; Ogawa, A.; Sato, K. I.; Kambe, N.; Sonoda, N. *J. Am. Chem. Soc.* **1992**, *114*, 5902−5903. (b) Ishino, Y.; Masaoka, T.; Hirashima, T. *Chem. Lett.* **1990**, *7*, 1185−1188. (c) Ogawa, A.; Ikeda, T.; Kimura, K.; Hirao, T. *J. Am. Chem. Soc.* **1999**, *121*, 5108−5114. (d) Ogawa, A.; Kudo, A.; Hirao. T. *Tetrahedron Lett.* **1998**, *39*, 5213−5216.

(22) Benati, L.; Montevecchi, P. C.; Spagnolo, P. *J. Chem. Soc., Perkin Trans. 1* **1991**, *9*, 2103-2109.

(23) (a) Zeni, G.; Stracke, M. P.; Nogueira, C. W.; Braga, A. L.; Menezes, P. H.; Stefani, H. A. *Org. Lett*. **2004**, *6*, 1135−1138. (b) Zeni, G.; Barros, O. S. D.; Moro, A. V.; Braga, A. L.; Peppe, C. *Chem. Commun.* **2003**, 1258−1259. (c) Barros, O. S. D.; Lang, E. S.; Peppe, C.; Zeni, G. *Synlett* **2003**, 1725−1727.

(24) (a) Zeni, G.; Braga, A. L.; Stefani, H. A. *Acc. Chem. Res.* **2003**, *36*, 731−738. (b) Zeni, G.; Panatieri, R. B.; Lissner, E.; Menezes, P. H.; Braga, A. L.; Stefani, H. A. *Org. Lett.* **2001**, *3*, 819−821.

TABLE 2. Vinyl Sulfides Prepared from Alkynes and Disulfides

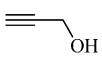
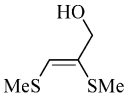
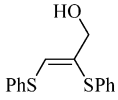
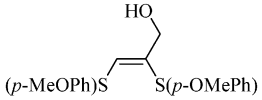
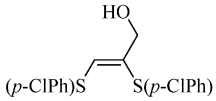
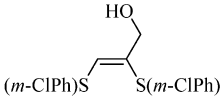
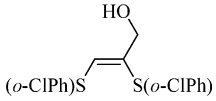
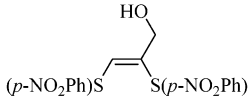
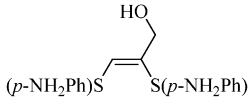
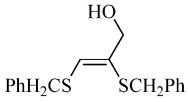
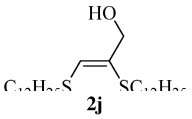
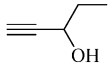
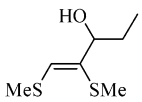
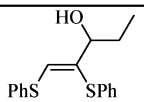
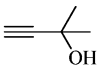
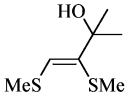
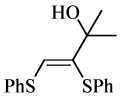
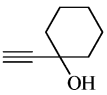
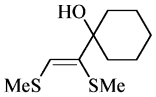
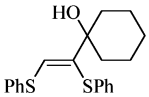
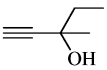
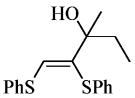
Entry	Alkyne	Disulfide	Vinyl Sulfide	Yield(%)
1		$(MeS)_2$	 **2a**	**98**
2		$(PhS)_2$	 **2b**	**80**
3		$(p\text{-MeOPhS})_2$	 **2c**	**79**
4		$(p\text{-ClPhS})_2$	 **2d**	**63**
5		$(m\text{-ClPhS})_2$	 **2e**	**59**
6		$(o\text{-ClPhS})_2$	 **2f**	**80**
7		$(p\text{-}NO_2PhS)_2$	 **2g**	**NR**
8		$(p\text{-}NH_2PhS)_2$	 **2h**	**NR**
9		$(PhCH_2S)_2$	 **2i**	**52**
10		$(C_{12}H_{25}S)_2$	 **2j**	**54**
11		$(MeS)_2$	 **2k**	**97**

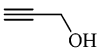
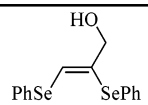
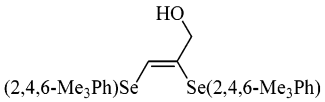
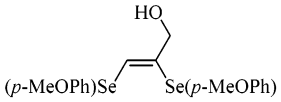
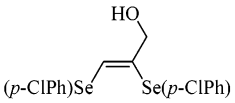
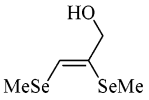
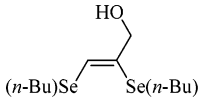
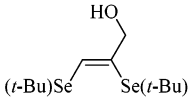
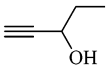
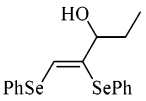
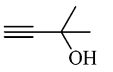
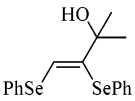
Table 2 (Continued)

Entry	Alkyne	Disulfide	Vinyl Sulfide	Yield(%)
12		$(PhS)_2$	 **2l**	**80**
13		$(MeS)_2$	 **2m**	**90**
14		$(PhS)_2$	 **2n**	**78**
15		$(MeS)_2$	 **2o**	**81**
16		$(PhS)_2$	 **2p**	**70**
17		$(PhS)_2$	 **2q**	**77**

Our first investigations focused on the influence of alkyl substituents at the propargyl position. Satisfactorily, all propargyl alcohols were found to be effective, although very poor yields were observed in more hindred propargyl alcohols (Table 3, entries 1, 8, and 9). Next, several diselenides having different substituents were tested. As shown in entry 2, bulky aryl diselenides afforded the vinylic selenide **2s** in excellent yield. Our experiments showed that the reaction with diphenyl diselenides having either neutral (entry 1), electron-donating (entry 3), or electron-withdrawing (entry 4) substituents also gave the vinylic selenides in good yields, although the yield was lower for the electron-withdrawing substituent (entry 4). Based on these results, we conclude that the reactivity order in the formation of vinylic selenides, considering the aromatic substituents in diselenides, is H > MeO > Cl. However, no significant influence of the substituents at the propargyl position in propargyl alcohol was observed. On the other hand, considerable difficulties were found when we attempted to react aliphatic diselenides with propargyl alcohol, where we observed that many byproducts were formed and the desired product was obtained in lower yields. For example, a small amount of vinylic selenides was isolated from the reaction of dimethyl diselenide, di-*n*-butyl diselenide, or di-*tert*-butyl diselenide with propargyl alcohols (entries 5−7).

