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Synthesis of functionalized CF_3-containing heterocycles via [2,3]-sigmatropic rearrangement and sequential catalytic carbocyclization

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ABSTRACT

A new efficient access to functionalized CF_3-substituted and nitrogen or sulfur-containing heterocycles has been developed directly from diazocompounds $CF_3C(N_2)Z$ (Z=CO_2Me, $P(O)(OEt)_2$). The method is based on the direct selective synthesis of doubly unsaturated substrates followed by metal-mediated carbocylization. The first step has been performed by Cu(II)-catalyzed [2,3]-sigmatropic rearrangement of propargyl- or/and allyl-containing sulfur and nitrogen ylides leading to fluorinated enynes, diolefins, and especially allenynes derivatives. The second step involves their carbocyclization via ring closing metathesis and Pauson–Khand reaction.

1. Introduction

The selective introduction of fluorine functionalities into biologically-relevant compounds has become an important tool in the drug discovery process.[1] Particular attention is focused on trifluoromethyl-containing compounds due to the unique properties of the CF_3 group,[2] such as high electronegativity, electron density, steric hindrance, and hydrophobic character that can essentially improve the pharmaco-kinetic profiles of potential drugs. These properties attract a considerable interest in developing new methods for the trifluoromethylation of organic molecules and especially of heterocycles.

We have recently developed an efficient pathway to a new family of trifluoromethyl-containing cyclic α-amino acids based on metal-catalyzed metathesis-type cyclizations and cyclotrimerizations of functionalized diolefins, enynes, and bisalkynes derived from highly electrophilic imines of methyl trifluoropyruvate (Fig. 1).[3]

On the other hand, α-trifluoromethyl-substituted α-diazocarboxylate **1** and α-diazophosphonate (**2**) (Fig. 2) are unique

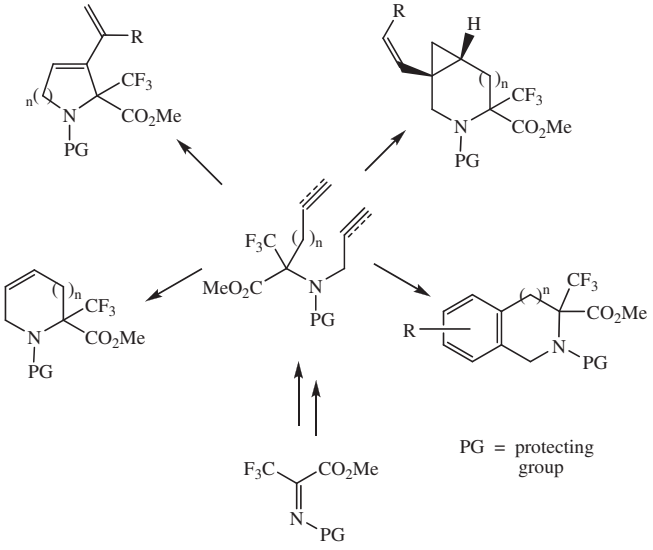

Fig. 1. Previous syntheses of CF_3-containing α-amino acid derivatives.

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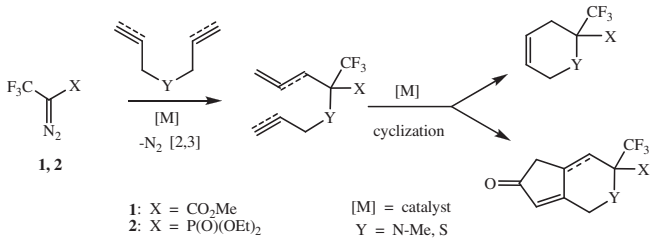


Fig. 2. Synthesis of functionalized CF_3-containing heterocycles.

building blocks for the simultaneous introduction of trifluoromethyl and carboxylic and phosphonic functionalities into organic molecules via the generation of highly electrophilic acceptor/acceptor carbenoids generated from **1** and **2** on rhodium- or copper-catalyzed extrusion of dinitrogen. The latter were effective for a range of useful transformation, such as cycloaddition,[4,5] ring expansion,[6] ylide generation,[7] and X–H insertion.[8]

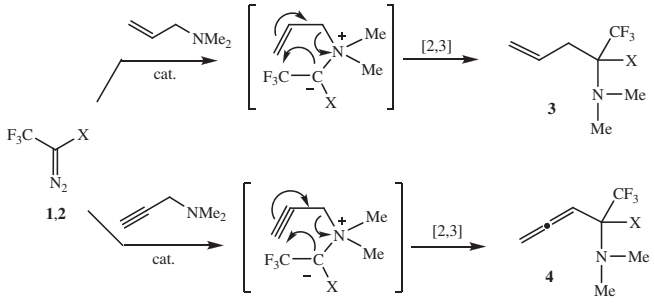
Now we wish to report: (i) the Cu(II)-catalyzed tandem ylide formation/[2,3]-sigmatropic rearrangement between CF_3-carbenoids and allyl- or/and propargyl-containing amines or sulfides to afford, in one-step, unique allenynes, enynes, and diolefins and (ii) their subsequent metal-mediated intramolecular carbocyclizations into heterocycles via ruthenium-catalyzed RCM and cobalt-mediated Pauson–Khand reactions.

To the best of our knowledge the combination of [2,3]-sigmatropic rearrangement with carbocyclization to access functionalized CF_3-heterocycles[9] has never been reported previously. These two-step reactions constitute an efficient approach to multifunctional CF_3-heterocyclic compounds, including cyclic α-amino carboxylic and α-amino phosphonic acids, based on two successive metal-catalyzed processes: ylide generation/rearrangement and carbocyclization (Fig. 2).

