Table I. ^{1}H NMR Data for the Various Diethyl Allylbenzo[*b*]thiophenemalonates

	5	10	17	24
Ar*H*	7.76–7.83 (m, 3H), 7.28–7.32 (m, 2H)	7.72–7.79 (m, 2H), 7.23–7.36 (m, 2H)	7.69–7.79 (m, 2H), 7.41 (s, 1H), 7.23–7.31 (m, 2H)	7.65–7.82 (m, 2H), 7.26–7.35 (m, 2H)
C*H*=CH$_2$	5.78 (ddt, 1H, *J* = 17, 10, 7.1 Hz)	5.99 (ddt, 1H, *J* = 16.9, 10.1, 6.2 Hz)	5.73 (ddt, 1H, *J* = 17, 10, 7.1 Hz)	5.91 (ddt, 1H, *J* = 16.7, 10, 5.8 Hz)
CH=C*H*$_2$	5.03 (dd, 1H, *J* = 17 Hz), 5.01 (dd, 1H, *J* = 10 Hz)	5.11–5.19 (m, 2H)	5.11 (dd, 1H, *J* = 17 Hz), 5.05 (dd, 1H, *J* = 10 Hz)	5.03 (dd, 1H, *J* = 10, 1.6 Hz), 5.01 (dd, 1H, *J* = 16.7, 1.6 Hz)
ArC*H*C		5.03 (s, 1H)		5.13 (s, 1H)
CC*H*$_2$R	3.19–3.22 (d, 2H, *J* = 7.1 Hz)	3.68 (dt, 2H, *J* = 6.23, 1.5 Hz)	3.17 (d, 2H, *J* = 7.1 Hz)	3.62 (ddd, 2H, *J* = 5.8, 1.6 Hz)
CO$_2$C*H*$_2$	4.12–4.33 (m, 4H)	4.11–4.29 (m, 4H)	4.16–4.29 (m, 4H)	4.17–4.29 (m, 4H)
C*H*$_3$	1.16 (t, 6H)	1.22 (t, 6H)	1.16 (t, 6H)	1.26 (t, 6H)

Table II. ^{1}H NMR Data of Thermally Rearranged Products of Diethyl α-Allyl-3-benzo[*b*]thiophenemalonate (5)

	trans-9a	*cis*-9b	diacid 11
Ar*H*	7.71–7.75 (d, 1H), 7.58–7.62 (d, 1H), 7.18–7.33 (m, 2H)	7.69–7.76 (m, 2H), 7.21–7.35 (m, 2H)	7.89–7.92 (d, 1H), 7.67–7.70 (d, 1H), 7.26–7.38 (m, 2H)
C1-H	4.23 (dd, 1H, *J* = 7.8, 1.8 Hz)	3.87 (dt, 1H, *J* = 4.2, 1.8 Hz)	3.80 (d, 1H, *J* = 5.1 Hz)
C2-H	3.35–3.61 (m, 1H)	3.64–3.77 (m, 1H)	3.42–3.55 (m, 1H)
C3-H	3.16 (dd, 1H, *J* = 16.3, 7.8 Hz)	3.47 (ddd,[a] 1H, *J* = 16.3, 8.2, 1.8 Hz)	3.33 (ddd,[a] 1H, *J* = 14, 8, 1.8 Hz)
C3-H	2.99 (ddd,[a] 1H, *J* = 16.3, 9.3, 1.8 Hz)	2.73 (dd, 1H, *J* = 16.3, 4.5 Hz)	2.72 (dd, 1H, *J* = 16, 5.1 Hz)
C*H*$_2$X	2.88 (dd, 1H, *J* = 16.3, 7.8 Hz)	2.69 (dd, 1H, *J* = 15.9, 7 Hz)	2.57–2.63 (m, 2H)
C*H*$_2$X	2.72 (dd, 1H, *J* = 16.3, 7.8 Hz)	2.60 (dd, 1H, *J* = 15.9, 7 Hz)	–
C*H*$_2$CH$_3$	4.03–4.21 (m, 4H)	4.20 (q, 2H), 4.15 (q, 2H)	–
CH$_3$	1.27 (t, 3H), 1.20 (t, 3H)	1.26 (t, 3H), 1.25 (t, 3H)	–
CO$_2$H	–	–	12.47 (s, 2H)

[a] Long-range coupling J_{1-3}H.

Table III. ^{1}H NMR Data of Thermally Rearranged Products of Diethyl α-Allyl-2-benzo[*b*]thiophenemalonate (17)

	major 25b	minor 25a	diacid 29
Ar*H*	7.75–7.78 (m, 1H), 7.54–7.58 (m, 1H), 7.24–7.36 (m, 2H)	7.73–7.79 (m, 1H), 7.52–7.63 (m, 1H), 7.21–7.39 (m, 2H)	7.89–7.92 (m, 1H), 7.63–7.67 (m, 1H), 7.27–7.48 (m, 2H)
C1-H	3.33 (ddd,[a] 1H, *J* = 15.3, 8.4, 1.8 Hz)	3.15 (dd, 1H, *J* = 14.7, 7.8 Hz)	3.22 (ddd, 1H, *J* = 15.2, 8.5, 1.8 Hz)
C1-H	2.64 (ddd,[a] 1H, *J* = 15.3, 6.2, 1.8 Hz)	2.81 (ddd,[a] 1H, *J* = 14.7, 8, 1.6 Hz)	2.60 (dd, 1H, *J* = 15.2, 1.8 Hz)
C2-H	3.64 (m, 1H)	3.61 (m, 1H)	3.44 (m, 1H)
C3-H	3.94 (dt, 1H, *J* = 6.4, 1.8 Hz)	*b*	4.00 (d, 1H, *J* = 6.8 Hz)
C*H*$_2$X	2.80 (dd, 1H, *J* = 15.6, 6.4 Hz)	2.83 (dd, 1H, *J* = 16.3, 7.3 Hz)	2.72 (dd, 1H, *J* = 16, 5.7 Hz)
C*H*$_2$X	2.65 (dd, 1H, *J* = 15.6, 8.1 Hz)	2.68 (dd, 1H, *J* = 16.3, 8.2 Hz)	2.59 (dd, 1H, *J* = 16, 8.7 Hz)
C*H*$_2$CH$_3$	4.09–4.30 (m, 4H)	4.10–4.29[b] (m, 5H), 4.15 (q, 2H)	–
CH$_3$	1.32 (t, 3H), 1.27 (t, 3H)	1.29 (t, 3H), 1.26 (t, 3H)	–
CO$_2$H	–	–	12.57 (bs, 2H)

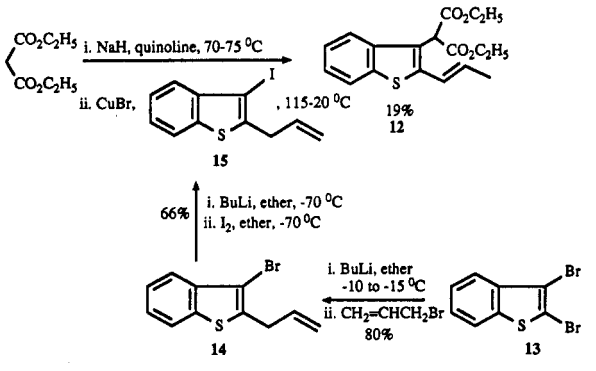
[a] Long-range coupling J_{1-3}H. [b] Hidden under.

Table IV. HETCOR Experimental Data for the Assignment of Carbon Peaks of Cyclopentane Ring

	trans-9a	*cis*-9b	diacid 11	major 25b	diacid 29
C1	48.79	52.43	51.74[a]	53.47	52.71
C2	43.71	43.79	43.62	42.91	42.52
C3	35.89[a]	35.50	34.95	33.18	32.65
*C*H$_2$X	35.25[a]	40.09	51.60[a]	38.81	38.99

[a] Assignments could be reversed.

Scheme IV

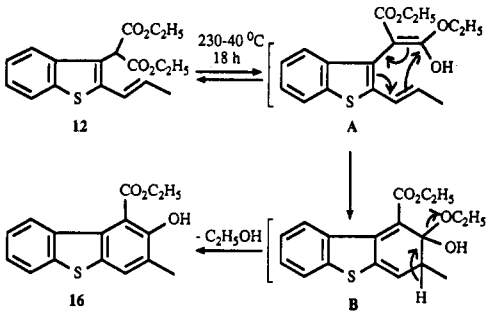


80% yield (Scheme IV). A second halogen–metal interchange at −70 °C was followed by treatment with an ethereal solution of iodine also at −70 °C to give 2-allyl-3-iodobenzo[*b*]thiophene (15) in 66% yield. This was used immediately without characterization, following the procedure described for the synthesis of 7 from 8 (Scheme II).

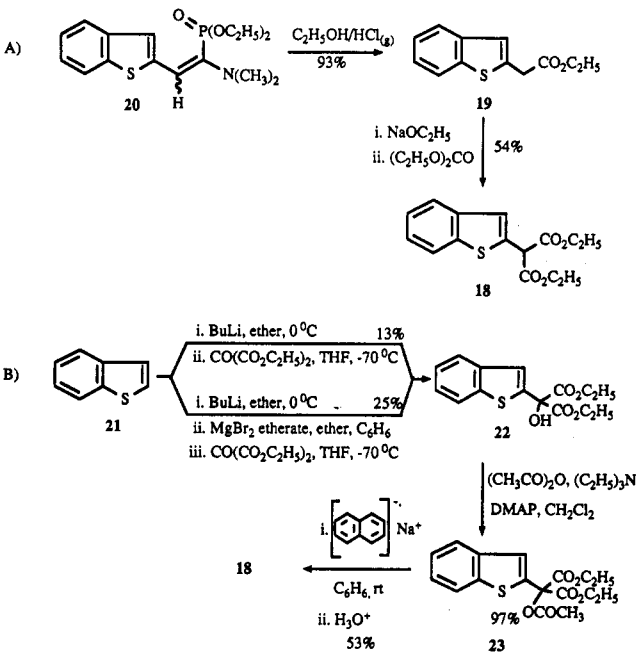
On the basis of spectroscopic data (^{1}H and ^{13}C NMR spectra and MS) the pure product obtained by chromatography was characterized as diethyl 2-(1-propenyl)-3-benzo[*b*]thiophenemalonate (12) wherein the terminal allylic double bond (δ 3.63 for C*H*$_2$CH=CH$_2$) had rearranged to a more substituted conjugated vinylic double bond (δ 1.90 for CH=CHC*H*$_3$). A yield of 19% based on 15 was obtained. No 10 was isolated. It is believed that in this reaction the presence of the copper(I) bromide together with the moderately elevated temperature may have caused the rearrangement to the propenyl derivative. This is surprising since the alkylation proceeded normally in the case of the thiophene analogue of 15.[4]