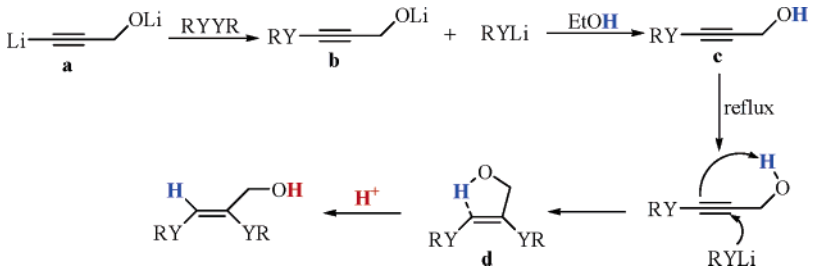
A plausible mechanism for the formation of vinylic sulfides **2a**−**q** and selenides **2r**−**z** is shown in Scheme 3. We believe that (a) the removal of acid hydrogens with *n*-BuLi from propargyl alcohols gave the lithium intermediate **a** and the reaction of **a** with dichalcogenide afforded the species **b**; (b) the addition of EtOH led to the protonation of the intermediate **b** to give the acetylenic chalcogenide **c**; (c) starting the reflux led to the addition of the chalcogenate anion onto the triple bond of the acetylenic chalcogenide **c** and the subsequent trapping of the vinyl anion with a proton from the acidic proton of the hydroxyl group, according to transition state **d**, leads to the desired vinyl compounds (Scheme 3). Here, different from our previous work,[23a] we have found that vinylic hydrogen came from hydroxyl group of propargyl alcohols. Thus, we believe that the presence of EtOH is required due to poor solubility of the intermediate **b** rather than as a proton source.

TABLE 3. Vinyl Selenides Prepared from Propargyl Alcohols and Diselenides

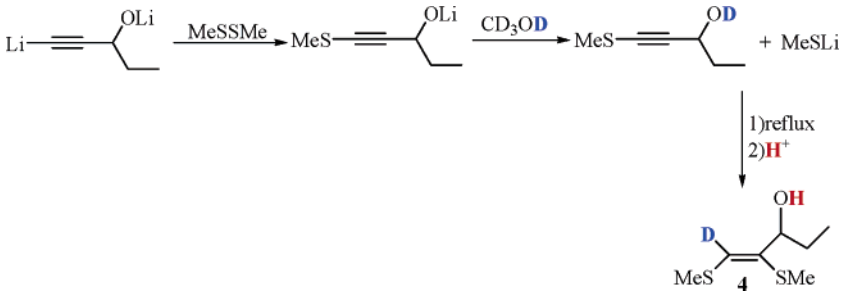
Entry	Alkyne	Diselenide	Vinyl Selenide	Yield(%)
1		$(PhSe)_2$	 **2r**	**90**
2		$(2,4,6\text{-}Me_3PhSe)_2$	 **2s**	**80**
3		$(p\text{-}MeOPhSe)_2$	 **2t**	**70**
4		$(p\text{-}ClPhSe)_2$	 **2u**	**65**
5		$(MeSe)_2$	 **2v**	**10**
6		$(n\text{-}BuSe)_2$	 **2w**	**27**
7		$(t\text{-}BuSe)_2$	 **2x**	**26**
8		$(PhSe)_2$	 **2y**	**83**
9		$(PhSe)_2$	 **2z**	**75**

Although the intermediate **b** could not be isolated from this reaction, several considerations and additional observations support the mechanism described in Scheme 3. First, when the reaction was stopped before starting the reflux (3 h at room temperature), a careful NMR analysis of the crude reaction mixture revealed the presence of acetylenic chalcogenide **c** as a major product. Second, when we carried out the addition of dimethyl disulfide to pent-1-yn-3-ol in MeOH-d_4, vinylic sulfide **4** was isolated as the sole product (Scheme 4). Finally,

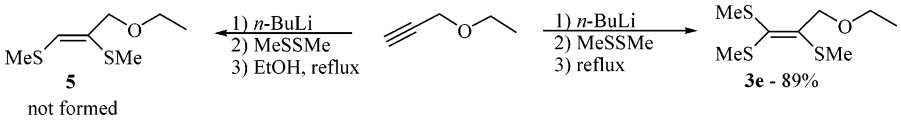
SCHEME 3



SCHEME 4



SCHEME 5



when the reaction was repeated with dimethyl disulfide and propargyl ether, without an acidic proton in the hydroxyl group, unexpectedly, tris-phenylthioalkene **3e** was obtained, instead of bis-phenylthioalkene **5** (Scheme 5). These results strongly suggest that the addition of dichalcogenides across the triple bond follows an anti-pathway addition, with the effective participation of the hydroxyl group from propargyl alcohols.

Based on the surprising results above, we initiated our investigations in the preparation of these compounds via reaction of dichalcogenides with alkynes in a one-pot procedure. At first, the reaction was carried out using the standard reaction conditions applied to prepare bis-chalcogen alkenes. Unfortunately, this condition was not effective, and tris-chalcogen alkenes were obtained only in a moderate yield. The use of other solvents such as benzene, hexane, ethyl ether, and toluene also failed to produce the chalcogenide in a satisfactory yield. However, it was gratifying to discover that simply changing the amount of disulfide from 1.2 to 3 mmol and performing the reaction in the absence of ethanol had a dramatic effect, giving tris-chalcogen alkene **3e** in 89% yield. Thus, careful analysis of the optimized reactions revealed that the general synthetic procedure for the reaction is as follows: *n*-butyllithium (1.1 mmol) is added to a solution of alkyne (1 mmol) and THF (2 mL), at 0 °C. The resulting solution is stirred for 30 min at room temperature. After that, dichalcogenide is added and the mixture is then heated at 74 °C for 12 h. Next, we extended our studies on the scope of the addition of disulfides and diselenides to different alkynes, and the results are summarized in Table 4.