2. Results and discussion

2.1. Catalyzed [2,3]-sigmatropic rearrangement and synthesis of fluorinated unsaturated compounds

The feasibility of [2,3]-sigmatropic rearrangement of allyl- and propargyl-containing CF_3-ylides catalytically generated from diazocompounds **1** and **2** was initially established by their reaction with commercially available *N*,*N*-dimethylallyl- and *N*,*N*-dimethylpropargyl-amines (Scheme 1). For this purpose, dirhodium tetraacetate and copper bisacetylacetonate, widely used for mild diazo decomposition, were evaluated. Thus, we found that the reactions of diazocompounds **1** or **2** with equimolar amount of above-mentioned amines can be performed in anhydrous toluene at 80–90 °C for 2–3 h in the presence of 5 mol % of $Rh_2(OAc)_4$ or 5 mol % of Cu(acac)$_2$ to afford the rearrangement products **3** and **4** in moderate to good yields (Table 1).



Scheme 1. Rh(II)- and Cu(II)-catalyzed reactions of **1** and **2** with *N*,*N*-dimethylallyl- and *N*,*N*-dimethylpropargyl-amines.

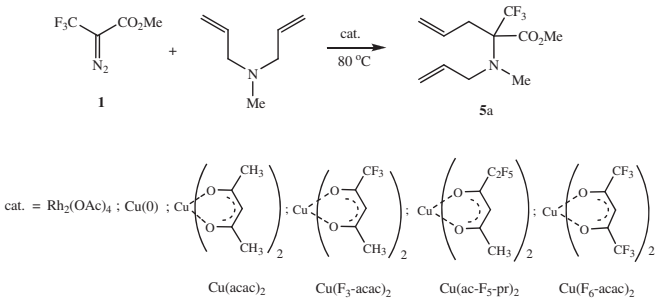
Table 1
Synthesis of α-allyl(allenyl)-amines **3** and **4**

Entry	Catalyst	X	Product	Yield,[a] %
1	$Rh_2(OAc)_4$	CO_2Me	**3a**	61
2	Cu(acac)$_2$	CO_2Me	**3a**	41
3	$Rh_2(OAc)_4$	$P(O)(OEt)_2$	**3b**	19[b]
4	Cu(acac)$_2$	$P(O)(OEt)_2$	**3b**	57
5	$Rh_2(OAc)_4$	CO_2Me	**4a**	63
6	Cu(acac)$_2$	CO_2Me	**4a**	55
7	$Rh_2(OAc)_4$	$P(O)(OEt)_2$	**4b**	22[b]
8	Cu(acac)$_2$	$P(O)(OEt)_2$	**4b**	62

[a] After column chromatography on silica gel.
[b] Determined by ^{19}F NMR spectra.

The incomplete conversion of the starting diazocompounds in some cases resulted in poor yields of the products under studied conditions (monitoring by ^{19}F NMR-spectroscopy). The variation of the reaction conditions, such as the amount of the catalyst, the ratio of substrates, the reaction temperature and the time, did not essentially affect the outcome of the reaction. Interestingly, the Rh-catalysis gave better yields in the case of diazocarboxylate **1** than Cu-catalysis. The situation has proved to be the reverse for diazophosphonate **2** (Table 1, entries 4 and 8).

However, our first attempt to apply $Rh_2(OAc)_4$ in the reaction of diazocarboxylate **1** with diallylmethylamine resulted in an unsatisfactory yield of the rearrangement product **5a** even in the presence of double the amount of catalyst (10 mol %) when heating in toluene (Scheme 2). Therefore, we decided to screen a number of copper-based catalysts, which are more available and much cheaper than rhodium-catalysts (Table 2). As result, copper trifluoroacetylacetonate (entry 5, Table 2) was selected as the most active in the series. The reasons for the observed advantage of copper-based catalysts over $Rh_2(OAc)_4$ requires further investigations. However, one possible explanation for this unusual fact could concern the poisoning of the catalyst via the coordination of rhodium atom on the double bond in diallyl-containing metal-ylide intermediate.



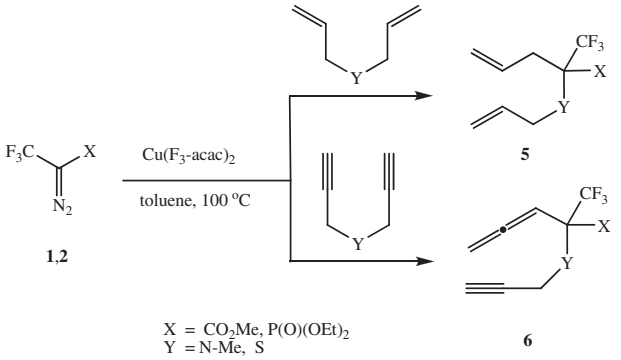
Scheme 2. Reaction of diazocaboxylate **1** with *N*,*N*-diallylamine.

Table 2
Screening of the most efficient catalyst for the synthesis of **5a**

Entry	Catalyst	mol %	NMR yield, %
1	$Rh_2(OAc)_4$	5	15
2	$Rh_2(OAc)_4$	10	25
3	Cu-powder	50	28
4	Cu(acac)$_2$	5	45
5	**Cu(F_3-acac)$_2$**	**5**	**85**
6	Cu(ac-F_5-pr)$_2$	5	75
7	Cu(F_6-acac)$_2$	5	70

Bold values indicate the most active catalyst.

This selected catalyst Cu(F_3-acac)$_2$ was then used in the reactions of both diazocompounds **1** and **2** with dipropargylmethylamine, diallyl- and dipropargylsulfides (Scheme 3). In all cases the catalytic reactions were performed on heating in toluene at 100 °C until the full conversion of diazocompound (usually for 2–3 h) furnishing the corresponding diolefins **5**. It is noteworthy this catalytic reaction constitutes a selective access to functional allenynes **6** (Table 3).



Scheme 3. Cu(II)-catalyzed reactions of diazocompounds **1** and **2** with diallyl(dipropargyl)amines and sulfides.