Thermal Rearrangement of Diethyl 2-(1-Propenyl)-3-benzo[*b*]thiophenemalonate (12). A sample of 12 was heated at 230–40 °C for 18 h (Scheme V). Isolation of a product by chromatography gave a light yellow solid (38%) as a major product. An ^{1}H NMR spectrum of the yellow solid material contained an A_3B_2 type splitting pattern typical of CH_3CH_2X in the ratio of 3:2 and a singlet at δ 2.36 corresponding to 3H. Also no vinyl hydrogens were present and there were singlets in the aromatic region at δ 7.68 and at 10.19 equivalent to 1H. An IR spectrum showed peaks at 3300(s) typical of an OH group. A ^{13}C NMR spectrum indicated twelve aromatic carbons besides three carbons in the upfield region and an ester carbonyl at δ 170.39. The mass spectrum indicated the molecular ion peak 286. On the basis of the spectroscopic data and

Scheme V



Scheme VI

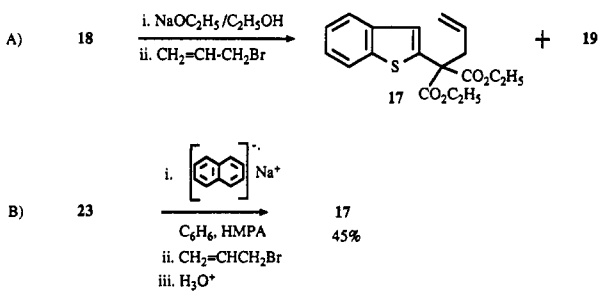


by analogy,[11] this compound was assigned the structure of 1-carbethoxy-2-hydroxy-3-methyldibenzothiophene (16). The formation of 16 by the thermal cyclization of 12 may have proceeded through an enol-type intermediate A. In a possible mechanism for this thermal cyclization, the first step in the process involves the formation of an enol-type structure which underwent cyclization to form a six-membered ring. Once formed, this ring undergoes aromatization by elimination of an ethanol molecule to form the hydroxy ester 16. In agreement with the mechanism as proposed in Scheme V, it was observed that the ^{1}H NMR spectrum of the crude cold thermal reaction product contained a peak suggesting the presence of ethanol.

Synthesis of Diethyl α-Allyl-2-benzo[b]thiophenemalonate (17). A straightforward approach involved allylation of diethyl 2-benzo[b]thiophenemalonate (18) which was first synthesized by two different methods as outlined in Scheme VI. In the first method 18 was obtained (54% yield) by reaction of ethyl 2-benzo[b]thiopheneacetate (19) with excess of diethyl carbonate in presence of dry sodium ethoxide (path A). The starting material 19 was obtained directly by treating diethyl [2-(2-benzo[b]-thienyl)-1-(dimethylamino)vinyl]phosphonate (20)[12] with saturated ethanolic HCl solution (93%).

The second route as outlined in Scheme VI (path B) served as a model reaction.[14] 2-Benzo[b]thienyllithium

Scheme VII



was treated with diethyl oxomalonate (DEOM)[13] below −70 °C to give 22 in 13% yield. It was hoped that the yield would be increased if the 2-benzo[b]thienyllithium was replaced with the less-reactive organomagnesium compound. 2-Benzo[b]thienylmagnesium bromide was obtained by treating 2-benzo[b]thienyllithium with the freshly prepared magnesium bromide etherate. Treatment of 2-benzo[b]thienylmagnesium bromide with DEOM at −70 °C on workup gave diethyl α-hydroxy-2-benzo[b]-thiophenemalonate (22) in 25% yield. Completion of the synthesis depends on removal of the vestigial α-hydroxy group of the intermediate 22. Acetylation of the hindered tertiary alcohol 22 was achieved (97%) with acetic anhydride and triethylamine in presence of the acylation catalyst 4-(dimethylamino)pyridine (DMAP) in methylene chloride. Reductive α-deacetoxylation[14] of diethyl α-acetoxy-2-benzo[b]thiophenemalonate (23) was carried out with naphthalenide radical anion, in effect as a titration. Acid workup, followed by chromatography to remove naphthalene, gave nearly pure 18 (53%) with an overall yield of 13% starting with benzo[b]thiophene (21) in three steps.

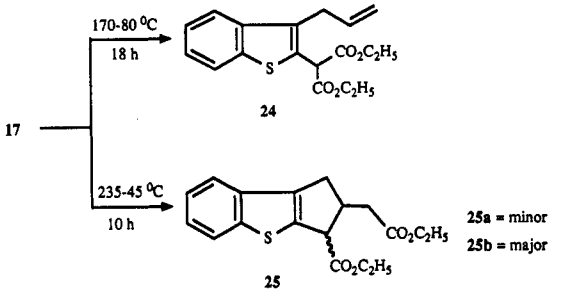
Direct allylation of 18 as for the synthesis of 17 (Scheme VII, path A) gave mostly an inseparable mixture. The lower boiling component was characterized as 19 by comparison (TLC, ^{1}H NMR) with an authentic sample synthesized for the preparation of 18. The higher boiling component (27%) was characterized as diethyl α-allyl-2-benzo[b]thiophenemalonate (17) on the basis of IR, ^{1}H and ^{13}C NMR spectra, and MS. With the difficulty encountered in the above method a second route (path B) for the preparation of 17 was undertaken as outlined in Scheme VII. The ester enolate of 18 was prepared by adding a solution of sodium naphthalenide in HMPA to a stirred solution of 23, as before. Treatment with allyl bromide followed by the usual workup gave 17 in 45% yield starting with 23.

Thermal Rearrangement of Diethyl α-Allyl-2-benzo[b]thiophenemalonate (17). Diethyl α-allyl-2-benzo-[b]thiophenemalonate (17) was heated at 170–80 °C for 18 h. By column chromatography of the crude material, 26% of the starting material was recovered; however, the ^{1}H NMR spectrum of a more polar compound 24 was significantly different from the spectrum of 17 and very similar to that of 10 except that the signal for the α-hydrogen of the malonate 24 was shifted downfield by 0.10 ppm. The doublet of the allyl hydrogen which resonates at δ 3.17 in 17 had shifted to δ 3.62 in 24. The singlet in the aromatic region at δ 7.41 with an integration value of one hydrogen for 17 disappeared at the same time

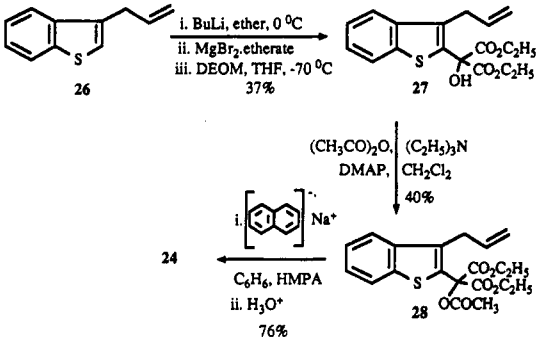
(11) Ashby, J.; Ayad, M.; Meth-Cohn, O. *J. Chem. Soc., Perkin Trans. 1* **1974**, 1744.

(12) Degenhardt, C. R. *Synth. Commun.* **1982**, *12*, 415.
(13) Pardo, S. N.; Salomon, R. G. *J. Org. Chem.* **1981**, *46*, 2598.
(14) Ghosh, S.; Pardo, S. N.; Salomon, R. G. *J. Org. Chem.* **1982**, *47*, 4692.

Scheme VIII



Scheme IX

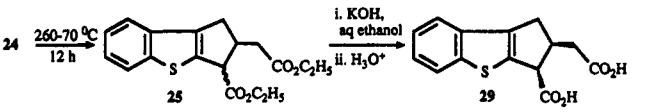


a singlet at δ 5.13 in the more polar product **24** was also found indicating that an α-hydrogen on the malonate group was present (Table I). A ^{13}C NMR spectrum showed significant change also where peaks at δ 60.52 and δ 42.16 in **17** were shifted upfield to δ 52.01 and δ 30.73, respectively, for **24**. This compound is believed to be the normal Cope-rearranged product diethyl 3-allyl-2-benzo[*b*]thiophenemalonate (**24**) (Scheme VIII). The isolated yield of **24** was 45%.

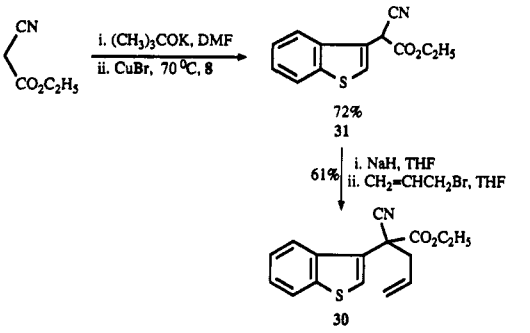
Diethyl α-allyl-2-benzo[*b*]thiophenemalonate (**17**) was then heated at 235–45 °C for 10 h. The ^1H NMR spectrum of the crude product showed it was a mixture of normal Cope-rearranged product **24** and the cyclized compound ethyl 1,2-dihydro-3-(ethoxycarbonyl)-3*H*-benzo[*b*]cyclopenta[*d*]thiophene-2-acetate (**25**) (Scheme VIII). The ratio of diastereomers of cyclized products **25a**/**25b** was 41:59 based on the integration of the protons of the cyclopentane ring. The isolation of the crude material by column chromatography gave 14% of nearly pure **24**. Further careful elution first gave a small amount of minor isomer **25a** (12%) followed by a mixture of diastereomers **25a** and **25b** in 50:50 ratio (based on integration of the ^1H NMR spectrum) (5%) and followed by a major isomer **25b** (24%). The stereochemistry of these two isomers was not established but each isomer had a different ^1H NMR spectrum wherein the doublet at δ 3.94 present in the major isomer **25b** was shifted downfield in the minor isomer **25a** and hidden under the methylene protons of the ester groups as shown in Table III.

Synthesis of Diethyl 3-Allyl-2-benzo[*b*]thiophenemalonate (24). The synthetic route shown in Scheme IX followed the method used for the synthesis of **18**. The Grignard reagent from 3-allylbenzo[*b*]thiophene (**26**)[21] was transferred to a solution of diethyl oxomalonate cooled below −70 °C. Nearly pure diethyl α-hydroxy-3-allyl-2-benzo[*b*]thiophenemalonate (**27**) was obtained (37%) on usual workup followed by acetylation which gave diethyl α-acetoxy-3-allyl-2-benzo[*b*]thiophenemalonate (**28**) in 40% yield. The crucial α-deacetoxylation reaction with sodium naphthalenide in HMPA gave **24** as a major product (76%) with an overall yield of 11%.

Scheme X



Scheme XI



Thermal Rearrangement of Diethyl 3-Allyl-2-benzo[*b*]thiophenemalonate (24). Diethyl 3-allyl-2-benzo[*b*]thiophenemalonate (**24**) was (Scheme X) heated at 260–70 °C for 12 h. A ^1H NMR spectrum of the crude material showed no vinyl protons but did show the presence of cyclized product. The separation of the crude material by column chromatography only gave a mixture of diastereomers of **25** (15%) which could not be further separated.

This mixture of diastereomers **25** was saponified with KOH in aqueous ethanol, which epimerized the secondary ester group at the C-3 position to yield the diacid **29** (69%) which was assigned the *trans* stereochemistry (Table III) by analogy with the results as obtained above and by the ^1H NMR spectrum (J = 6.8 Hz).