Concerning the structure of alkynes, we found some limitations in this methodology. For example, no reaction was observed with alkynes bearing a *t*-Bu or *n*-Bu group (Table 4, entries 3 and 4). The use of a long chain alcohol also failed to produce the desired product (Table 4, entry 14). However, checking Table 4, we observed that the reaction worked well with hindered and nonhindered protected propargylic alcohols, tertiary propargylamines, and propargyl morpholynes. Regarding diselenides and disulfides, dialkyl disulfides and diaryl diselenides afforded tris-vinylic chalcogenides in good yields, although the yield was lower to diaryl diselenides, both electron-withdrawing and electron-rich (Table 4, entries 7 and 8). Finally, it is worth mentioning that, through our methodology, it was possible to prepare highly functionalized chalcogene alkenes, such as **3o** and **3p** (Table 4, entries 15 and 16).

In all cases where no desired vinyl chalcogenide was formed, we recovered a small amount of dichalcogenide and observed the formation of a large amount of alkynyl chalcogenide. The latter product was presumably formed by the known reaction of *n*-BuLi with alkynes and the trapping of the lithium intermediate with disulfide as an electrophilic reagent (Scheme 6).[17]

The reaction pathways leading to tris-chalcogen alkene **h** products seem to depend on the amount of dichalcogenides present in the reaction (1.2 and 2.2 mmol of dichalcogenides gave poor yields) and the absence of the potentially acidic hydroxyl group protons in the structure of alkynes. Thus, the removal of acid hydrogens with *n*-BuLi from alkynes gave lithium intermediate **e** and the reaction of this intermediate with dichalcogenide afforded acetylenic chalcogenide **f** together with lithium chalcogenate. Starting the reflux led to the addition of the chalcogenate anion onto the triple bond of acetylenic chalcogenide **f**, with concomitant attack on the dichalco-

TABLE 4. Tris-chalcogen Alkenes Prepared from Alkynes and Dichalcogenides

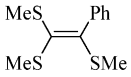
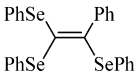
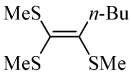
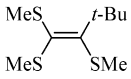
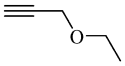
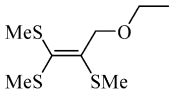
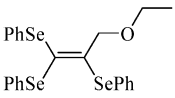
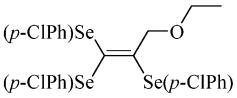
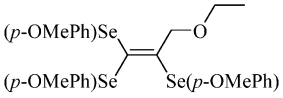
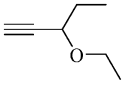
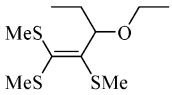
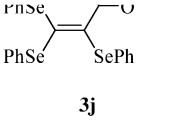
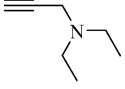
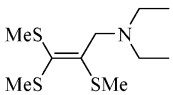
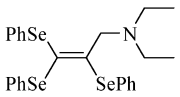
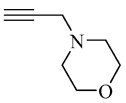
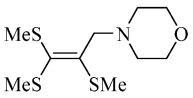
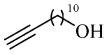
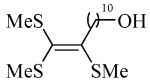
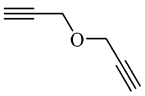
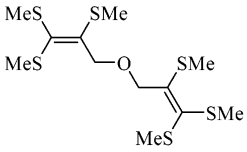
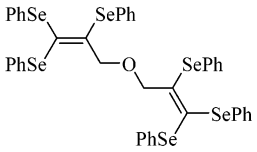
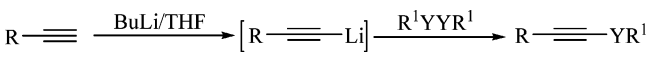
Entry	Alkyne	Dichalcogenide	Tris-chalcogen alkenes	Yield (%)
1		$(MeS)_2$	 **3a**	**85**
2		$(PhSe)_2$	 **3b**	**76**
3		$(MeS)_2$	 **3c**	**NR**
4		$(MeS)_2$	 **3d**	**NR**
5		$(MeS)_2$	 **3e**	**89**
6		$(PhSe)_2$	 **3f**	**87**
7		$(p\text{-ClPhSe})_2$	 **3g**	**67**
8		$(p\text{-MeOPhSe})_2$	 **3h**	**50**
9		$(MeS)_2$	 **3i**	**73**
10		$(PhSe)_2$	 **3j**	**71**
11		$(MeS)_2$	 **3k**	**64**

Table 4 (Continued)

Entry	Alkyne	Dichalcogenide	Tris-chalcogen alkenes	Yield (%)
12		$(PhSe)_2$	 **3l**	**57**
13		$(MeS)_2$	 **3m**	**77**
14		$(MeS)_2$	 **3n**	**NR**
15		$(MeS)_2$	 **3o**	**53**
16		$(PhSe)_2$	 **3p**	**45**

SCHEME 6



genides, according to transition state **g**, leading to the desired vinyl compounds (Scheme 7).

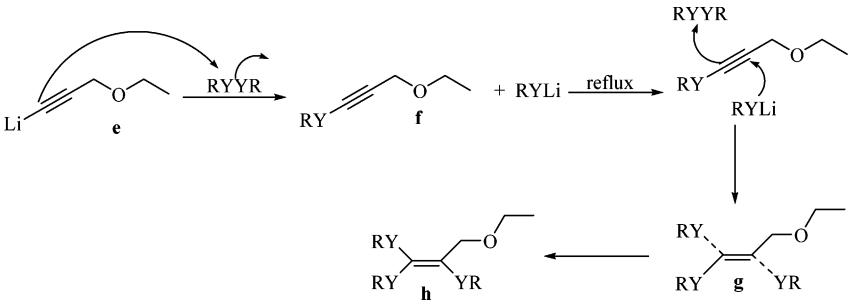
Finally, we completed our investigations by examining the reaction of diorganoyl ditellurides with terminal alkynes, and we found that when this reaction was carried out under experimental conditions, similar to those used for the preparation of bis-**2a**−**z** and tris-**3a**−**p**, neither vinylic telluride **6** nor **7** was obtained. In an attempt to obtain these compounds, a variety of conditions were investigated, including temperature, solvent, stoichiometry, alkynes, and ditellurides. Unfortunately, all conditions tested were found to be ineffective, and neither bis-arganoyltelluride alkene **6** nor tris-arganoyltelluride alkene **7** was obtained (Scheme 8). In these cases, we recovered alkyne and ditelluride as products. Based on these results and with the knowledge that the carbon−tellurium bond exhibits an easier heterolytic cleavage toward nucleophilic reagents than the carbon−sulfur and carbon−selenium bonds, due to the large volume and greater ionic character of the tellurium atom and the easy polarization of the bonds, we assumed that alkynyl telluride was formed as an intermediate. However, a direct attack of RTeLi to the heteroatom (Te) regenerated the starting materials, ditelurides, and alkynes (Scheme 9).[12c,23a]