Table 3
Synthesis of diolefins **5** and allenynes **6**

Entry	X	Y	Product	Yield,[a] %
1	CO_2Me	N-Me	**5a**	75
2	CO_2Me	S	**5b**	84
3	$P(O)(OEt)_2$	N-Me	**5c**	55
4	$P(O)(OEt)_2$	S	**5d**	89
5	CO_2Me	N-Me	**6a**	71
6	CO_2Me	S	**6b**	74
7	$P(O)(OEt)_2$	N-Me	**6c**	54
8	$P(O)(OEt)_2$	S	**6d**	60

[a] After column chromatography on silica gel.

Then we studied, which group, allyl or propargyl, reacts more rapidly in the [2,3]-sigmatropic rearrangement process. The reactions of diazocompounds **1** and **2** with 'mixed' substrates: the allylpropargylmethylamine and allylpropargylsulfide have been performed under conditions described for the preparation of **5** and **6**. It turned out that the reaction of **1** with allylpropargylmethylamine leads to formation of enyne **7a** with high selectivity (entry 1, Table 4). The product of competitive rearrangement of propargyl group **8a** was detected in the reaction mixture by means of ^{19}F NMR-spectroscopy in amounts less than 5% showing that allyl group is migrating faster than the propargylic one.

In the case of diazophosphonate **2** a ratio of enyne **7b**/allenene **8b** was found to be 85:15, respectively. Both major products **7a**,**b** and minor **8b** can be easily separated using flash chromatography on silica gel.

However, the reactions of **1** and **2** with allylpropargylsulfide occur nonspecifically[10] to give almost equal ratio of the corresponding products **7** and **8** (entries 3 and 4, Table 4).

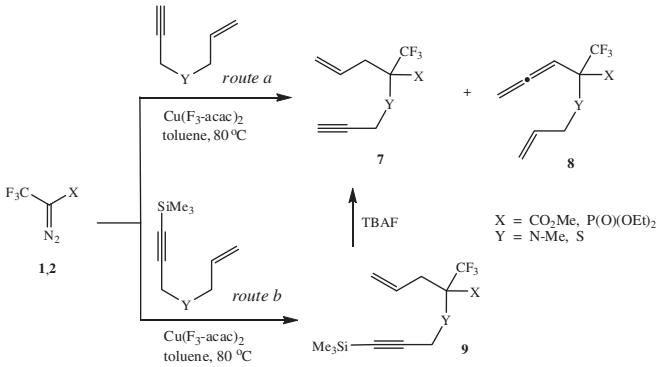
Such a difference in the reactivity between nitrogen-and sulfur-containing enynes can be explained by greater termodinamic stability of the sulfonium ylides compared to the related ammonium species.[11] Therefore, the rearrangement of *S*-ylides requires enhanced energy consumption resulting in less selectivity of the reaction. Moreover, the sigmatropic rearrangement is believed to proceed via a transition state involving a five-membered cycle (see Scheme 1). The activation energy for such transformation depends on the cycle strain which, due to longer C–S^+ bond (typically 1.80 Å) compared to C–N^+ one (typically 1.51 Å),[12] should be significantly less for sulfur-containing species. Thus, formation of more flexible sulfur-containing intermediate may proceed with participation both of propargyl and allyl moieties leading to final products in commensurable amounts.

Table 4
Cu(II)-catalyzed synthesis of enynes **7**

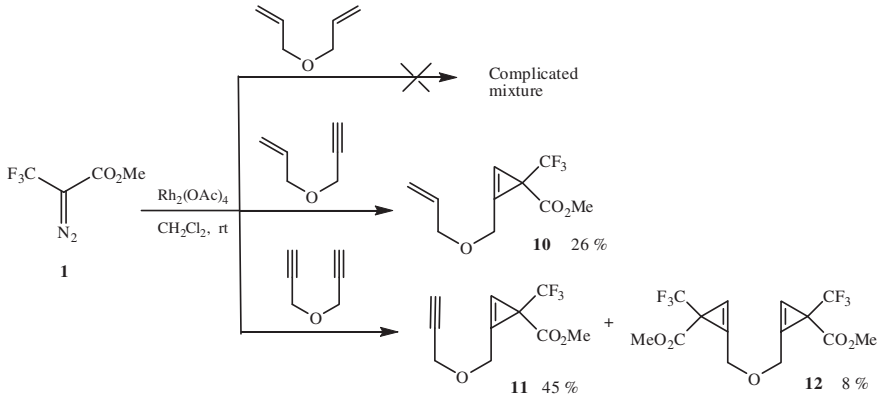
Entry	X	Y	Product	Yield, %
1	CO_2Me	N-Me	**7a**+**8a**	**7a**:**8a**=95:5[a] **7a**—64[b]
2	$P(O)(OEt)_2$	N-Me	**7b**+**8b**	**7b**:**8b**=85:15[a] **7b**—55[b]
3	CO_2Me	S	**7c**+**8c**	**7c**:**8c**=55:45[a] **7c**—85[c]
4	$P(O)(OEt)_2$	S	**7d**+**8d**	**7d**:**8d**=40:60[b] **7d**—86[c]
5	CO_2Me	S	**9a**	68
6	$P(O)(OEt)_2$	S	**9b**	75

[a] Ratio measured by ^{19}F NMR-spectroscopy before separation.
[b] Isolated yield after column chromatography (*route a*).
[c] Isolated yield after column chromatography (obtained from **9**, *route b*).

At the same time we found that rearrangements CF_3-ylides derived from **1** and **2** and TMS-containing sulfide proceed regioselectively leading to the formation of enynes **9a**,**b** in high yields. The standard treatment of latter compounds with tetrabutylammonium fluoride (TBAF) gave the desired derivatives **7c**,**d** offering a selective approach to enynes **7** (route b, Scheme 4).