Synthesis of Ethyl α-Allyl-α-cyano-3-benzo[*b*]thiopheneacetate (30). When diethyl malonate was substituted by ethyl cyanoacetate, in the method as described by Houbiers and Muris,[6] it gave nearly pure ethyl α-cyano-3-benzo[*b*]thiopheneacetate (**31**) in 40% yield [72% yield based on recovered 3-iodobenzo[*b*]thiophene (**8**)] (Table V). Allylation of **31** was carried out in an aprotic solvent using NaH[15] to afford ethyl α-allyl-α-cyano-3-benzo[*b*]thiopheneacetate (**30**) in 61% yield (Scheme XI).

Thermal Rearrangement of Ethyl α-Allyl-α-cyano-3-benzo[*b*]thiopheneacetate (30). The thermal rearrangement of **30** was undertaken for two reasons: first, to study the effect of replacement of one of the ethoxycarbonyl groups of **5** by a cyano group to give **30**; second, to throw some light on the proposed mechanism of cyclization of the normal Cope product where both the ester groups are participating in the proposed mechanism[4] and to ascertain whether or not the rearrangement of **30** will give a product analogous to the cyclopentabenzo[*b*]thiophene derivative **9**.

When **30** was heated at 205–215 °C for 7 h (Scheme XII), the ^1H NMR spectrum of the crude product showed it to be a mixture of **32** and **30** in ratio of 80:20 based on the allylic protons of these compounds. The purification of the crude product by distillation gave 73% of **32** as a yellow viscous oil.

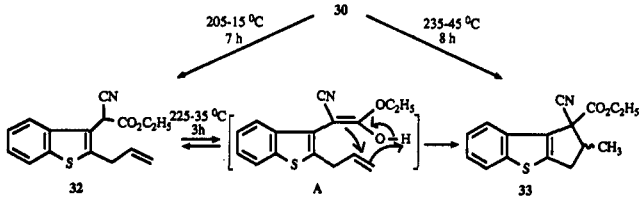
The ^1H NMR spectrum of the yellow viscous oil showed no peak at δ 7.58 but there was a singlet at δ 5.15 for the

(15) MacDowell, D. W. H.; Patrik, T. B.; Frame, B. K.; Ellison, D. L. *J. Org. Chem.* **1967**, *32*, 1226.

Table V. ^{1}H NMR Data for the Various Ethyl α-Cyano-benzo[b]thiopheneacetate Derivatives

	31	30	32
Ar-*H*	7.80–7.86 (m, 2H), 7.60 (s, 1H), 7.32–7.43 (m, 2H)	8.01–8.05 (m, 1H), 7.83–7.87 (m, 1H), 7.58 (s, 1H), 7.33–7.46 (m, 2H)	7.78–7.89 (m, 2H), 7.23–7.76 (m, 2H)
C*H*=CH$_2$		5.88 (ddt, 1H, J = 17, 10, 7 Hz)	5.98 (ddt, 1H, J = 17.2, 9.7, 6.2 Hz)
CH=C*H*$_2$		5.29 (dd, 1H, J = 17, 1.4 Hz), 5.27 (dd, 1H, J = 10, 1.4 Hz)	5.16–5.24 (m, 2H)
ArC*H*C	5.10 (s, 1H)		5.15 (s, 1H)
CC*H*$_2$R		3.12–3.30 (m, 2H)	3.70–3.73 (dt, 2H, J = 6.2, 1.5 Hz)
CO$_2$C*H*$_2$	4.13–4.24 (m, 2H)	4.23 (q, 2H)	4.11–4.31 (m, 2H)
C*H*$_3$	1.20 (t, 3H)	1.20 (t, 3H)	1.20 (t, 3H)

Scheme XII



methine hydrogen of the cyanoacetate group. The quartet at δ 4.23 for the methylene protons of the ethyl group had changed in a multiplet and the allylic protons were shifted downfield from δ 3.12–3.30 to δ 3.70–3.73 (Table V). A ^{13}C NMR spectrum of the yellow viscous oil also revealed that peaks at δ 117.54, 50.36, and 39.93 for the cyano carbon, tertiary carbon, and allylic carbon, respectively, of **30** had shifted upfield to δ 114.72, 35.93, and 32.65 in **32**. In **32** these peaks were assigned to the cyano carbon, methine carbon, and allylic carbon by comparison with corresponding peaks for ethyl α-cyano-3-benzo[b]thiopheneacetate (**31**). With this spectroscopic evidence the product was assigned the structure **32**.

Following the isolation of the regular Cope-rearrangement product **32**, thermal studies were conducted to ascertain if a cyclized product similar to **9** could also be obtained. Initially, **30** was heated under nitrogen at 235–45 °C for 8 h (Scheme XII). Elution of the crude product by column chromatography gave 6% of **32** and an unexpected unseparable mixture (16%) of what appeared to be diastereomers of **33**; however, considerable decomposition had occurred. The ^{1}H NMR spectrum of the major product revealed that no allyl, vinyl, or methine hydrogen of cyanoacetate were present. Also a singlet in the aromatic region was absent and the methyl group of the ethyl ester moiety showed two nonequivalent triplets in the upfield region. Two more doublets in the ratio of 64:36 were found at δ 1.51 and 1.43, respectively. Irradiation of a proton at δ 3.56–3.79 transformed the two doublets into singlets at δ 1.5 and 1.43, respectively. This effect was also observed for signals between δ 2.4–3.5 which also collapsed to doublets from the doublet of doublets. When a proton at δ 3.38 was irradiated in a decoupling experiment, it showed the effect on a multiplet of the proton at δ 3.56–3.79 and on a doublets of doublet at δ 2.83 which then collapsed into a single doublet. It seems that the proton at δ 3.56–3.79 is coupled with the protons of the major isomer at δ 3.38, 2.83, and 1.51 and the minor isomer at δ 3.22, 2.99, and 1.43 in the unseparable mixture of diastereomers. A ^{13}C NMR spectrum also showed the two diastereomeric ester carbonyl carbons peaks at δ 167.43 and 166.11, respectively. A GC/MS spectrum also showed two peaks, both having a molecular ion peak at 285. On the basis of the above data, this thermal rearranged product was assigned the structure 1-cyano-1-(ethoxycarbonyl)-2-methyl-2,3-dihydro-1*H*-benzo[b]cyclopenta[d]thiophene (**33**) where both cyano and ester groups are on the same carbon.

It was also found that heating the isolated **32** at 225–35 °C for 3 h afforded the cyclized product **33** in 5% yield, as a mixture of diastereomers in the ratio of 59:41, along with unchanged starting material. This result suggests that this rearrangement may have occurred *via* a hetero-ene reaction of the normal Cope product in which the first step probably involves the enolization of the ester group as in Scheme V. This then undergoes cyclization to produce **33** (Scheme XII).

In conclusion, the above studies show that allylated benzo[b]thiophenemalonates and an analogous cyanoacetate, unlike allylated naphthalenemalonate or phenanthrenemalonate and like allylthiophene analogues, undergo thermal rearrangement to give normal Cope products. Furthermore, the normal Cope rearrangement products thus obtained undergo cyclization to give cyclopenta derivatives as in the case of naphthalene and phenanthrene analogues.

Experimental Section

All boiling and melting points are uncorrected and the latter were measured in a Mel-Temp apparatus. Infrared (IR) spectra were recorded on a Perkin-Elmer 1310 spectrophotometer. ^{1}H (270 MHz) and ^{13}C (67.9 MHz) NMR spectra were obtained on a JEOL GX-270 spectrometer using tetramethylsilane as an internal standard. 2D ^{1}H NMR spectra were obtained on a Varian Gemini-300 spectrometer. All NMR spectra were recorded in deuteriochloroform unless otherwise noted and are expressed in parts per million downfield from tetramethylsilane: couplings are in hertz. Mass spectra were obtained on a Finnigan 4500 GC/MS instrument at 70 eV and a Hewlett-Packard 5890 GC/MS instrument. Thin-layer chromatography (TLC) was performed with Eastman Kodak silica gel 13181 plates. Developed plates were visualized by UV light or in an I_2 crystal chamber. Column chromatography was carried out on Merck silica gel 60 (70–230 mesh ASTM). Elemental analyses were performed by Galbraith Laboratories, Inc., Knoxville, TN.

Synthesis of Diethyl α-Allyl-3-benzo[b]thiophenemalonate (5). (A) Synthesis of Diethyl 3-Benzo[b]thiophenemalonate (7). This procedure was modeled after the method of Houbiers and Muris.[6] A solution of 38.5 g (0.24 mol) of diethyl malonate in 200 mL of freshly distilled quinoline was stirred at 60–65 °C. To this solution was added portionwise 10.9 g (0.23 mol) of a 50% dispersion of sodium hydride in mineral oil under N_2.

After the liberation of hydrogen gas had ceased, 35.7 g (0.14 mol) of **8**[7] and 21.6 g (0.16 mol) of copper(I) bromide were added to the reaction mixture. The mixture was stirred overnight at 100–105 °C and was then poured into a mixture of ice, concentrated HCl, and water. The precipitated copper salts were removed by filtration and washed with methylene chloride. The methylene chloride layer was removed and the aqueous layer was extracted with methylene chloride. The methylene chloride layers were combined and were washed with water and saturated salt solution and dried (Na_2SO_4). Removal of the methylene chloride left a viscous brown residue which was distilled under reduced pressure to remove excess of unreacted diethyl malonate. Chromatography of the tar-like residue with a chloroform/benzene mixture (2:3) as eluant allowed isolation of 11.2 g of **7**

in a yield of 48% based on the recovered 15 g of recyclable starting material 8. The product was crystallized from ligroin (bp 63–75 °C) to give light yellow crystals; mp 49–50 °C; IR (KBr) 2990, 1740, 1720, 1265, 1040, 780 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.76–7.86 (m, 2H, Ar*H*), 7.65 (s, 1H, Ar*H*), 7.30–7.42 (m, 2H, Ar*H*), 5.06 (s, 1H, CC*H*Ar), 4.17–4.29 (pair of q, 4H, $CO_2CH_2CH_3$), 1.25 (t, 6H, $CO_2CH_2CH_3$); ^{13}C NMR δ 167.44, 139.97, 137.94, 126.70, 126.24, 124.50, 124.28, 122.84, 121.66, 62.00, 51.78, 14.01. Anal. Calcd for $C_{15}H_{16}O_4S$: C, 61.63; H, 5.52; S, 10.97. Found: C, 61.99; H, 5.54; S, 11.21.

(B). Synthesis of Diethyl α-Allyl-3-benzo[*b*]thiophenemalonate (5). To an ethanolic solution of sodium ethoxide prepared from 463 mg (20 mmol) of sodium metal was added dropwise a solution of 5.88 g (20 mmol) of diethyl 3-benzo[*b*]-thiophenemalonate in 30 mL of absolute ethanol. The reaction mixture was heated to reflux for 1.5 h and was then cooled to room temperature. A solution of 2.44 g (20 mmol) of allyl bromide in 25 mL of absolute ethanol was added in one portion to the reaction mixture which was heated to reflux for 3 h and was then cooled to room temperature. Removal of sodium bromide and ethanol followed by washing and drying gave 5.25 g of a yellow viscous liquid residue. The ^{1}H NMR spectrum and TLC, using benzene/hexane (1:1) as a developing system, clearly showed the presence of a mixture of 6 and 5, when compared to authentic samples. This mixture proved to be inseparable by fractional distillation. To the mixture, was added hexane and the solution was kept in a refrigerator overnight when colorless crystals were obtained (3.1 g).