Analysis of the ^1H and ^{13}C NMR spectra showed that both bis-vinylic chalcogenides **2a**−**z** and tris-vinylic chalcogenides **3a**−**p** presented data in full agreement with their assigned structures. The stereochemistry of these substituted alkenes was established by NOE experiments. For example, when compound **2k** was irradiated at the signal attributed to vinylic hydrogen (6.51 ppm), an enhancement of allylic hydrogens (4.10 ppm) was observed, showing a cis relation between them. The results have shown that the addition of dichalcogenides to alkynes occurs stereoselectively to give exclusively the corresponding *Z* isomers.

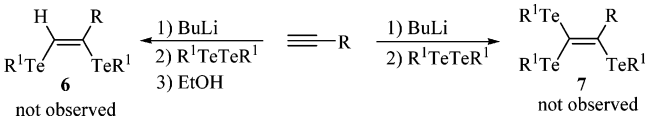
Conclusion

In summary, we present here the first chalcogenation reaction of alkynes by a one-pot procedure to selectively prepare bis-vinylic chalcogenides and tris-vinylic chalcogenides, avoiding the previous preparation of chalcogen alkynes. We observed that the selectivity control was governed by the effective participation of the hydroxyl group from propargyl alcohols. In addition, bis-vinylic chalcogenides were exclusively obtained with propargyl alcohol containing acidic hydroxyl group protons. Con-

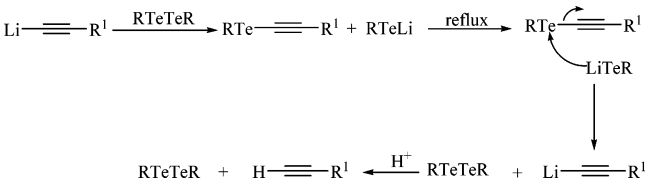
SCHEME 7



SCHEME 8



SCHEME 9



versely, alkynes with no potentially acidic hydroxyl group protons, at propargyl positons, gave exclusively trisvinylic chalcogenides. We hope that these findings will be useful to assist in choosing a method for the chalcogenation of alkynes containing different functional groups. This reaction, associated with the Ni/CuI-catalyzed cross-coupling reaction of vinylic selenides[11] with alkynes, may constitute an interesting alternative route to the regio- and stereoselective preparation of functionalized alkenes. The pharmacological activity of these compounds is under study in our laboratory.

Experimental Section

General Procedure for the Preparation of the Bis-chalcogenide Alkenes. *n*-Butyllithium (1.34 mL of a 1.567 M solution in hexane, 2.1 mmol) was added, under argon, to a solution of alkyne (1 mmol) in THF (2 mL) previously cooled at 0 °C. The resulting solution was stirred for 30 min at room temperature. After this time, the mixture was cooled at 0 °C, and the disulfide or diselenide (1.2 mmol) in THF (1 mL) was added. The reaction was warmed at room temperature, stirred for 3 h, and then treated with ethanol (0.5 mL). The mixture was then heated at reflux for 12 h. After this time, the mixture was cooled at room temperature, diluted with ethyl acetate (20 mL), and washed with brine (2 × 20 mL). The organic phase was separated, dried over $MgSO_4$, and concentrated under vacuum. The residue was purified by flash chromatography and eluted with hexane/ethyl acetate (80:20). **(*Z*)-2,3-Bis(methylthio)prop-2-en-1-ol (2a).** Yield: 0.147 g (98%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 6.40 (s, 1H), 4.21 (s, 2H), 2.35 (s, 3H), 2.32 (s, 3H), 2.16 (s, 1H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 130.8, 130.4, 64.8, 16.9, 14.3. MS (EI, 70 eV) *m/z* (relative intensity): 151 (7), 121 (100), 103 (14), 73 (14), 59 (40), 47 (13). HRMS: calcd for $C_5H_{10}OS_2$ 150.0173, found 150.0178.

(*Z*)-2,3-Bis(phenylthio)prop-2-en-1-ol (2b). Yield: 0.219 g (80%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.44−7.19 (m, 10H), 7.01 (t, J = 1.02 Hz, 1H), 4.12 (s, 2H), 2.15 (s, 1H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 134.8, 134.5, 133.1, 130.3, 129.9, 129.8, 129.2, 129.1, 127.3, 126.9, 65.3. MS (EI, 70 eV) *m/z* (relative intensity): 274 (100), 186 (10), 167 (43), 147 (27), 135 (52), 91 (14), 77 (5). HRMS: calcd for $C_{15}H_{14}OS_2$ 274.0486, found 274.0491.

(*Z*)-2,3-Bis(4-methoxyphenylthio)prop-2-en-1-ol (2c). Yield: 0.264 g (79%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.38−7.35 (m, 4H), 6.86−6.81 (m, 4H), 6.72 (s, 1H), 4.02 (s, 2H), 3.77−3.75 (m, 6H), 2.15 (m, 1H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 159.4, 159.3, 133.2, 132.9, 132.9, 130.3, 125.3, 123.1, 114.7, 114.7, 64.9, 55.3, 55.2. MS (EI, 70 eV) *m/z* (relative intensity): 333 (1), 318 (91), 227 (95), 179 (90), 164 (100), 139 (85), 96 (25), 77 (10). HRMS: calcd for $C_{17}H_{18}O_3S_2$ 334.0697, found 334.0703.