Scheme 4. Catalytic reaction of **1** and **2** with allylpropargylamine and sulfides.



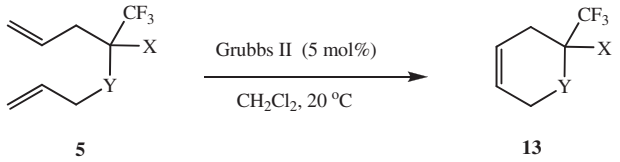
Scheme 5. Cyclopropenation of propargyl ethers.

It should pointed out the Cu- or Rh-catalyzed [2,3]-sigmatropic rearrangement does not occur in the reaction of **1** and **2** with diallyl-, dipropargyl-, and allylpropargylethers. In this case, [2+1]-cycloadducts on the triple bond, the corresponding cyclopropenes **10**–**12**, were obtained under Rh-catalysis (Scheme 5).

2.2. Catalytic synthesis of fluorinated heterocycles

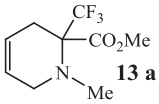
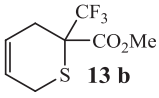
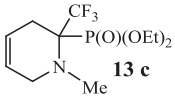
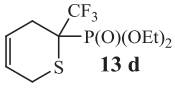
The synthetic potential of novel unsaturated compounds **5**–**7** for the preparation of functionalized and fluorinated heterocycles has been investigated using two intramolecular metal-catalyzed/mediated cyclizations, olefin metathesis RCM, and Pauson–Khand reactions.

Thus, we found that diolefins **5** can be readily transformed into the corresponding six-member fluorocontaining heterocycles **13** under standard RCM conditions using 5 mol % of Grubbs(II)-catalyst. The RCM reactions go to completion after 4–5 h at room temperature in methylene chloride and the heterocycles **13a**–**d** were isolated in 83–91% yields (Scheme 6, Table 5).



Scheme 6. Ring closing metathesis of dienes **5**.

Table 5
Ruthenium-catalyzed synthesis of cyclic amines and sulfides **13**

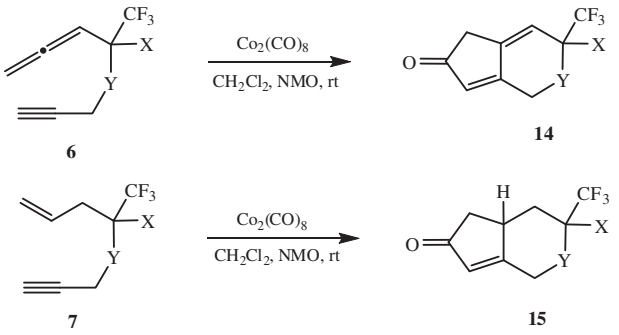
Entry	X	Y	Product	Yield,[a] %
1	CO_2Me	N-Me	 **13 a**	91
2	CO_2Me	S	 **13 b**	88
3	$P(O)(OEt)_2$	N-Me	 **13 c**	83
4	$P(O)(OEt)_2$	S	 **13 d**	86

[a] After column chromatography on silica gel.

RCM reactions were previously used for the formation of CF_3-containing piperidines arising from multistep syntheses from imines $CF_3CH]NR$[9b] and $CF_3C(OSiMe_3)N]CR_2$.[9a]

The Pauson–Khand (PK) reaction is widely used for the construction of cyclopentenone ring systems.[13] The intramolecular version of the reaction has gained much popularity since it can afford cyclopentenone-fused ring systems, which are difficult to construct.[14] It has also been used as a key step in the synthesis of a number of biologically-relevant compounds[15] including CF_3-containing piperidine/cyclopentenone-fused cycles.[9b]

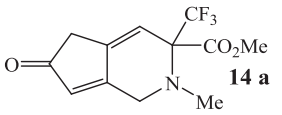
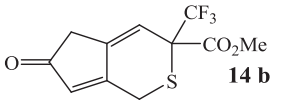
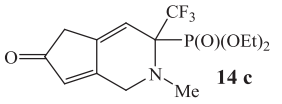
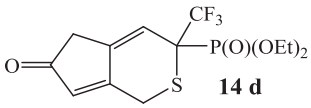
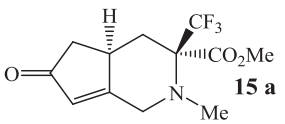
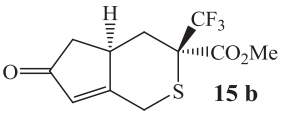
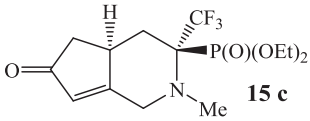
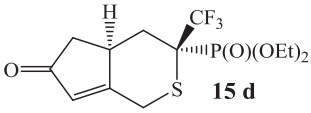
We have investigated the cobalt-mediated reaction of allenynes **6** and enynes **7** to establish an efficient access to novel CF_3-substituted nitrogen and sulfur bicyclic compounds (Scheme 7). Thus, it was found that the intramolecular [2+2+1]-cycloaddition of allenynes **6** occur under consecutive treatment with 1.2 equiv of $Co_2(CO)_8$ and 10 equiv of *N*-methylmorpholine-*N*-oxide (NMO) to



Scheme 7. Pauson–Khand reaction of allenynes **6** and enynes **7**.

afford the corresponding cyclopentenones **14** in satisfactory yields, except for the sulfur-containing product **14b** (entry 2, Table 6). Such a poor yield of **14b** is likely due to enhanced ability of sulfide for oxidation under reaction conditions. All our attempts to overcome this problem via careful temperature and time control, and variation of several oxidants failed. In contrast, the better yield of phosphorus analog **14d** (entry 4, Table 6) can be explained by favorable electronic and steric effects of phosphonate group. In the case of enynes **7** the bicyclic products **15** are formed as mixtures of diastereomers, which can be separated by flash chromatography on silica gel.