On evaporation of the hexane a liquid was obtained. It was found to be identical (IR, ^{1}H NMR, ^{13}C NMR) with an authentic sample[5] of 6 (2.15 g): IR (neat) 3060–3040, 2900, 1730, 1180, 1155, 760 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.69–7.80 (m, 2H, Ar*H*), 7.25–7.35 (m, 3H, Ar*H*), 4.11 (q, 2H, $CO_2CH_2CH_3$), 3.78 (s, 1H, $ArCH_2C$), 1.18 (t, 3H, $CO_2CH_2CH_3$); ^{13}C NMR δ 170.50, 140.15, 138.58, 128.37, 124.40, 124.31, 124.07, 122.74, 121.70, 60.90, 34.43, 14.11.

The colorless crystals were then identified as 5 (47%); mp 47–48 °C [lit.[5] bp 159–63 °C (0.2 mm)]; IR (KBr) 3120, 2980, 1730, 1240, 1043, 920, 765 cm^{-1}; ^{1}H NMR ($CDCl_3$) (Table I); ^{13}C NMR δ 169.56, 140.24, 137.33, 132.96, 131.10, 125.28, 124.03, 123.76, 123.24, 122.81, 118.63, 61.69, 60.15, 39.97, 13.94; MS *m/e* (rel inten) 332 (M^+, 31), 291 (56), 240 (100), 217 (43), 185 (70). Anal. Calcd for $C_{18}H_{20}O_4S$: C, 65.04; H, 6.06. Found: C, 64.96; H, 6.02.

Thermal Rearrangement of Diethyl α-Allyl-3-benzo[*b*]-thiophenemalonate (5). General Method: The following general procedure was used to prepare the samples which were subjected to thermal rearrangement. Samples were placed in thick-walled tubes, degassed, and then sealed under a nitrogen atmosphere at reduced pressure (calcd <1 mm). Once the tube was sealed, it was placed in a tube furnace and heated at the desired temperature. Sometimes sample tubes were also heated to the desired temperature in a silicon oil bath or mineral oil bath. After the heating period was completed, the tube was allowed to cool to room temperature and then was opened carefully.

Method A: A glass tube (20 × 2 cm) containing 260 mg of 5 was heated at 175–180 °C for 36 h. The TLC of the crude product in hexane/toluene (3:2) system on a silica gel plate showed two spots, one due to starting material and the other due to the diethyl 2-allyl-3-benzo[*b*]thiophenemalonate (10). The crude product (250 mg) was loaded on a silica gel column and eluted with hexane/toluene (3:7) mixture in 50-mL fractions. Elution, monitored by TLC, gave 175 mg of starting material and 80 mg of 10 (31%). The crude 10 was further purified by short-path distillation to obtain an analytical sample as a light yellow viscous oil: IR (neat) 3030–2990, 1730–20, 1300, 1140, 1035, 930, 760, 730 cm^{-1}; ^{1}H NMR ($CDCl_3$) (Table I); ^{13}C NMR δ 167.63, 142.20, 138.98, 138.25, 134.97, 124.06, 123.89, 123.00, 122.65, 122.06, 117.09, 61.84, 50.62, 33.01, 14.00; MS *m/e* (rel inten) 332 (M^+, 20), 286 (8), 258 (12), 240 (5), 185 (100). Anal. Calcd for $C_{18}H_{20}O_4S$: C, 65.04; H, 6.06, S, 9.65. Found: C, 65.04; H, 6.04, S, 9.78.

Method B: In a similar operation 5 (3.0 g) was heated at 180–185 °C for 42 h. The chromatographic separation of the crude product on a silica gel column using hexane/benzene (1:9) as an eluant gave 1.32 g (44%) 10 and 1.39 g of starting material. The yield of product was 82% based on the starting material consumed.

Method C: A glass tube (20 cm × 2 cm) containing 600 mg of 5 was heated at 215–225 °C for 11 h. The crude compound (598 mg) was chromatographed over silica gel. Elution with hexane/toluene (1:4), monitored both by TLC and the ^{1}H NMR spectrum of the fractions collected, gave 46 mg of 10. Further gradient elution with toluene/chloroform (6.5:1) gave 58 mg of yellow *trans*-9a (10%) and 30 mg of reddish-brown *cis*-9b (5%). In the overall yield of 40% isolated by column chromatography, the yield of normal Cope product was 8% and was found to be identical with the authentic sample obtained previously. IR and elemental analysis of the diastereomeric mixture 9 gave the following results: IR (neat) 3000–2800, 1740–10, 1430, 1370, 1180–50, 1020, 755, 730 cm^{-1}. Anal. Calcd for $C_{18}H_{20}O_4S$: C, 65.04; H, 6.06; S, 9.65. Found: C, 64.94; H, 6.12; S, 9.71.

trans-9a: ^{1}H NMR ($CDCl_3$) (Table II); ^{13}C NMR ($CDCl_3$) δ 172.18, 171.76, 144.73, 144.33, 137.35, 134.35, 124.37, 123.53, 123.32, 121.33, 60.65, 60.51, 14.28, 14.22, and Table IV.

cis-9b: ^{1}H NMR ($CDCl_3$) (Table II); ^{13}C NMR ($CDCl_3$) δ 172.74, 171.98, 144.87, 143.85, 135.90, 134.46, 124.36, 123.56, 123.36, 121.84, 61.16, 60.65, 14.31, 14.27, and Table IV.

Method D: Thermal Rearrangement of Diethyl 2-Allyl-3-benzo[*b*]-thiophenemalonate (10). The isolated 10 (690 mg) was sealed in a glass tube (20 × 2 cm). The tube was heated to 235–245 °C for 8 h. The ^{1}H NMR spectrum of the crude material showed a mixture of starting material and cyclized product which was then loaded on a silica gel column. Then the elution with hexane/benzene (60%), monitored by proton NMR spectrum and TLC, first gave 252 mg starting material. Then the gradient elution with benzene/chloroform (30–50%) gave 180 mg (26%) of *trans*-9a and 46 mg (7%) of *cis*-9b, respectively.

Saponification of Ethyl 2,3-Dihydro-1-(ethoxycarbonyl)-1*H*-benzo[*b*]cyclopenta[*d*]thiophene-2-acetate (9). A mixture of 1 mL of ethanol and 1 mL of 5% aqueous KOH was added to 144 mg of 9. The mixture was stirred at room temperature for 15 min and was then extracted with (3 × 2 mL) ether to remove organic impurities. The aqueous layer was then acidified with concd HCl and the buff-colored precipitate thus obtained was crystallized from ethyl acetate–hexane to give 60 mg (50%) of 3-carboxy-1,2-dihydro-3*H*-benzo[*b*]cyclopenta[*d*]thiophene-2-acetic acid (11) as white crystals: mp 189–91 °C (dec); IR (KBr) 3500–2700, 1680, 1420–1390, 1210, 1185, 900, 740, 720 cm^{-1}; ^{1}H NMR (DMSO-d_6) (Table II); ^{13}C NMR (DMSO-d_6) δ 173.91, 173.21, 143.97, 143.34, 136.47, 134.14, 124.41, 123.53, 121.53, 121.55, and Table IV. Anal. Calcd for $C_{14}H_{12}O_4S$: C, 60.86; H, 4.38; S, 11.60. Found: C, 60.83; H, 4.43; S, 11.49.

Attempted Synthesis of Diethyl 2-Allyl-3-benzo[*b*]thiophenemalonate (10): Synthesis of Diethyl 2-(1-Propenyl)-3-benzo[*b*]thiophenemalonate (12). (A) Synthesis of 2,3-Dibromobenzo[*b*]thiophene (13). This compound was prepared in 93% yield by a modification of the procedure described by Ried and Bender.[9] A solution of 53.6 g (0.40 mol) of 21 in 200 mL of chloroform was magnetically stirred and to this mixture was added 128 g (41.3 mL, 0.80 mol) of bromine in 100 mL of chloroform dropwise at room temperature over 1.5 h. After stirring for 18 h, solid Na_2CO_3 was added to neutralize the hydrobromic acid. The organic layer was washed with water and $Na_2S_2O_3$ and then dried (Na_2SO_4). On evaporation of the solvent 112 g brown solid was obtained which was crystallized from methanol to give a sticky yellow solid. Further purification of this solid by distillation under reduced pressure gave a light yellow colored solid which was then recrystallized from methanol to give 109 g (93%) of the desired product 13, mp 58–59 °C [lit.[9] mp 58 °C].

(B) Synthesis of 2-Allyl-3-bromobenzo[*b*]thiophene (14). To a solution of 3-bromo-2-benzo[*b*]thienyllithium[10] prepared from 13 (120 g, 0.41 mol) by halogen–metal exchange with 1.1 equiv BuLi at 0 °C was added with stirring a solution of allyl bromide (39 mL, 0.45 mol) in ether (40 mL) in one portion. After 10 h stirring at room temperature, the ice-cold water was added to the clear yellow mixture. The organic layer was separated and the aqueous layer was extracted with ether. The organic layer and ether extracts were combined and washed with saturated Na_2CO_3 and saturated salt solution and dried (Na_2SO_4). Removal of the ether left a brownish-yellow liquid which was fractionated to give 83 g (80%) of 14 boiling at 111–13 °C (0.15 mm) as a greenish-yellow liquid. 14 was then redistilled in order to obtain an analytical sample; bp 105–6 °C (0.05 mm); IR (neat) 3060,

3000–2900, 1630, 1430, 1250, 750, 725, 620 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.66–7.72 (m, 2H, ArH), 7.23–7.38 (m, 2H, ArH), 5.94 (ddt, J = 16.8, 10 and 6.4 Hz, 1H, CH=CH_2), 5.18 (dd, J = 16.8 and 1.2 Hz, 1H, CH=CH_2), 5.14 (dd, J = 10 and 1.2 Hz, 1H, CH=CH_2), 3.63 (d, 2H, CH_2-CH=CH_2); ^{13}C NMR δ 138.34, 138.01, 137.36, 134.04, 124.83, 124.80, 122.67, 122.22, 117.41, 106.14, 34.11. Anal. Calcd for $C_{11}H_9BrS$: C, 52.19; H, 3.58; S, 12.67. Found: C, 52.19; H, 3.72; S, 12.74.