(*Z*)-2,3-Bis(4-chlorophenylthio)prop-2-en-1-ol (2d). Yield: 0.215 g (63%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.38−7.26 (m, 8H), 6.97 (t, J = 1.17 Hz, 1H), 4.15 (d, J = 5.11 Hz, 2H), 1.85 (t, J = 5.55 Hz, 1H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 134.6, 133.8, 133.2, 133.1, 131.8, 131.6, 131.1, 130.1, 129.4, 129.4, 65.4. MS (EI, 70 eV) *m/z* (relative intensity): 257 (9), 168 (20), 111 (15), 97 (26), 83 (34), 69 (51), 67 (73), 55 (100). HRMS: calcd for $C_{15}H_{12}Cl_2OS_2$ 341.9706, found 341.9712.

(*Z*)-2,3-Bis(3-chlorophenylthio)prop-2-en-1-ol (2e). Yield: 0.202 g (59%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.43−7.19 (m, 8H), 7.07 (s, 1H), 4.19 (s, 2H), 1.93 (s, 1H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 136.4, 135.2, 135.0, 134.8, 134.5, 130.3, 130.2, 130.0, 129.9, 128.9, 128.3, 127.7, 127.4, 127.1, 65.5. MS (EI, 70 eV) *m/z* (relative intensity): 341 (3), 222 (100), 178 (23), 161 (11), 143 (6). HRMS: calcd for $C_{15}H_{12}Cl_2OS_2$ 341.9707, found 341.9714.

(*Z*)-2,3-Bis(2-chlorophenylthio)prop-2-en-1-ol (2f). Yield: 0.274 g (80%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.49−7.47 (m, 1H), 7.42−7.33 (m, 3H), 7.27−7.13 (m, 4H), 7.06 (s, 1H), 4.17 (s, 2H), 2.12 (s, 1H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 135.0, 134.3, 134.1, 133.6, 132.2, 131.6, 130.4, 130.1, 130.0, 129.8, 128.6, 127.7, 127.4, 127.3, 65.5. MS (EI, 70 eV) *m/z* (relative intensity): 342 (1), 326 (66), 291 (24), 235 (100), 183 (30), 148 (98), 108 (86), 69 (31). HRMS: calcd for $C_{15}H_{12}Cl_2OS_2$ 341.9706, found 341.9814.

(*Z*)-2,3-Bis(benzylthio)prop-2-en-1-ol (2i). Yield: 0.157 g (52%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.30−7.17 (m, 10H), 6.51 (s, 1H), 3.92 (s, 2H), 3.90 (s, 2H), 3.87 (s, 2H), 1.81 (s, 1H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 137.9, 137.6, 132.6, 129.5, 128.7, 128.7, 128.6, 128.3, 127.2, 127.0, 66.2, 37.7, 35.8. MS (EI, 70 eV) *m/z* (relative intensity): 284 (33), 162 (100), 147 (17), 128 (50), 115 (25), 91 (38). HRMS: calcd for $C_{17}H_{18}OS_2$ 302.0799, found 302.0805.

(*Z*)-2,3-Bis(dodecylthio)prop-2-en-1-ol (2j). Yield: 0.247 g (54%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 6.51 (s, 1H), 4.17 (s, 2H), 2.77−2.70 (m, 4H), 1.66−1.55 (m, 4H), 1.39−1.26 (m, 36H), 0.88 (t, J = 7.02 Hz, 6H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 132.3, 129.3, 65.8, 34.1, 34.1, 31.9, 31.9, 31.7, 31.7, 30.4, 30.0, 29.63, 29.62, 29.61, 29.58, 29.57, 29.51, 29.5, 29.3, 29.25, 29.2, 28.8, 28.6, 22.7, 22.7, 14.1, 14.1. MS (EI, 70 eV) *m/z* (relative intensity): 458 (3), 257 (97), 240 (35), 227 (39), 199 (90), 87 (100), 59 (70). HRMS: calcd for $C_{27}H_{54}OS_2$ 458.3616, found 458.3621.

(*Z*)-1,2-Bis(methylthio)pent-1-en-3-ol (2k). Yield: 0.172 g (97%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 6.52 (s, 1H), 4.10

(t, J = 6.28 Hz, 1H), 2.48 (s, 1H), 2.35 (s, 3H), 2.29 (s, 3H), 1.77−1.57 (m, 2H), 0.91 (t, J = 7.45 Hz, 3H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 134.6, 132.8, 76.8, 28.7, 16.7, 15.9, 9.8. MS (EI, 70 eV) *m/z* (relative intensity): 160 (100), 145 (80), 130 (7), 112 (5), 97 (52). HRMS: calcd for $C_7H_{14}OS_2$ 178.0486, found 178.0490.

(*Z*)-1,2-Bis(phenylthio)pent-1-en-3-ol (2l). Yield: 0.242 g (80%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.43−7.16 (m, 10H), 7.11 (s, 1H), 4.12 (q, J = 6.43 Hz, 1H), 1.93 (s, 1H), 1.80−1.58 (m, 2H), 0.91 (t, J = 7.45 Hz, 3H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 136.2, 134.8, 134.1, 132.0, 130.2, 129.0, 128.9, 128.6, 127.2, 126.2, 76.4, 29.0, 9.7. MS (EI, 70 eV) *m/z* (relative intensity): 284 (100), 269 (29), 175 (46), 167 (27), 143 (20), 77 (3). HRMS: calcd for $C_{17}H_{18}OS_2$ 302.0799, found 302.0807.

(*Z*)-2-Methyl-3,4-bis(methylthio)but-3-en-2-ol (2m). Yield: 0.160 g (90%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 6.70 (s, 1H), 2.36 (s, 3H), 2.29 (s, 3H), 2.27 (s, 1H), 1.43 (s, 6H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 137.2, 135.1, 74.6, 28.8, 16.9, 16.5. MS (EI, 70 eV) *m/z* (relative intensity): 130 (80), 82 (100), 71 (23), 67 (55), 59 (21). HRMS: calcd for $C_7H_{14}OS_2$ 178.0486, found 178.0492.