Table 6
Cobalt-mediated synthesis of heterocycles fused with cyclopentenone ring

Entry	X	Y	Product	Yield,[a] % (*syn*/*anti*, %)
1	CO_2Me	N-Me	 **14 a**	52
2	CO_2Me	S	 **14 b**	5
3	$P(O)(OEt)_2$	N-Me	 **14 c**	48
4	$P(O)(OEt)_2$	S	 **14 d**	45
5	CO_2Me	N-Me	 **15 a**	68(83/17)
6	CO_2Me	S	 **15 b**	40(62/38)
7	$P(O)(OEt)_2$	N-Me	 **15 c**	81(35/65)
8	$P(O)(OEt)_2$	S	 **15 d**	59(75/25)

[a] After column chromatography on silica gel.

The relative configuration of **15a** was determined by single-crystal XRD obtained via crystallization from hexane (Fig. 3) and for **15b–d** it was devised from 2D NOESY and ^{19}F NMR-analysis by analogy with **15a** (see Supplementary data).

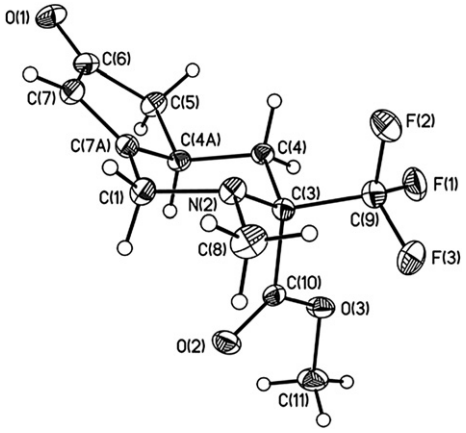


Fig. 3. Structure of *syn*-**15a** crystal. Atoms are represented by thermal ellipsoids (p=50%).

3. Conclusion

In summary, we have developed a new efficient access to functionalized CF_3-substituted nitrogen- and sulfur-containing heterocycles including cyclic α-amino acid derivatives and their phosphonates analogs. The key point of this methodology is the [2,3]-sigmatropic rearrangement of propargyl- or/and allyl-containing ylides catalytically derived from the Cu(II)-catalyzed reaction of α-CF_3-α-diazocarboxylates or phosphonates with unsaturated amines and sulfides furnishing, in one step, a variety of new fluorinated diolefins, enynes, and especially allenes derivatives, the doubly unsaturated precursors for the subsequent intramolecular carbocyclizations. The catalytic RCM metathesis and cobaltcarbonyl mediated Pauson–Khand reactions were shown to selectively transform these unsaturated molecules into CF_3-substituted heterocycles.

4. Experimental section

4.1. General methods

All solvents used in reactions were freshly distilled from appropriate drying agents before use. All other reagents were recrystallized or distilled as necessary. Starting diazocompounds **1** and **2** were prepared according the procedures described in Refs. 4a and 8c, respectively. Reactions were performed under an atmosphere of dry argon. Analytical TLC was performed with Merck silica gel 60 F_{254} plates. Visualization was accomplished by UV light or spraying by $Ce(SO_4)_2$, solution in 5% H_2SO_4. Flash chromatography was carried out using Merck silica gel 60 (230–400 mesh ASTM) and ethyl acetate/hexanes as eluent. IR spectra were recorded on a Nicolet 6700 FT-IR instrument. NMR spectra were obtained at room temperature on a Bruker AV-300, AV-400, AV-600 spectrometers operating at 300 MHz, 400 MHz, 600 MHz, respectively (TMS) for ^1H; 75, 100, and 151 MHz for ^{13}C; 282 MHz for ^{19}F (CF_3COOH).

4.2. Typical procedure for [2,3]-sigmatropic rearrangement

A mixture of the substituted amine or sulfide (1.0 mmol), copper trifluoroacetylacetonate (5 mol %) and the corresponding diazocompound (1.0 mmol) in anhydrous toluene (3–5 mL) was stirred under heating (90–100 °C) for 1–2 h. After the reaction completion (TLC) the solvent was removed under reduced pressure and the crude product was purified by column chromatography on silica gel (EtOAc–hexanes).

*4.2.1. Diethyl [1-(dimethylamino)-1-(trifluoromethyl)but-3-en-1-yl]-phosphonate (**3b**).* Yield (0.35 g, 57%) as a colorless oil. [Found: C, 43.69; H, 7.05; N, 4.78. $C_{11}H_{21}F_3NO_3P$ requires C, 43.57; H, 6.98; N, 4.62%]. R_f (EtOAc/hexane=1/3) 0.26. IR (neat) ν_{max}=3082, 2987, 1641, 1439, 1252, 1025 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$) δ 1.40 (t, 6H, $2CH_3$, J=7.1 Hz), 2.66 (s, 6H, NMe_2), 2.73–3.04 (m, 2H, CH_2), 4.15–4.38 (m, 4H, 2 OCH_2), 5.14–5.32 (m, 2H, CH_{2allyl}), 5.90–6.15 (m, 1H, CH_{allyl}). ^{19}F NMR (282 MHz, $CDCl_3$) δ 15.40 (d, 3F, CF_3, J=5.4 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 20.12 (d, J=5.7 Hz). ^{13}C NMR (75 MHz, $CDCl_3$) δ 16.4, 34.1, 37.6, 61.5, 61.8, 68.3 (dq, J=153.1, 24.2 Hz), 116.2, 117.0, 126.0 (dq, J=295.1, 14.03 Hz), 135.8.