(C) Synthesis of 2-Allyl-3-iodobenzo[b]thiophene (15). According to the method of Dickinson and Iddon,[10] a solution of 2-allyl-3-benzo[b]thienyllithium was prepared under N_2 by adding dropwise 91 mL (1.65 M solution in hexane) of butyllithium to a yellow-colored solution of 38.0 g (0.15 mol) of **14** in 250 mL of anhydrous ether at −70 °C. The resulting mixture was stirred at −70 °C for a further 45 min. The yellow solution of 2-allyl-3-benzo[b]thienyllithium was then added to 42.3 g (0.33 mol) of iodine in 500 mL of anhydrous ether also cooled to −70 °C. After the addition of the lithiated compound was complete, the violet color of the ethereal iodine solution disappeared. The reaction mixture was then allowed to warm up to room temperature at which point ice-cold water was added. The organic layer was separated, the aqueous layer was extracted with ether, and the ether and organic layers were combined. The combined organic phase was washed with saturated $Na_2S_2O_3$, water, and saturated salt solution and dried (Na_2SO_4). Removal of the ether left a dark purple liquid which was fractionated to give 29.5 g (66%) of **15** as a yellow liquid, bp 121–7 °C (0.3 mm), which darkened on storing to a reddish-brown liquid. It was used immediately without characterization.

(D) Synthesis of Diethyl 2-(1-Propenyl)-3-benzo[b]thiophenemalonate (12). This procedure was an adaptation of the method Houbiers and Muris.[16] To a stirred solution of 9.22 g (0.058 mol) of diethyl malonate in 60 mL of freshly distilled quinoline under N_2 was added 2.6 g of a 50% suspension of NaH in mineral oil (0.054 mol) portionwise at a temperature of 70–75 °C. After the liberation of hydrogen gas had ceased, 9.96 g (0.033 mol) of **15** and 6.48 g (0.036 mol) of copper(I) bromide were added. The temperature was raised to 115–120 °C and the reaction mixture was stirred for 6 h under N_2. The usual workup, followed by chromatography on a silica gel column and eluted first with hexane/benzene (1:1), gave 3.76 g of the starting material. Further elution with 40% chloroform/benzene afforded a semisolid (2.09 g) which was recrystallized from hexane to give light yellow crystals, mp 90–91 °C: yield 19% based on the starting **15**; IR (KBr) 3000–2800, 1710, 1240, 1190, 1020, 975, 750 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.65–7.76 (m, 2H, ArH), 7.20–7.31 (m, 2H, ArH), 6.72 (dq, J = 15.3 and 1.7 Hz, 1H, C=CHAr), 6.24 (dq, J = 15.3 and 6.6 Hz, 1H, C=CHCH_3), 5.09 (s, 1H, CCHAr), 4.19 (q, 4H, $CO_2CH_2CH_3$), 1.90 (dd, J = 6.6 and 1.7 Hz, 3H, C=CHCH_3), 1.19 (t, 6H, $CO_2CH_2CH_3$); ^{13}C NMR δ 167.67, 141.59, 139.37, 137.52, 131.19, 124.52, 124.19, 122.82, 122.73, 121.97, 61.90, 50.66, 18.81, 14.02; MS m/e (rel inten) 332 (M^+, 35), 259 (7), 185 (100). Anal. Calcd for $C_{18}H_{20}O_4S$: C, 65.04; H, 6.06; S, 9.65. Found: C, 65.26; H, 5.90; S, 10.04.

Thermal Rearrangement of Diethyl 2-(1-Propenyl)-3-benzo[b]thiophenemalonate (12). **12** (600 mg, 1.81 mmol) was heated (N_2) at 230–240 °C for 18 h. The crude product was obtained on cooling. Chromatography on a silica gel column using hexane/benzene (1:1) as a eluant gave 230 mg of **16** as a major product. An analytical sample of **16** was obtained by recrystallization from chloroform to afford a yellow crystals: mp 120–1 °C; IR (KBr) 3300, 3000–2900, 1690, 1440, 1285, 1170, 860, 740 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 10.19 (s, 1H, OH), 8.17–8.21 (m, 1H, ArH), 7.78–7.82 (m, 1H, ArH), 7.68 (s, 1H, ArH), 7.31–7.42 (m, 2H, ArH), 4.56 (q, 2H, $CO_2CH_2CH_3$), 2.36 (s, 3H, CH_3), 1.41 (t, 3H, $COCH_2CH_3$); ^{13}C NMR δ 170.39, 157.39, 140.62, 134.87, 131.40, 131.31, 128.51, 126.68, 126.01, 125.91, 123.17, 122.68, 109.08, 61.88, 16.49, 13.88; MS, m/e (rel inten) 286 (M^+, 36), 257 (2), 240 (100), 212 (35), 184 (100), 171 (3), 152 (22). Anal. Calcd for $C_{16}H_{14}O_3S$: C, 67.11; H, 4.93; S, 11.20. Found: C, 67.18; H, 4.99; S, 10.94.

Synthesis of Diethyl α-Allyl-2-benzo[b]thiophenemalonate (17). (A) Synthesis of Diethyl 2-Benzo[b]thiophenemalonate (18). Method I: (a) Synthesis of Ethyl 2-Benzo[b]thiopheneacetate (19). This procedure was modeled after the general method of Ogura, Ito, and Tsuchihashi.[18] A stirred solution of **20**[12] (29.9 g, 0.088 mol) in absolute ethanol (150 mL) saturated with HCl gas was heated to reflux for 24 h and was then concentrated *in vacuo*. Usual workup gave **19** (18.1 g, 93%) as a pale yellow liquid: bp 125–6 °C (0.2 mm) [lit.[17] bp 150 °C (2 mm)]; IR (neat) 3060, 2900–2980, 1730, 1200, 1030, 750, 730 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.62–7.74 (m, 2H, ArH), 7.19–7.29 (m, 2H, ArH), 7.10 (s, 1H, ArH), 4.15 (q, 2H, $CO_2CH_2CH_3$), 3.80 (s, 2H, $ArCH_2C$), 1.22 (t, 3H, $CO_2CH_2CH_3$); ^{13}C NMR δ 169.83, 140.02, 139.68, 136.32, 124.19, 124.02, 123.42, 123.16, 122.05, 61.22, 36.34, 14.10.

(b) Synthesis of Diethyl 2-Benzo[b]thiophenemalonate (18). According to the method of Blicke and Leonard,[19] to dry sodium ethoxide prepared from sodium (1.99 g, 87 mmol) was added an excess of freshly distilled diethyl carbonate (66.3 g, 66 mL, 56 mmol) in one portion, and the resulting solution was rapidly stirred while 18.2 g (83 mmol) of **19** was added. The temperature of the mixture was maintained at 78–85 °C while the ethanol formed was continuously removed from the reaction mixture under reduced pressure. After 5 h only diethyl carbonate was being removed from the reaction mixture which was allowed to cool to room temperature, worked up as usual to give a solid (21.2 g) which was purified by recrystallization from hexane to give 17 g (54%) of pale yellow needles: mp 70–72 °C; IR (KBr) 3000–2900, 1750, 1730, 1220, 1180, 1115, 1030, 750, 725 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.71–7.81 (m, 2H, ArH), 7.35 (s, 1H, ArH), 7.30–7.33 (m, 2H, ArH), 4.96 (s, 1H, ArCHC), 4.23–4.31 (pair of q, 4H, $CO_2CH_2CH_3$), 1.29 (t, 6H, $CO_2CH_2CH_3$); ^{13}C NMR δ 166.92, 140.37, 139.09, 134.52, 124.78, 124.54, 124.31, 123.66, 122.14, 62.31, 53.94, 14.03. Anal. Calcd for $C_{15}H_{16}O_4S$: C, 61.63; H, 5.52; S, 10.97. Found: C, 61.55; H, 5.27; S, 11.30.

Method II: (a) Synthesis of Diethyl α-Hydroxy-2-benzo[b]thiophenemalonate (22). Method A: *Via* 2-Benzo[b]thienyllithium. To a magnetically stirred solution of **21** (10.1 g, 0.075 mol) in ether (200 mL) at 0 °C was added dropwise a solution of 47 mL of butyllithium (1.6 M solution in hexane) diluted with ether (50 mL) under N_2. After the complete addition, the reaction mixture was stirred for 0.5 h. The yellow-colored solution thus obtained was added to a stirred solution of DEOM (14.8 g, 0.085 mol) in THF (100 mL) below −70 °C. The bath temperature was then allowed to increase slowly to room temperature, and stirring was continued at room temperature for 2 h. The reaction mixture was poured into a crushed ice–HCl mixture and washed up by standard procedure to give a dark reddish-brown viscous. The chromatography of the crude mixture with a hexane/benzene (10%) mixture, loaded on a silica gel column, first gave the starting material **21** (3.65 g), followed by elution with a benzene/$CHCl_3$ (10%) mixture to give 3.0 g (13%) of a yellow oil (21% based on starting material recovered) of **22**. Further purification by distillation gave a light yellow solid which was then crystallized from hexane: mp 41–43 °C [bp 183–5 °C (0.9 mm)]; IR (neat) 3600–3200, 3020–2900, 1750–10, 1450, 1250–10, 1135, 850, 740, 710 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.70–7.79 (m, 2H, ArH), 7.57 (s, 1H, ArH), 7.23–7.33 (m, 2H, ArH), 4.80 (bs, 1H, OH), 4.21–4.39 (m, 4H, $CO_2CH_2CH_3$), 1.28 (t, 6H, -$CO_2CH_2CH_3$); ^{13}C NMR δ 168.58, 140.00, 139.91, 139.25, 124.61, 124.26, 123.92, 123.68, 122.06, 78.66, 63.43, 13.89. Anal. Calcd for $C_{15}H_{16}O_5S$: C, 58.43, H, 5.23, S, 10.40. Found: C, 58.05, H, 5.23, S, 10.60.

Method B: *Via* 2-Benzo[b]thienylmagnesium Bromide. To a suspension of $MgBr_2$ etherate prepared from Mg turnings (4.74 g) and freshly distilled ethylene dibromide (24.2 g, 0.13 mol) in ether–benzene was added 200 mL of ether. The resulting solution of $MgBr_2$ etherate was then transferred to a freshly prepared 2-benzo[b]thienyllithium (ca. 0.12 mol) solution, under positive N_2 pressure, maintaining the temperature between −10° to 0 °C during the addition and then allowing it to warm up to room temperature over a 30-min period.

The resulting grey solution of 2-benzo[b]thienylmagnesium bromide was transferred to a THF solution of DEOM (22.6 g, 0.13 mol) held rigorously at −70 °C. The cloudy bright yellow

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reaction mixture was stirred for an additional hour at −70 °C and was then allowed to warm slowly overnight to room temperature. Decomposition and workup as in the previous preparation gave a viscous oil which was subjected to column chromatography over silica gel. Purification by chromatography as described in the previous preparation gave 10.2 g (25%) of **22**, identified by the comparison of its IR and ^{1}H NMR spectra with those of the authentic sample obtained by the previous method.