(*Z*)-2-Methyl-3,4-bis(phenylthio)but-3-en-2-ol (2n). Yield: 0.235 g (78%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.42−7.24 (m, 10H), 7.17−7.13 (m, 1H), 2.18 (s, 1H), 1.46 (s, 6H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 137.7, 135.0, 134.95, 134.9, 130.5, 129.1, 128.9, 127.4, 127.0, 125.6, 75.0, 29.3. MS (EI, 70 eV) *m/z* (relative intensity): 284 (100), 207 (18), 176 (99), 143 (62), 130 (14), 66 (8). HRMS: calcd for $C_{17}H_{18}OS_2$ 302.0799, found 302.0808.

(*Z*)-1-(1,2-Bis(methylthio)vinyl)cyclohexanol (2o). Yield: 0.185 g (85%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 6.70 (s, 1H), 2.35 (s, 3H), 2.28 (s, 3H), 1.97 (s, 1H), 1.79−1.56 (m, 10H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 138.1, 135.9, 75.5, 36.2, 25.4, 21.9, 17.3, 16.8. MS (EI, 70 eV) *m/z* (relative intensity): 200 (63), 185 (100), 137 (25), 110 (10). HRMS: calcd for $C_{10}H_{18}OS_2$ 218.0799, found 218.0805.

(*Z*)-1-(1,2-Bis(phenylthio)vinyl)cyclohexanol (2p). Yield: 0.239 g (70%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.40−7.24 (m, 10H), 7.15−7.11 (m, 1H), 1.92 (s, 1H), 1.82−1.53 (m, 10H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 138.0, 135.4, 135.1, 135.0, 130.3, 129.0, 128.7, 127.2, 126.7, 125.3, 75.7, 36.1, 25.1, 21.7. MS (EI, 70 eV) *m/z* (relative intensity): 342 (1), 324 (100), 247 (14), 215 (59), 182 (47), 147 (33), 109 (22), 77 (43). HRMS: calcd for $C_{20}H_{22}OS_2$ 342.1112, found 342.1118.

(*Z*)-3-Methyl-1,2-bis(phenylthio)pent-1-en-3-ol (2q). Yield: 0.243 g (77%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.41−7.25 (m, 10H), 7.15 (t, J = 7.75 Hz, 1H), 2.02 (s, 1H), 1.84−1.66 (m, 2H), 1.41 (s, 3H), 0.88 (t, J = 7.45 Hz, 3H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 138.1, 135.0, 134.8, 134.0, 130.3, 129.0, 128.8, 127.2, 125.6, 77.5, 33.8, 26.6, 8.1. MS (EI, 70 eV) *m/z* (relative intensity): 298 (100), 222 (34), 190 (42), 162 (39), 148 (18), 77 (7). HRMS: calcd for $C_{18}H_{20}OS_2$ 316.0955, found 316.0960.

(*Z*)-2,3-Bis(phenylselanyl)prop-2-en-1-ol (2r). Yield: 0.333 g (90%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.59−7.53 (m, 4H), 7.39 (s, 1H), 7.32−7.27 (m, 6H), 4.14 (s, 2H), 1.86 (s, 1H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 133.4, 133.2, 132.4, 132.2, 130.3, 129.4, 129.3, 128.6, 127.8, 127.5, 67.6. MS (EI, 70 eV) *m/z* (relative intensity): 369 (86), 312 (41), 212 (67), 195 (100), 181 (72), 155 (68), 78 (20). HRMS: calcd for $C_{15}H_{14}OSe_2$ 369.9375, found 369.9382.

(*Z*)-2,3-Bis(mesitylselanyl)prop-2-en-1-ol (2s). Yield: 0.363 g (80%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 6.95 (s, 2H), 6.94 (s, 2H), 6.71 (s, 1H), 3.78 (d, J = 5.70 Hz, 2H), 2.53 (s, 6H), 2.50 (s, 6H), 2.28 (s, 3H), 2.27 (s, 3H), 1.40 (t, J = 5.70 Hz, 1H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 143.3, 142.8, 138.8, 138.7, 132.7, 128.8, 128.7, 128.2, 127.0, 125.5, 66.8, 24.5, 24.3, 20.9, 20.9. MS (EI, 70 eV) *m/z* (relative intensity): 453 (5), 237 (32), 225 (100), 198 (29), 119 (46). HRMS: calcd for $C_{21}H_{26}OSe_2$ 454.0314, found 454.0320.

(*Z*)-2,3-Bis(4-methoxyphenylselanyl)prop-2-en-1-ol (2t). Yield: 0.301 g (70%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.54−7.51 (m, 4H), 7.16 (s, 1H), 6.86−6.83 (m, 4H), 4.06 (s, 2H), 3.80 (s, 3H), 3.79 (s, 3H), 2.00 (s, 1H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 159.8, 159.8, 135.5, 135.4, 134.2, 134.2, 132.6, 132.1, 115.1, 115.0, 67.2, 55.3, 55.3. MS (EI, 70 eV) *m/z* (relative intensity): 251 (100), 242 (94), 225 (53), 213 (91), 198 (39), 188 (48), 107 (19). HRMS: calcd for $C_{17}H_{18}O_3Se_2$ 429.9586, found 429.9592.

(*Z*)-2,3-Bis(4-chlorophenylselanyl)prop-2-en-1-ol (2u). Yield: 0.285 g (65%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.51−7.45 (m, 4H), 7.34 (s, 1H), 7.30−7.25 (m, 4H), 4.15 (d, J = 5.41 Hz, 2H), 1.83 (t, J = 6.28 Hz, 1H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 134.5, 134.3, 133.9, 133.6, 133.4, 132.3, 129.5, 129.5, 128.2, 126.7, 67.5. MS (EI, 70 eV) *m/z* (relative intensity): 438 (10), 379 (17), 251 (62), 228 (52), 216 (100), 190 (77), 156 (58), 111 (38). HRMS: calcd for $C_{15}H_{12}Cl_2OSe_2$ 437.8596, found 437.8601.