*4.2.2. Methyl 2-(dimethylamino)-2-(trifluoromethyl)penta-3,4-dienoate (**4a**).* Yield (0.83 g, 63%) as a colorless oil. [Found: C, 48.65; H, 5.05; N, 6.01. $C_9H_{12}F_3NO_2$ requires C, 48.43; H, 5.42; N, 6.28%]. R_f (EtOAc/hexane=1/5) 0.54. IR (neat) ν_{max}=3003–2810 (br), 1963, 1755, 1464, 1439, 1255, 1181, 863 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$) δ 2.55 (q, 6H, NMe_2, J=1.2 Hz), 3.44 (s, 3H, OCH_3), 4.73 (d, 2H, $CH_{2allene}$, J=6.8 Hz), 5.46 (t, 1H, CH_{allene}, J=6.8 Hz). ^{19}F NMR (282 MHz, $CDCl_3$) δ 10.41 (s, 3F, CF_3). ^{13}C NMR (75 MHz, $CDCl_3$) δ 38.1, 52.3, 74.5, 76.0 (q, J=25.5 Hz), 89.9, 123.6 (q, J=289.8 Hz), 166.9, 208.7.

*4.2.3. Diethyl [1-(dimethylamino)-1-(trifluoromethyl)buta-2,3-dien-1-yl]phosphonate (**4b**).* Yield (0.38 g, 62%) as a colorless oil. [Found: C, 43.64; H, 6.52; N, 4.73. $C_{11}H_{19}F_3NO_3P$ requires C, 43.86; H, 6.36; N, 4.65%]. R_f (EtOAc/hexane=1/3) 0.27. IR (neat) ν_{max}=3010–2880 (br), 1957, 1431, 1320, 1269, 1150, 1063, 1034, 866 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$) δ 2.59 (td, 6H, $2CH_3$, J=7.0, 4.0 Hz), 4.29 (q, 6H, NMe_2, J=1.9 Hz), 5.43–5.75 (m, 4H, 2 OCH_2), 6.22–6.39 (m, 2H, $CH_{2allene}$), 6.89–7.04 (m, 1H, CH_{allene}). ^{19}F NMR (282 MHz, $CDCl_3$) δ 17.34 (d, 3F, CF_3, J=4.5 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 17.81 (d, J=5.7 Hz). ^{13}C NMR (75 MHz, $CDCl_3$) δ 16.5, 38.7, 62.3, 62.6, 67.4 (dq, J=152.8, 23.9 Hz), 77.3, 88.3, 125.7 (dq, J=290.3, 14.9 Hz), 205.1.

*4.2.4. Methyl 2-[allyl(methyl)amino]-2-(trifluoromethyl)pent-4-enoate (**5a**).* Yield (0.56 g, 75%) as a colorless oil. [Found: C, 52.78; H, 6.53; N, 5.87. $C_{11}H_{16}F_3NO_2$ requires C, 52.59; H, 6.42; N, 5.57%]. R_f (EtOAc/hexane=1/10) 0.52. IR (neat) ν_{max}=3085–2844 (br), 1755, 1644, 1458, 1438, 1139, 1043 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$) δ 2.47 (s, 3H, NMe), 2.81 (d, 2H, CH_2, J=7.1 Hz), 3.24 (dd, 1H, CH_2, J=14.5, 5.6 Hz), 3.43 (dd, 1H, CH_2, J=14.5, 6.0 Hz), 3.83 (s, 3H, OCH_3), 5.11–5.30 (m, 4H, $2CH_2$), 5.77–5.93 (m, 2H, 2CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 11.21 (s, 3F, CF_3). ^{13}C NMR (75 MHz, $CDCl_3$) δ 35.3, 36.4, 52.1, 55.3, 73.1 (q, J=26.5 Hz), 116.5, 118.8 (−CH_2=CH−), 123.1 (q, J=295.2 Hz), 130.9, 136.0, 167.8.

*4.2.5. Methyl 2-(allylthio)-2-(trifluoromethyl)pent-4-enoate (**5b**).* Yield (0.64 g, 84%) as a light-yellow oil. [Found: C, 46.94; H 4.94$C_{10}H_{13}F_3O_2S$ requires C, 47.26; H, 5.12%]. R_f (EtOAc/hexane=1/10) 0.62. IR (neat) ν_{max}=3088, 2955, 1747, 1641, 1440, 1325, 1170. ^1H NMR (300 MHz, $CDCl_3$) δ 2.77–2.92 (m, 2H, CH_2), 3.37–3.51 (m, 2H, CH_2), 3.87 (s, 3H, OCH_3), 5.18–5.31 (m, 4H, 2 CH_2), 5.77–5.90 (m, 2H, 2 CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 9.07 (s, 3F, CF_3). ^{13}C NMR (75 MHz, $CDCl_3$) δ 33.8, 37.2, 52.7, 58.8 (q, J=26.3 Hz), 118.8, 119.7, 125.3 (q, J=282.6 Hz), 130.4, 131.8, 166.4.

*4.2.6. Diethyl [1-[allyl(methyl)amino]-1-(trifluoromethyl)but-3-ene-1-yl]phosphonate (**5c**).* Yield (0.37 g, 55%) as a colorless oil. [Found: C, 47.15; H, 6.90; N, 4.32. $C_{13}H_{23}F_3NO_3P$ requires C, 47.42; H, 7.04; N, 4.25%]. R_f (EtOAc/hexane=1/3) 0.37. IR (neat) ν_{max}=3084, 2987, 1643, 1463, 1447, 1257, 1167, 1055, 1028 cm^{-1}. ^1H NMR (300 MHz,

$CDCl_3$) δ 1.34 (t, 6H, $2CH_3$, J=7.1 Hz), 2.55 (s, 3H, NMe), 2.78–2.99 (m, 2H, CH_2), 3.38 (dd, 1H, CH_2, J=14.9, 6.0 Hz), 3.68 (dd, 1H, CH_2, J=14.9, 6.0 Hz), 4.17–4.34 (m, 4H, 2 OCH_2), 5.12–5.35 (m, 4H, $2CH_2$), 5.79–5.85 (m, 1H, CH), 5.96–6.06 (m, 1H, CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 14.71 (d 3F, CF_3, J=6.3 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 19.90 (s). ^{13}C NMR (75 MHz, $CDCl_3$) δ 16.1 (m), 34.4, 36.1, 55.6, 62.5 (dd, J=25.8, 7.7 Hz), 69.3 (dq, J=145.7, 23.0 Hz), 115.9, 117.8, 126.1 (qd, J=294.1, 13.7 Hz), 131.6 (d, J=6.6 Hz), 136.5.