(b) Synthesis of Diethyl α-Acetoxy-2-benzo[*b*]thiophenemalonate (23). The general procedure of acetylation of diethyl aryltartronates as described by Saloman, Pardo, and Ghosh[14] was used. A solution of **22** (10.3 g, 0.033 mol) in CH_2Cl_2 (150 mL) was stirred magnetically under N_2. To this solution were added 44.7 mL of acetic anhydride (0.47 mol), 22.3 mL of triethylamine (0.16 mol), and 2.23 g of 4-(dimethylamino)pyridine (0.018 mol), and the resulting mixture was stirred for 2 days at room temperature. The dark-brown reaction mixture was poured into ice-cold water. The acetic acid generated was then neutralized by adding solid $NaHCO_3$ until no more evolution of CO_2 was observed. The organic residue was extracted with ether. The combined organic phases were washed with ice-cold aqueous 10% HCl, water, and brine and dried (Na_2SO_4). Removal of the ether gave a dark-brown liquid which was purified by column chromatography on a silica gel column using hexane/ether (30%) as eluant to give 11.2 g (97%) of nearly pure **23** which was crystallized from benzene/hexane to give yellow crystals: mp 65–68 °C; IR (neat) 3000–2900, 1770–20, 1430, 1360, 1230, 1150, 1055, 745, 720 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.72–7.81 (m, 2H, Ar*H*), 7.60 (s, 1H, Ar*H*), 7.30–7.34 (m, 2H, Ar*H*), 4.26–4.34 (pair of q, 4H, CO_2CH_2-CH_3), 2.27 (s, 3H, $COCH_3$), 1.23 (t, 6H, $CO_2CH_2CH_3$); ^{13}C NMR δ 169.17, 164.77, 140.05, 138.73, 136.84, 125.12, 124.52, 124.16, 122.05, 81.00, 63.02, 20.86, 13.85. Anal. Calcd for $C_{17}H_{18}O_6S$: C, 58.27; H, 5.18; S, 9.15. Found: C, 58.10; H, 5.10; S, 9.29.

(c) Synthesis of Diethyl 2-Benzo[*b*]thiophenemalonate (18) by Reductive α-Deacetoxylation. To a yellow stirred solution of 500 mg (1.43 mmol) of **23** and 20 mL of dry benzene under N_2 was slowly added a solution of sodium naphthalenide in HMPA[14] until the dark green color persisted for 20–30 s. The resulting mixture was quenched by pouring it into ice-cold 10% HCl and the usual workup was followed. The solid crude product (contaminated with naphthalene) was chromatographed through a short column of silica gel; naphthalene was eluted first with hexane. The reduced product was eluted with toluene to afford 230 mg (53%) of a yellow solid, mp 70–72 °C, found to be identical (TLC, ^{1}H NMR) with the authentic sample of **18** obtained by previous method.

(B) Synthesis of Diethyl α-Allyl-2-benzo[b]thiophenemalonate (17). Method I: Following the method used for the analogous compound **5**, alkylation of **18** (6.27 g, 0.023 mol) with an excess of allyl bromide (5.56 g, 0.046 mol) gave after usual workup 7.34 g (96%) of a yellow mobile liquid. TLC of the crude product using benzene as a developing system clearly showed the presence of two products very close in R_f values and less polar than starting **18**. The crude product was inseparable by column chromatography and upon fractionation under reduced pressure gave 2.33 g of **19**, bp 127–144 °C (0.35 mm), having an ^{1}H NMR spectrum identical with that of the authentic sample as obtained before and 2.05 g (27%) of **17**, bp 150–57 °C (0.35 mm): IR (neat) 3100–2900, 1730, 1460, 1430, 1230–20, 1150, 925, 860, 750, 730 cm^{-1}; ^{1}H NMR ($CDCl_3$) (Table I); ^{13}C NMR δ 168.98, 140.06, 139.94, 138.81, 132.07, 124.29, 124.06, 123.50, 123.48, 121.79, 119.19, 61.96, 60.52, 42.16, 13.90; MS *m/e* (rel inten) 332 (M^+, 42), 291 (88), 259 (36), 240 (71), 217 (61), 185 (100). Anal. Calcd for $C_{18}H_{20}O_4S$: C, 65.04; H, 6.06. Found: C, 64.96; H, 6.07.

Method II: By Reductive Allylation. To a stirred solution of **23** (4.36 g, 0.012 mol) in dry benzene (400 mL) was added dropwise a solution of sodium naphthalenide in HMPA until the dark-green color of the reagent persisted for 20–30 s. Allyl bromide (1.5 mL, 0.017 mol) was then added dropwise to the reaction mixture with stirring which was then heated to reflux for 1.5 h. After cooling, the resulting suspension was filtered and the benzene was evaporated. Then the reaction mixture was quenched by pouring it into cold 10% HCl. The usual workup gave a viscous oil which was chromatographed over silica gel, and the naphthalene was eluted first with hexane/toluene (1:1). Further elution with toluene/chloroform (30%) gave 1.85 g of **17** as a yellow viscous liquid (45%), found to be identical (TLC, ^{1}H NMR) with the authentic sample obtained previously.

Thermal Rearrangement of Diethyl α-Allyl-2-benzo[*b*]thiophenemalonate (17). Method A: A glass tube (20 × 2 cm) containing 200 mg of **17** was heated to 170–180 °C for 18 h. TLC of the crude product using a toluene system showed the presence of a slightly more polar spot along with the starting material spot. When the column was eluted with hexane/toluene (60%) and monitored by TLC, 52 mg (26%) of starting material was recovered and its identity was confirmed by ^{1}H NMR spectroscopy. On further elution with neat toluene 90 mg (45%) of **24** was isolated. Yield was 61% on the basis of starting material recovered. An analytical sample was obtained by short-path distillation; IR (neat) 3100–2900, 1740, 1470, 1440, 1220, 1160, 1040, 770, 745 cm^{-1}; ^{1}H NMR ($CDCl_3$) (Table I); ^{13}C NMR δ 167.04, 139.84, 138.84, 134.78, 132.64, 130.10, 124.65, 123.95, 122.27, 122.20, 116.17, 62.21, 52.01, 30.73, 13.99. Anal. Calcd for $C_{18}H_{20}O_4S$: C, 65.04; H, 6.08; S, 9.65. Found: C, 64.97; H, 5.96; S, 10.04.

Method B: In a similar operation 2.0 g of **17** was heated to 235–245 °C for 10 h. The crude dark product (1.99 g) in toluene was then loaded on a silica gel column. Elution first with petroleum ether/toluene (50%) gave 266 mg of a mixture of starting material and normal Cope product. Further elution with toluene gave 308 mg (14%) of nearly pure normal Cope product **24**. Further careful elution with toluene/$CHCl_3$ (12%) gave 240 mg (12%) of nearly pure minor isomer **25a** as a yellow viscous oil, followed by a mixture of cyclized diastereomers of **25** (100 mg) (5%) in a 50:50 ratio based on the integration curve of the ^{1}H NMR spectrum. Continued elution with toluene/$CHCl_3$ (40%) gave 480 mg (24%) of major isomer **25b** as a yellow viscous oil. The total yield was 76%. Analysis of the diastereomeric mixture **25** gave the following results. Anal. Calcd for $C_{18}H_{20}O_4S$: C, 65.04; H, 6.06. Found: C, 65.04; H, 5.95.

Major **25b**: IR (neat) 3100–2800, 1750–30, 1440, 1380, 1200, 1035, 760, 740 cm^{-1}; ^{1}H NMR ($CDCl_3$) (Table III); ^{13}C NMR ($CDCl_3$) δ 172.01, 171.83, 145.08, 140.14, 138.58, 134.67, 124.30, 123.91, 123.38, 121.79, 61.34, 60.34, 14.22, and Table IV.

Minor **25a**: IR (neat) 3100–2800, 1750–30, 1450, 1380, 1190, 1050, 760, 740 cm^{-1}; ^{1}H NMR ($CDCl_3$) (Table III); ^{13}C NMR ($CDCl_3$) δ 172.25, 171.44, 144.88, 141.68, 139.29, 134.72, 124.32, 123.98, 123.46, 121.98, 61.00, 60.59, 50.83, 43.49, 36.17, 32.96, 14.24.

Synthesis of Diethyl 3-Allyl-2-benzo[*b*]thiophenemalonate (24). (a) Synthesis of Diethyl α-Hydroxy-3-allyl-2-benzo[*b*]thiophenemalonate (27). To a stirred solution of 15.7 g (0.090 mol) of **26**[21] in 300 mL of ether cooled to 0 °C under N_2 was added dropwise 84 mL of butyllithium (1.6 M solution in hexane) in ether (100 mL). After the addition was complete, the colored solution was stirred for a further 0.5 h. To the resulting 3-allyl-2-benzo[*b*]thienyllithium was added a freshly prepared solution of magnesium bromide etherate (ca. 0.090 mol) in ether (300 mL) at 0 °C. The grey suspension of 3-allyl-2-benzo[*b*]-thienylmagnesium bromide warmed up to room temperature (0.5 h) and then cooled down to 0 °C was transferred to a solution of 23.5 g (20.6 mL, 0.14 mol) of diethyl oxomalonate (DEOM) in 500 mL of dry THF at −70 °C. The temperature was maintained at −70 °C for 1 h and then the mixture was warmed up to room temperature. A mixture of ice and 10% HCl was added and the reaction mixture was rapidly stirred. Ether was added and the solution was worked up as usual. The crude product was purified by column chromatography on silica gel using hexane/chloroform (30%) as eluant to give 11.7 g (37% and 57% based on 10.3 g of starting material recovered) of nearly pure **27** which was further purified by distillation to give a viscous brown-red oil, bp 175–78 °C (4.5 mm); IR (neat) 3700–3100, 3100–2900, 1760–30, 1440, 1380, 1290–20, 1110, 1040, 780, 750 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ 7.69–7.78 (m, 2H, Ar*H*), 7.26–7.35 (m, 2H, Ar*H*), 5.92 (ddt, *J* = 17, 10.4 and 5.7 Hz, 1H, CH=CH_2), 4.99–5.08 (m, 2H, CH=CH_2), 4.80 (s, 1H, –OH), 4.20–4.39 (m, 4H, $CO_2CH_2CH_3$), 3.69 (ddd, *J* = 5.7 and 1.6 Hz, 2H, CH_2-CH=CH_2), 1.28 (t, 6H, $CO_2CH_2CH_3$); ^{13}C NMR δ 169.08, 140.56, 138.54, 135.51, 135.22, 132.18, 124.62, 123.89, 122.83, 122.10, 116.02, 78.66, 63.47, 31.83, 13.86.

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The hydroxy ester was not further purified but was used directly in the next step.