(*Z*)-1,2-Bis(phenylselanyl)pent-1-en-3-ol (2y). Yield: 0.330 g (83%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.57−7.53 (m, 4H), 7.46 (s, 1H), 7.30−7.24 (m, 6H), 4.07 (q, J = 5.99 Hz, 1H), 1.89 (d, J = 5.55 Hz, 1H), 1.76−1.56 (m, 2H), 0.89 (t, J = 7.45 Hz, 3H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 135.9, 135.2, 133.2, 131.4, 130.5, 129.6, 129.3, 127.8, 127.1, 78.5, 29.4, 9.9. MS (EI, 70 eV) *m/z* (relative intensity): 397 (1), 380 (27), 223 (60), 157 (33), 142 (100), 128 (32), 77 (31). HRMS: calcd for $C_{17}H_{18}OSe_2$ 397.9688, found 397.9693.

(*Z*)-2-Methyl-3,4-bis(phenylselanyl)but-3-en-2-ol (2z). Yield: 0.298 g (75%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.61 (s, 1H), 7.56−7.49 (m, 4H), 7.30−7.19 (m, 6H), 2.13 (s, 1H), 1.45 (s, 6H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 139.1, 136.8, 133.3, 130.7, 130.4, 130.0, 129.3, 129.3, 127.8, 126.6, 75.9, 29.4. MS (EI, 70 eV) *m/z* (relative intensity): 380 (46), 314 (14), 222 (41), 157 (31), 142 (100), 128 (23), 77 (13). HRMS: calcd for $C_{17}H_{18}OSe_2$ 397.9688, found 397.9695.

General Procedure for the Preparation of the Tris-chalcogenide Alkenes. *n*-Butyllithium (0.7 mL of a 1.567 M solution in hexane, 1.1 mmol) was added, under argon, to a solution of alkyne (1 mmol) in THF (2 mL) previously cooled at 0 °C. The resulting solution was stirred for 30 min at room temperature. After this time, the mixture was cooled at 0 °C and the disulfide or diselenide (3 mmol) in THF (1 mL) was added. The mixture was then heated at reflux for 12 h, cooled at room temperature, diluted with ethyl acetate (20 mL), and washed with brine (2 × 20 mL). The organic phase was separated, dried over $MgSO_4$, and concentrated under vacuum. The residue was purified by flash chromatography and eluted with hexane/ethyl acetate (90:20) or hexane. **1-(1,2,2-Tris-(methylthio)vinyl)benzene (3a).** Yield: 0.206 g (85%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.40−7.18 (m, 5H), 2.44 (s, 3H), 2.14 (s, 3H), 1.83 (s, 3H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 145.2, 138.2, 129.2, 128.1, 127.7, 127.3, 18.3, 17.0, 16.7. MS (EI, 70 eV) *m/z* (relative intensity): 242 (100), 194 (7), 179 (17), 160 (11), 147 (7). HRMS: calcd for $C_{11}H_{14}S_3$ 242.0258, found 242.0263.

1-(1-Phenyl-2,2-bis(phenylselanyl)vinylselanyl)-benzene (3b). Yield: 0.435 g (76%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.44−6.97 (m, 20H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 148.9, 140.5, 135.8, 133.4, 132.7, 132.3, 131.8, 130.6, 129.0, 128.8, 128.5, 128.4, 127.8, 127.4, 127.35, 127.3, 127.2, 117.3. MS (EI, 70 eV) *m/z* (relative intensity): 334 (26), 312 (13), 258 (89), 179 (100), 153 (15). HRMS: calcd for $C_{26}H_{20}Se_3$ 571.9061, found 571.9068.

3-Ethoxy-1,1,2-tris(methylthio)prop-1-ene (3e). Yield: 0.199 g (89%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 4.59 (s, 2H), 3.51 (q, J = 7.02 Hz, 2H), 2.44 (s, 3H), 2.37 (s, 3H), 2.27 (s, 3H), 1.23 (t, J = 7.02 Hz, 3H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 141.5, 130.2, 68.7, 64.8, 18.3, 16.7, 15.2, 15.1. MS (EI, 70 eV) *m/z* (relative intensity): 224 (100), 179 (48), 161 (9), 128 (9). HRMS: calcd for $C_8H_{16}OS_3$ 224.0363, found 224.0369.

1-(3-Ethoxy-1,1-bis(phenylselanyl)prop-1-en-2-ylselanyl)benzene (3f). Yield: 0.482 g (87%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.33−7.15 (m, 15H), 4.26 (s, 2H), 3.21 (q, J = 7.02 Hz, 2H), 1.07 (t, J = 7.02 Hz, 3H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 144.1, 135.4, 133.9, 132.4, 132.3, 131.4, 130.0, 128.9, 128.7, 128.6, 128.3, 127.6, 127.1, 124.0, 72.6, 65.2, 15.0. MS (EI, 70 eV) *m/z* (relative intensity): 312 (29), 270 (58), 234 (34), 195 (81), 155 (35), 114 (100). HRMS: calcd for $C_{23}H_{22}OSe_3$ 553.9166, found 553.9171.

1-(1,1-Bis(4-chlorophenylselanyl)-3-ethoxyprop-1-en-2-ylselanyl)-4-chlorobenzene (3g). Yield: 0.439 g (67%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.61−7.12 (m, 12H), 4.23 (s, 2H), 3.24 (q, J = 7.02 Hz, 2H), 1.11 (t, J = 7.02 Hz, 3H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 144.1, 136.7, 135.2, 135.0, 134.4, 134.3, 133.8, 133.7, 130.0, 129.2, 129.0, 128.9, 127.9, 123.8, 72.6, 65.5, 15.1. MS (EI, 70 eV) *m/z* (relative intensity): 656 (4), 460 (22), 381 (19), 273 (33), 228 (100), 188 (81), 154 (65). HRMS: calcd for $C_{23}H_{19}Cl_3OSe_3$ 655.7997, found 655.8004.

1-(3-Ethoxy-1,2-bis(4-methoxyphenylselanyl)prop-1-enylselanyl)-4-methoxybenzene (3h). Yield: 0.322 g (50%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.63−6.72 (m, 12H), 4.21 (s, 2H), 3.81 (s, 3H), 3.79 (s, 3H), 3.78 (s, 3H), 3.21 (q, J = 7.02 Hz, 2H), 1.10 (t, J = 7.02 Hz, 3H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 160.1, 159.6, 159.3, 143.3, 137.8, 135.9, 134.7, 123.9, 122.6, 122.0, 120.3, 114.5, 114.4, 114.3, 72.0, 65.1, 55.2, 55.2, 55.2, 15.1. MS (EI, 70 eV) *m/z* (relative intensity): 642 (3), 371 (53), 293 (58), 267 (27), 187 (100), 145 (65). HRMS: calcd for $C_{26}H_{28}O_4Se_3$ 643.9483, found 643.9490.