*4.2.7. Diethyl[1-(allylthio)-1-(trifluoromethyl)but-3-en-1-yl]phosphonate (**5d**).* Yield (0.6 g, 89%) as a light-yellow oil. [Found: C, 43.41; H, 6.14; P, 9.10; F, 16.92. $C_{12}H_{20}F_3O_3PS$ requires C, 43.40; H, 6.02; P, 9.33; F, 17.15%]. R_f (EtOAc/hexane=1/10) 0.58. IR (neat) ν_{max}=3086, 2987, 1631, 1443, 1393, 1276, 1170, 1056, 1029 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.38–1.44 (m, 6H, $2CH_3$), 2.68–2.90 (m, 2H, CH_2), 3.59–3.65 (m, 1H, CH_2), 3.82–3.88 (m, 1H, CH_2), 4.23–4.40 (m, 4H, $2OCH_2$), 5.14–5.32 (m, 4H, $2CH_2$), 5.81–6.05 (m, 2H, 2 CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 14.87 (d, 3F, CF_3, J=3.8 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 16.58 (q, J=4.4 Hz). ^{13}C NMR (75 MHz, $CDCl_3$) δ 15.72 (m), 33.4, 35.7, 52.6 (dq, J=143.5, 25.7 Hz), 63.0 (d, J=7.1 Hz), 64.0 (d, J=7.1 Hz), 118.5, 118.7, 125.1 (qd, CF_3, J_{C-F}=283.7, 5.5 Hz), 130.4 (d, J=7.1 Hz), 131.7.

*4.2.8. Methyl 2-[methyl(prop-2-yn-1-yl)amino]-2-(trifluoromethyl) penta-3,4-dienoate (**6a**).* Yield (0.52 g, 71%) as a colorless oil. [Found: C, 53.59; H, 4.73; N, 5.50. $C_{11}H_{12}F_3NO_2$ requires C, 53.44; H, 4.89; N, 5.67%]. R_f (EtOAc/hexane=1/8) 0.35. IR (neat) ν_{max}=3310–3246 (br), 3072, 2938–2879 (br), 2125, 1954, 1757, 1639, 1453, 1181, 862 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.3 (t, 1H, $CH_{propargyl}$, J=2.5 Hz), 2.68–2.71 (m, 3H, NMe), 3.66 (d, 2H, CH_2, J=1.84 Hz), 3.86 (s, 3H, OCH_3), 5.08 (d, 2H, $CH_{2allene}$, J=6.8 Hz), 5.42 (t, 1H, CH_{allene}, J=6.8 Hz). ^{19}F NMR (282 MHz, $CDCl_3$) δ 10.16 (s, 3F, CF_3). ^{13}C NMR (75 MHz, $CDCl_3$) δ 37.2, 42.1 (d, J=1.9 Hz), 52.5, 72.0, 73.5 (q, J=25.3 Hz), 79.3, 80.3, 87.4, 124.5 (q, J=290.4 Hz), 167.0, 209.2.

*4.2.9. Methyl 2-(prop-2-yn-1-ylthio)-2-(trifluoromethyl)penta-3,4-dienoate (**6b**).* Yield (0.55 g, 74%) as a light-yellow oil. [Found: C, 48.13; H, 3.81. $C_{10}H_9F_3O_2S$ requires C, 48.00; H, 3.63%]. R_f (EtOAc/hexane=1/10) 0.59. IR (neat) ν_{max}=3313–3249 (br), 3069, 2938–2879 (br), 2123, 1956, 1754, 1632, 1453, 1337, 1176, 864 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.3 (t, 1H, $CH_{propargyl}$, J=2.7 Hz), 3.56 (d, 2H, CH_2, J=2.6 Hz), 3.90 (s, 3H, OCH_3), 5.16 (d, 2H, $CH_{2allene}$, J=6.8 Hz), 5.52 (t, 1H, CH_{allene}, J=6.8 Hz). ^{19}F NMR (282 MHz, $CDCl_3$) δ 8.67 (s, 3F, CF_3). ^{13}C NMR (75 MHz, $CDCl_3$) δ 19.3 (d, J=2 Hz), 53.3, 58.2 (q, J=25.5 Hz), 71.9, 78.9, 80.3, 85.6, 124.2 (q, J=283.1 Hz), 165.4, 209.3.

*4.2.10. Diethyl [1-[methyl(prop-2-yn-1-yl)amino]-1-(trifluoromethyl)buta-2,3-dien-1-yl] phosphonate (**6c**).* Yield (0.35 g, 54%) as a colorless oil. [Found: C, 48.34; H, 5.95; N, 4.58. $C_{13}H_{19}F_3NO_3P$ requires C, 48.00, H, 5.89; N, 4.31%]. R_f (EtOAc/hexane=1/3) 0.40. IR (neat) ν_{max}=3308–3252 (br), 3069, 2936–2880 (br), 2122, 1956, 1636, 1449, 1265, 1168, 1063, 1025, 864 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.35–1.52 (m, 6H, $2CH_3$), 2.24 (t, 1H, $CH_{propargyl}$, J=2.4 Hz), 2.85 (br s, 3H, NMe), 3.75 (d, 1H, CH_2, J=17.2 Hz), 4.05 (d, 1H, CH_2, J=17.2 Hz), 4.13–4.47 (m, 4H, $2OCH_2$), 5.04–5.12 (m, 2H, CH_2), 5.27–5.35 (m, 1H, CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 14.79 (d, 3F, CF_3, J=6.6 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 15.47 (q, J=6.6 Hz). ^{13}C NMR (75 MHz, $CDCl_3$) δ 16.5, 38.9, 41.5, 63.0, 63.2, 68.1 (dq, J=149.4, 24.3 Hz), 71.9, 78.6, 79.7, 86.2, 128.7 (dq, J=291.5, 14.8 Hz), 206.7.