(b) Synthesis of Diethyl α-Acetoxy-3-Allyl-2-benzo[b]thiophenemalonate (28). A mixture of **27** (2.65 g, 7.61 mmol), acetic anhydride (10.3 mL, 109 mmol), 4-(dimethylamino)pyridine (0.51 g, 4.1 mmol), and triethylamine (5.1 mL, 37 mmol) in CH_2Cl_2 (50 mL) was stirred for 2 days at room temperature under N_2 followed by workup as for **23** as described above to give a dark brown viscous liquid which was purified by chromatography on a silica gel column using toluene as eluant to give 1.2 g (40%) of **28** which was distilled under reduced pressure to give a yellow viscous liquid; bp 180–7 °C (0.25 mm); IR (neat) 3100–2800, 1770–20, 1360, 1250–10, 1175, 1050, 760, 730 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.65–7.80 (m, 2H, Ar*H*), 7.30–7.34 (m, 2H, Ar*H*), 5.93 (ddt, *J* = 17.2, 10.2, and 5.3 Hz, 1H, C*H*=CH_2), 5.02 (dd, *J* = 10.3 and 1.6 Hz, 1H, CH=C*H*$_2$), 4.88 (dd, *J* = 17.2 and 1.6, 1H, CH=C*H*$_2$), 4.17–4.36 (m, 4H, $CO_2CH_2CH_3$), 3.80 (d, *J* = 5.3 Hz, 2H, CH_2-CH=CH_2), 2.21 (s, 3H, $COCH_3$), 1.24 (t, 6H, $CO_2CH_2CH_3$); ^{13}C NMR δ 168.95, 165.01, 139.58, 139.17, 135.10, 133.15, 131.69, 125.11, 124.06, 122.81, 122.05, 116.01, 81.07, 63.01, 30.86, 20.68, 13.82. Anal. Calcd for $C_{20}H_{22}O_6S$: C, 61.52; H, 5.68; S, 8.21. Found: C, 61.33; H, 5.69; S, 8.14.

(c) Synthesis of Diethyl 3-Allyl-2-benzo[b]thiophenemalonate (24). To a stirred solution of **28** (4.0 g, 0.01 mol) in dry benzene (300 mL) under N_2 was added dropwise a solution of sodium naphthalenide in HMPA, as described before, giving 2.6 g of a product (76%) which was further purified by short-path distillation to give **24**, as a yellow mobile liquid. The IR and ^1H NMR spectra of **24** were identical with the spectra described in method A under the thermal rearrangement of **17**.

Thermal Rearrangement of Diethyl 3-Allyl-2-benzo[b]thiophenemalonate (24). A glass tube (20 × 2 cm) containing 500 mg of **24** was heated to 260–270 °C for 12 h. A ^1HNMR spectrum of the crude material revealed that no starting material was present but did show the presence of cyclized product **25**. The elution with toluene/chloroform (70%) gave 74 mg (15%) of a mixture of unseparable diastereomers of **25** which could not be separated.

Saponification of Ethyl 1,2-Dihydro-3-(ethoxycarbonyl)-3*H*-benzo[b]cyclopenta[d]thiophene-2-acetate (25). As described before for analogous diester **9**, saponification of **25** (131 mg) on workup followed by crystallization from ethanol/hexane gave 75 mg (69%) of 3-carboxy-1,2-dihydro-3*H*-benzo[*b*]cyclopenta[*d*]thiophene-2-acetic acid (**29**) as white crystals, mp 249–52 °C dec; IR (KBr) 3550–2500, 1690, 1420, 1275, 1240–1220, 750, 720 cm^{-1}; ^1H NMR (DMSO-d_6) (Table III); ^{13}C NMR (DMSO-d_6) δ 173.28, 172.94, 144.03, 139.63, 139.11, 134.29, 124.34, 123.80, 123.37, 121.70, and Table IV. Anal. Calcd for $C_{14}H_{12}O_4S$: C, 60.86; H, 4.38. Found: C, 60.90; H, 4.30.

Synthesis of Ethyl α-Allyl-α-cyano-3-benzo[b]thiopheneacetate (30). (A) Synthesis of Ethyl α-Cyano-3-benzo[b]thiopheneacetate (31). This procedure was an adaptation of the method of Houbiers and Muris.[6] To 150 mL of DMF was added with stirring 8.7 g (77 mmol) of ethyl α-cyanoacetate and 8.66 g (77 mmol) of anhydrous potassium *tert*-butoxide. Then 13.4 g (51.5 mmol) of **8** and 8.66 g (51.5 mmol) of copper(I) bromide were added. The resulting mixture was stirred under N_2 at a temperature of 70 °C for 3 h and the *tert*-butyl alcohol formed during the reaction was removed by distillation. The workup as before followed by chromatography on a silica gel column using benzene as an eluant gave 5.1 g (40%) of **31**, as a yellow oil (72% based on recovered starting material). The product was further purified by distillation: bp 168–70 °C (0.8 mm); IR (neat) 3100, 3000–2900, 2260, 1745, 1460, 1430, 1250, 1025, 770, 735 cm^{-1}; ^1H NMR ($CDCl_3$) (Table V); ^{13}C NMR δ 164.06, 140.33, 136.10, 127.17, 125.12, 124.80, 123.68, 123.06, 121.53, 115.1, 63.44, 38.22, 13.82. Anal. Calcd for $C_{13}H_{11}NO_2S$: C, 63.65; H, 4.52; S, 13.07. Found: C, 63.59; H, 4.67; S, 13.03.

(B) Synthesis of Ethyl α-Allyl-α-cyano-3-benzo[b]thiopheneacetate (30). The preparation of ethyl α-allyl-α-cyano-3-benzo[*b*]thiopheneacetate followed a literature procedure.[15] To a solution of 0.56 g (11.6 mmol) of a 50% dispersion of NaH in mineral oil in 50 mL of dry THF was added a solution 2.36 g (9.64 mmol) of **31** in 10 mL of dry THF dropwise over a 5-min period, and the mixture was stirred for 30 min, after which time hydrogen evolution had ceased. To the stirred mixture was then added dropwise a solution of 1.75 g (1.4 mL, 14.5 mmol) of freshly distilled allyl bromide in 10 mL of THF. The resulting mixture was stirred and heated to reflux for 3 h. Ice and water were added to the cooled mixture followed by the usual workup to give an oily residue which was purified by chromatography on a silica gel column with a hexane/benzene (1:1) system as an eluant and yielded 1.69 g (61%) of **30**, as a yellow viscous oil. An analytical sample was obtained by short-path distillation as a yellow transparent viscous oil; bp 158 °C (0.25 mm); IR (neat) 3140–2920, 2250, 1740, 1225, 770, 735 cm^{-1}; ^1H NMR ($CDCl_3$) (Table V); ^{13}C NMR δ 166.50, 140.81, 135.55, 130.34, 127.93, 125.78, 124.98, 124.74, 123.22, 122.32, 121.42, 117.54, 63.41, 50.36, 39.93, 13.91; MS *m/e* (rel inten) 285 (M^+, 43), 244 (100), 216 (94), 212 (57), 185 (45). Anal. Calcd for $C_{16}H_{15}NO_2S$: C, 67.34; H, 5.30; S, 11.24. Found: C, 67.68; H, 5.29; S, 11.41.

Thermal Rearrangement of Ethyl α-Allyl-α-cyano-3-benzo[b]thiopheneacetate (30). Method A: A glass tube (10 × 2 cm) containing 16.5 g of **30** was heated to 205–215 °C for 7 h. The crude dark brown liquid was then fractionated to give 1.2 g (73%) of **32**, as a yellow viscous oil: IR (neat) 3100–3060, 3000–2900, 2250, 1745, 1460, 1440, 1250, 1100, 1030, 765, 740 cm^{-1}; ^1H NMR ($CDCl_3$) (Table V); ^{13}C NMR δ 164.28, 143.23, 138.19, 137.45, 134.13, 124.83, 124.62, 122.46, 121.37, 119.04, 117.85, 114.72, 63.39, 35.93, 32.65, 13.98. Anal. Calcd for $C_{16}H_{15}NO_2S$: C, 67.34; H, 5.30; S, 11.24. Found: C, 66.98; H, 5.32; S, 11.05.

Method B: In a similar method **30** (5.04 g) was heated to 235–245 °C for 8 h. The reddish-brown crude material thus obtained was chromatographed on a silica gel column using benzene/hexane (3:1) system as an eluant, giving 312 mg (6%) **32** and 760 mg (16%) of a mixture of diastereomers of **33**, as a yellow viscous oil: IR (neat) 3100–2800, 2240, 1730, 1425, 1230, 1020, 760, 730 cm^{-1}; ^1H NMR ($CDCl_3$) δ 7.24–7.41 (m, 4H, Ar*H*), 7.71–7.80 (m, 4H, Ar*H*), 4.17–4.37 (m, 4H, $CO_2CH_2CH_3$), 3.56–3.79 (m, 2H, C*H*-CH_3), 3.34–3.43 (dd, *J* = 15.9, 7.5 Hz, 1H, C-C*H*$_2$-C), 3.18–3.27 (dd, *J* = 15.4, 7.7 Hz, 1H, C-C*H*$_2$-C), 2.95–3.04 (dd, *J* = 15.4, 9.2 Hz, 1H, CC*H*$_2$C), 2.79–2.87 (dd, *J* = 15.9, 6.6 Hz, 1H, CC*H*$_2$C), 1.51 (d, *J* = 7.14 Hz, 3H, CHCH_3), 1.43 (d, *J* = 6.96 Hz, 3H, CHCH_3), 1.33 (t, 3H, $CO_2CH_2CH_3$), 1.26 (t, 3H, CO_2-CH_2CH_3). Integration of ^1H NMR spectrum indicated a ratio of 64:36 between these two diastereomers: ^{13}C NMR δ 167.43, 166.11, 147.41, 147.09, 144.35, 143.96, 134.69, 133.44, 132.80, 132.56, 132.50, 125.06, 125.01, 124.34, 123.55, 121.02, 120.68, 118.16, 115.75, 63.34, 62.90, 55.21, 53.35, 51.96, 48.09, 36.68, 36.25, 17.84, 15.03, 14.17, 14.09; MS *m/e* (rel inten) 285 (M^+, 31), 258 (0.4), 212 (100), 185 (30). Anal. Calcd for $C_{16}H_{15}NO_2S$: C, 67.34; H, 5.30, S, 11.24. Found: C, 67.04; H, 5.47; S, 11.38.

Method C: Thermal Rearrangement of Ethyl α-Cyano-2-allyl-3-benzo[b]thiopheneacetate (32). **32** (293 mg) was similarly heated to 225–235 °C for 3 h. The crude material upon elution with benzene/hexane (50:50) gave 38 mg of a mixture of **32** and **33** in the ratio of 65:35 and 15 mg of pure unreacted starting material. The yield of **33** was 5% and consists of a mixture of diastereomers in the ratio of 59:41.

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A New Method for Regiospecific Deuteriation and Reduction of 5,10,15,20-Tetraphenylporphyrins: Nucleophilic Reaction of Borohydride Ion with 2-Nitro-5,10,15,20-tetraphenylporphyrins

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New methods for specific reduction and deuteriation of 5,10,15,20-tetraarylporphyrins are reported. Free-base and metalated 2-nitroporphyrins are converted into the corresponding nitrochlorins (2,3-dihydro-2-nitro-5,10,15,20-tetraphenyl-22*H*,24*H*-porphyrins) by reaction with borohydride followed by aqueous workup. These nitrochlorins may be readily converted into the denitrated chlorin by treatment with tributyltin hydride or into the corresponding denitrated porphyrin by elimination of nitrous acid by heating or treatment with silica. Deuterium labeling studies show that the formation of nitrochlorin from nitroporphyrin involves attack by hydride at the β-pyrrolic carbon next to that bearing the nitro group followed by protonation of the resultant nitronate in aqueous workup. Specific deuteriation at the β-pyrrolic next to that previously occupied by a nitro group is readily achieved by borodeuteride ion reaction with a 2-nitroporphyrin (50 atom % deuterium incorporation) or with a 2-methoxy-3-nitroporphyrin (100 atom % deuterium incorporation).