3-Ethoxy-1,1,2-tris(methylthio)pent-1-ene (3i). Yield: 0.184 g (73%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 4.99 (t, J = 7.16 Hz, 1H), 3.54−3.28 (m, 2H), 2.41 (s, 3H), 2.40 (s, 3H), 2.28 (s, 3H), 1.86−1.59 (m, 2H), 1.19 (t, J = 7.02 Hz, 3H), 0.89 (t, J = 7.16 Hz, 3H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 143.6, 138.6, 82.7, 64.0, 27.5, 18.4, 17.8, 17.1, 15.2, 10.2. MS (EI, 70 eV) *m/z* (relative intensity): 251 (100), 222 (24), 206 (83), 195 (9). HRMS: calcd for $C_{10}H_{20}OS_3$ 252.0676, found 252.0682.

1-(3-Ethoxy-1,1-bis(phenylselanyl)pent-1-en-2-ylselanyl)benzene (3j). Yield: 0.413 g (71%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.31−7.10 (m, 15H), 4.67 (m, 1H), 3.51−3.26 (m, 2H), 1.88−1.44 (m, 2H), 1.10 (t, J = 6.87 Hz, 3H), 0.88 (t, J = 7.31 Hz, 3H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 144.6, 135.5, 132.7, 132.3, 131.9, 131.7, 131.6, 129.2, 129.0, 128.7, 128.3, 127.9, 127.1, 127.0, 85.1, 64.5, 27.8, 15.2, 10.3. MS (EI, 70 eV) *m/z* (relative intensity): 578 (18), 426 (44), 334 (76), 312 (100), 256 (60), 176 (64), 154 (33). HRMS: calcd for $C_{25}H_{26}OSe_3$ 581.9479, found 581.9485.

***N,N*-Diethyl-2,3,3-tris(methylthio)prop-2-en-1-amine (3k).** Yield: 0.161 g (64%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 3.68 (s, 2H), 2.54 (q, J = 7.16 Hz, 4H), 2.50 (s, 3H), 2.35 (s, 3H), 2.25 (s, 3H), 1.03 (t, J = 7.16 Hz, 6H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 144.8, 127.4, 54.8, 45.7, 18.2, 16.8, 15.5, 11.4. MS (EI, 70 eV) *m/z* (relative intensity): 251 (100), 204 (27), 179 (18), 156 (7), 86 (39). HRMS: calcd for $C_{10}H_{21}NS_3$ 251.0836, found 251.0841.

***N,N*-Diethyl-2,3,3-tris(phenylselanyl)prop-2-en-1-amine (3l).** Yield: 0.331 g (57%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.31−7.15 (m, 15H), 3.45 (s, 2H), 2.44 (q, J = 7.02 Hz, 4H), 0.88 (t, J = 7.02 Hz, 6H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ(ppm): 135.0, 133.5, 133.3, 132.9, 132.3, 131.2, 128.9, 128.6, 128.6, 128.4, 127.8, 127.3, 127.2, 127.1, 59.5, 45.2, 11.1. MS (EI, 70 eV) *m/z* (relative intensity): 263 (17), 177 (190), 148 (100), 115 (33), 85 (43). HRMS: calcd for $C_{25}H_{27}NSe_3$ 580.9639, found 580.9645.

4-(2,3,3-Tris(methylthio)allyl)morpholine (3m). Yield: 0.204 g (77%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 3.69 (t, J = 4.53 Hz, 4H), 3.63 (s, 2H), 2.50 (s, 3H), 2.48 (t, J = 4.53 Hz, 4H), 2.35 (s, 3H), 2.24 (s, 3H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 142.2, 128.0, 67.1, 58.9, 52.8, 17.9, 16.7, 15.2. MS (EI, 70 eV) *m/z* (relative intensity): 265 (100), 252 (34), 218 (85), 170 (58) 100 (67). HRMS: calcd for $C_{10}H_{19}NOS_3$ 265.0629, found 265.0634.

3-(2,3,3-Tris(methylthio)allyloxy)-1,1,2-tris(methylthio)prop-1-ene (3o). Yield: 0.198 g (53%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 4.61 (s, 2H), 2.46 (s, 3H), 2.38 (s, 3H), 2.29 (s, 3H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 140.7, 131.8, 68.4, 18.4, 16.8, 15.4. MS (EI, 70 eV) *m/z* (relative intensity): 373 (8), 327 (9), 195 (22), 177 (62), 160 (100). HRMS: calcd for $C_{12}H_{22}OS_6$ 373.9995, found 374.0002.

1-(3-(2,3,3-Tris(phenylselanyl)allyloxy)-1,1-bis(phenylselanyl)prop-1-en-2-ylselanyl)benzene (3p). Yield: 0.465 g (45%). ^{1}H NMR, $CDCl_3$, 400 MHz, δ (ppm): 7.30−7.11 (m, 15H), 4.18 (s, 2H). ^{13}C NMR, $CDCl_3$, 100 MHz, δ (ppm): 142.4, 134.8, 134.2, 132.5, 132.4, 131.6, 130.4, 129.1, 128.7, 128.6, 128.1, 127.6, 127.1, 127.1, 72.6. HRMS: calcd for $C_{42}H_{34}OSe_6$ 1033.7601, found 1033.7609.

Acknowledgment. We thank the following agencies for support: FAPERGS, CNPq, CAPES, and UFSM. CNPq is also acknowledged for an MS fellowship (A.V.M.). G.Z. is the recipient of a CNPq fellowship.

Supporting Information Available: Experimental procedures, additional experimental details for the preparation of compounds **2a**−**z** and **3a**−**p**, and ^{1}H and ^{13}C NMR spectra for all reaction products. This material is available free of charge via the Internet at http://pubs.acs.org.

JO050448O