The relationship between the various members of the porphyrin, chlorin, and bacteriochlorin macrocyclic family is principally one of oxidation level. The porphyrin macrocycle is fully unsaturated while the chlorin macrocycle contains one saturated C–C bond[1] and the bacteriochlorin and isobacteriochlorin macrocycles contain two saturated C–C bonds. The degree of saturation of the ring profoundly affects the spectral and redox properties of the macrocycle.[2-4] To extend our studies of tautomerism and aromaticity within this class of macrocycles,[5-9] we required a number of specifically reduced and substituted 5,10,15,20-tetraarylporphyrin derivatives.

Porphyrins are readily reduced to chlorins or bacteriochlorins in vitro by standard hydrogenation procedures;[10,11] however, mixtures of regioisomers are obtained and the method is prone to give over-reduced products. Smith and Simpson have reported that the photoreduction of several octa-substituted zinc(II) porphyrins to zinc(II) chlorins is ring specific depending on the substituents present.[12] In general, however, methods for the directed reduction of a porphyrin pyrrole ring have been lacking. Herein, we address this deficiency in the case of the 5,10,15,20-tetraarylporphyrins.

Borohydride ion is an effective nucleophile for conjugate addition to nitroene systems leading to reduction of the double bond.[13,14] As 2-nitroporphyrins show many similaries in their reactions to simpler nitroenes, we thought that a nitro group on a β-pyrrolic position of a porphyrin should direct the reduction of the porphyrin ring. Regioselective reduction of the pyrrolic β–β bond bearing the nitro group, by conjugate addition of hydride, in free-base and metalated 2-nitroporphyrin would afford the corresponding 2-nitro-2,3-dihydroporphyrins (2-nitrochlorins). Reductive denitration of 2,3-dihydro-2,2-dimethoxy-3-nitroporphyrins has been achieved using tributyltin hydride and 2,2′-azobis(isobutyronitrile) (AIBN),[15] and the successful application of this reaction seemed likely in the present case. A regiospecific route from 2-nitroporphyrin 1 to the corresponding chlorin 3 was envisaged (Scheme I). The realization of this procedure is reported herein. Use of deuteriated reagents and deliberate promotion of nitrous acid elimination from deuterium labeled 2-nitro-2,3-dihydroporphyrins intermediates also provides a new route for the regiospecific synthesis of deuteriated porphyrins and chlorins.

(1) The IUPAC recommendations (Moss, G. P. *Pure Appl. Chem.* **1987**, *59*, 779–832) propose that chlorins should be named as 2,3-dihydroporphyrins. This name implies that the inner hydrogens are on the nitrogen atoms at positions 21 and 22 in the free-base compounds. We (Crossley, M. J.; Harding, M. M.; Sternhell, S. *J. Org. Chem.* **1988**, *53*, 1132–1137) and others (Schlabach, M.; Scherer, G.; Limbach, H.-H. *J. Am. Chem. Soc.* **1991**, *113*, 3550–3558) have pointed out the actual structures of free-base chlorins are not consistent with this nomenclature as only one tautomer, that with the inner hydrogens on the other two nitrogens, can be directly detected in solution NMR studies. There is no difficulty in the 2,3-dihydroporphyrin name for a metalloporphyrin, as the issue of detectable tautomeric forms does not arise because there are no mobile inner hydrogens. Free-base chlorins, however, should be named either as a 7,8-dihydroporphyrin (just as bacteriochlorins are 7,8,17,18-tetrahydroporphyrins) or as 2,3-dihydro-22*H*,24*H*-porphyrins. In this paper and forthcoming papers, we prefer the later nomenclature as it maintains a link with the nomenclature of the starting porphyrins, rather than suggesting that it is the β-pyrrolic substituents that are moving positions rather than the inner hydrogens, and maintains consistency with the metallochlorin nomenclature.

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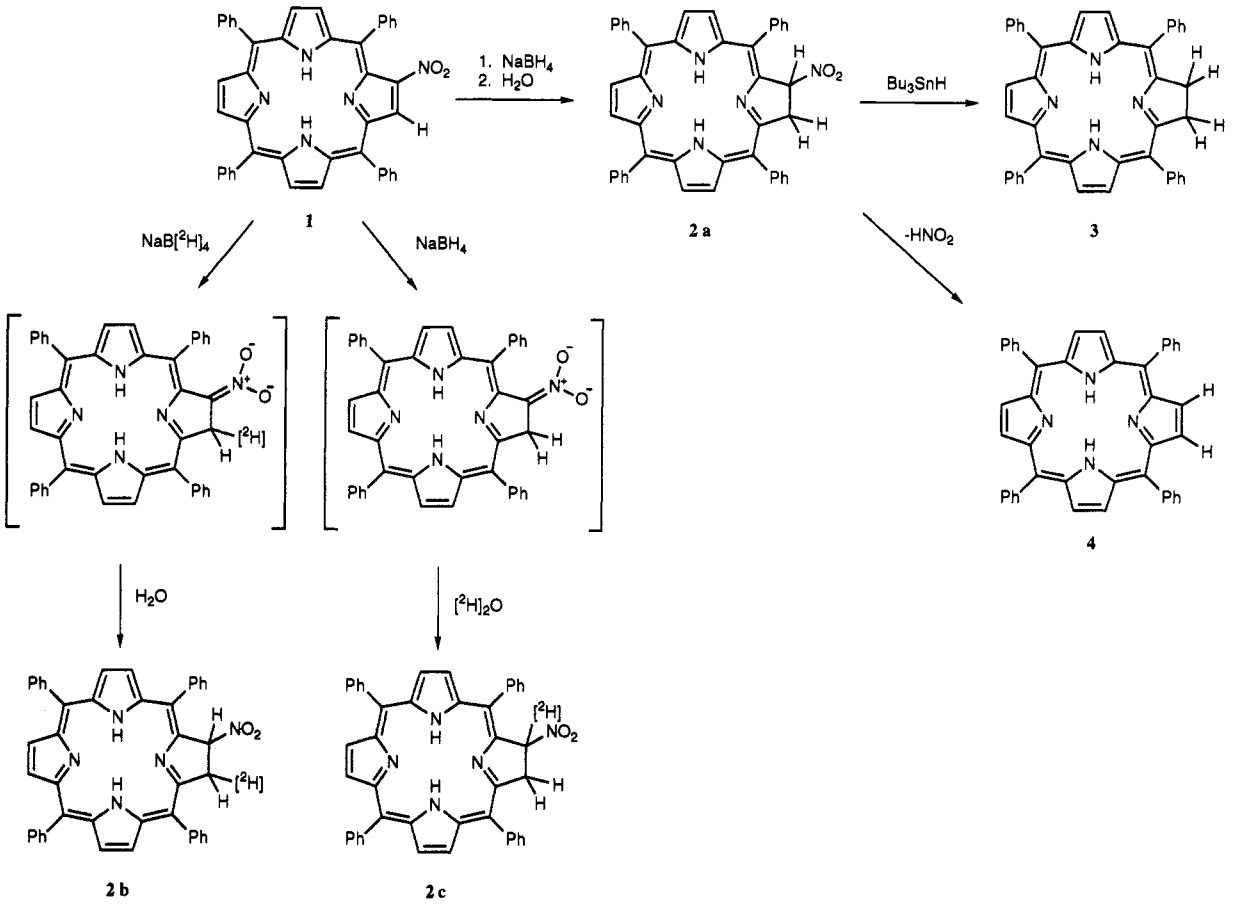
Scheme I



Results and Discussion

Treatment of a solution of 2-nitro-5,10,15,20-tetraphenylporphyrin (**1**) (3 mM) in dimethyl sulfoxide (Me_2SO) with sodium borohydride (2.4 equiv) for 15 min afforded the nitrochlorin, 2,3-dihydro-2-nitro-5,10,15,20-tetraphenyl-22*H*,24*H*-porphyrin (**2a**), in essentially quantitative yield after aqueous workup (Scheme I). A ^4J coupling (1 Hz) between the inner NH's and the protons at C-7, C-8, C-17, and C-18 confirms that the inner hydrogens reside on N-22 and N-24 as expected;[7,16,17] this tautomer has an 18-atom 18-π-electron aromatic delocalization pathway whereas the tautomer with the inner hydrogens on N-21 and N-23 has a less-stabilized 17-atom 18-π-electron aromatic delocalization pathway.[7]

The nitrochlorin **2a** proved unstable to warming and to chromatography as these processes caused the elimination of nitrous acid to afford the parent porphyrin **4**. The nitrochlorin **2a** was, therefore, reductively denitrated without further purification by a protocol involving sequential addition of AIBN (10 equiv), tributyltin hydride (51 equiv), and the nitrochlorin **2a** to a refluxing solution of benzene under nitrogen. This procedure afforded the parent chlorin, 2,3-dihydro-5,10,15,20-tetraphenyl-22*H*,24*H*-porphyrin[18] (**3**), in 81% yield with minimal formation of the byproduct **4**, formed by thermal elimination of nitrous acid.

The formation of the nitrochlorin **2a** from **1** could have involved initial hydride attack at either the carbon bearing the nitro group or at the adjacent β-pyrrolic position. The use of deuteriated reagents in NMR spectroscopy experiments clarified the mechanism of the reaction and suggested a new protocol whereby one or more deuteriums may be introduced regiospecifically to a β-pyrrolic ring of 5,10,15,20-tetraarylporphyrins and -chlorins. The NMR spectrum of the unlabeled nitrochlorin, 2,3-dihydro-2-nitro-5,10,15,20-tetraphenyl-22*H*,24*H*-porphyrin (**2a**), showed the C-2 and two C-3 hydrogens as a three-spin system. In d_6-Me_2SO solution, the C-2 hydrogen resonated at δ 7.42, consistent with it being in a geminal position to the 2-nitro group. It showed a 9.4-Hz coupling to hydrogen H_α (δ 4.94) at C-3, the two hydrogens being cis and in an essentially eclipsed relative orientation, and it showed a 1.4-Hz coupling to hydrogen H_β (δ 4.39). The two C-3 hydrogens showed a geminal coupling of 17.8 Hz. When the reaction was carried out using sodium borodeuteride and quenched with H_2O, one deuterium was introduced; it was evenly distributed (~50 atom %) at the two positions on C-3, and the 17.8 Hz geminal coupling seen in the ^1H NMR spectrum of unlabeled material was absent. The product was clearly **2b**. Quenching a reaction using $NaBH_4$ with $[^2H]_2O$ resulted in the regiospecific introduction of deuterium (~100 atom %) at C-2 (the resonance at δ 7.42 and the corresponding couplings to the vicinal hydrogens seen in unlabeled material were absent in the ^1H NMR spectrum of the reaction product). In this case the product was clearly **2c**. These data require a reaction mechanism (Scheme I) involving addition of hydride (or deuteride) to the porphyrin at the β-pyrrolic carbon adjacent to that bearing the nitro group thereby leading to an approximately planar nitronate which is quenched by protonation at C-2 from either face (with equal probability) of the

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