*4.2.11. Diethyl [1-(prop-2-yn-1-ylthio)-1-(trifluoromethyl)buta-2,3-dien-1-yl]phosphonate (**6d**).* Yield (0.35 g, 60%) as a light-yellow oil. [Found: C, 44.12; H 4.73. $C_{12}H_{16}F_3O_3PS$ requires C, 43.90; H, 4.91%]. R_f (EtOAc/hexane=1/5) 0.43. IR (neat) ν_{max}=3312–3250 (br), 3071, 2937–2876 (br), 2124, 1957, 1631, 1445, 1272, 1176, 1064, 1035, 865. ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.39 (t, 6H, $2CH_3$, J=7.1 Hz), 2.30 (t, 1H, $CH_{propargyl}$, J=2.7 Hz), 3.69 (dd, 1H, CH_2, J=15.8, 2.6 Hz), 3.84 (dd, 1H, CH_2, J=15.8, 2.6 Hz), 4.24–4.43 (m, 4H, $2OCH_2$), 5.07–5.26 (m, 2H, CH_2), 5.43–5.57 (m, 1H, CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 12.56 (d, 3F, CF_3, J=3.7 Hz) ppm. ^{31}P NMR (121 MHz, $CDCl_3$) δ 13.20 (br s). ^{13}C NMR (75 MHz, $CDCl_3$) δ 15.8 (m), 19.0, 53.9 (dq, J=145.5, 27.6 Hz), 64.3 (d, J=7.5 Hz), 65.0 (d, J=7.2 Hz), 72.2, 78.1, 80.1, 84.2, 124.5 (qd, J=282.8, 3.5 Hz), 209.4 (d, J=9.8 Hz).

*4.2.12. Methyl 2-[methyl(prop-2-yn-1-yl)amino]-2-(trifluoromethyl) pent-4-enoate (**7a**).* Yield (0.47 g, 64%) as a colorless oil. [Found: C, 53.22; H, 5.81; N, 5.38. $C_{11}H_{14}F_3NO$ requires C, 53.01; H, 5.66; N, 5.62%]. R_f (EtOAc/hexane=1/8) 0.55. IR (neat) ν_{max}=3310, 3087, 2958–2826 (br), 2127, 1755, 1643, 1454, 1439, 1174 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.29 (t, 1H, $CH_{propargyl}$, J=2.3 Hz), 2.68 (s, 3H, NMe), 2.83 (d, 2H, CH_2, J=6.9 Hz), 3.69–3.44 (m, 2H, CH_2), 3.85 (s, 3H, OCH_3), 5.17–5.29 (m, 2H, CH_{2allyl}), 5.77–5.95 (m, 1H, CH_{allyl}). ^{19}F NMR (282 MHz, $CDCl_3$) δ 11.12 (s, 3F, CF_3). ^{13}C NMR (75 MHz, $CDCl_3$) δ 36.0, 36.3, 41.6, 52.3, 71.7, 72.5 (q, J=23.7 Hz), 79.9, 119.3, 125.7 (q, J=294.1 Hz), 130.6, 167.9.

*4.2.13. Diethyl [1-[methyl(prop-2-yn-1-yl)amino]-1-(trifluoromethyl)but-3-en-1-yl]phosphonate (**7b**).* Yield (0.36 g, 55%) as a colorless oil. [Found: C, 47.89; H, 6.54; N, 4.45. $C_{13}H_{21}F_3NO_3P$ requires C, 47.71; H, 6.47; N, 4.28%]. R_f (EtOAc/hexane=1/3) 0.3. IR (neat) ν_{max}=3312, 3083, 2988–2845 (br), 2124, 1643, 1452, 1435, 1269, 1172, 1043, 1027 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.27 (td, 6H, $2CH_3$, J=7.1, 2.4 Hz), 2.11 (t, 1H, $CH_{propargyl}$, J=2.4 Hz), 2.62 (s, 3H, NMe), 2.66–2.98 (m, 2H, CH_2), 3.48 (d, 1H, CH_2, J=17.1 Hz), 3.88 (d, 1H, CH_2, J=17.1 Hz), 4.01–4.25 (m, 4H, $2OCH_2$), 5.02–5.18 (m, 2H, CH_{2allyl}), 5.75–5.98 (m, 1H, CH_{allyl}). ^{19}F NMR (282 MHz, $CDCl_3$) δ 14.59 (d, 3F, CF_3, J=6.1 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 19.03 (br s). ^{13}C NMR (151 MHz, $CDCl_3$) δ 16.3, 34.5, 36.8 (d, J=5.5 Hz), 42.6, 62.7 (d, J=7.4 Hz), 63.4 (d, J=7.4 Hz), 68.6 (dq, J=152.7, 23.3 Hz), 71.2, 81.0, 118.4, 126.0 (qd, J=293.8, 13.6 Hz), 131.5 (d, J=6.1 Hz).

4.3. Procedure for trimethylsilylation of allylpropargylsulfide

Lithium hexamethyldisylaside (10.2 mmol, 10.2 mL of 1 M solution in THF) was added dropwise to a stirred solution of sulfide (1.03 g, 9.2 mmol) in 20 mL of dry diethyl ether at −78 °C. The reaction mixture was stirred for 2 h, then TMSCl (1.2 g, 11.1 mmol) was added dropwise over 20 min. The resulting mixture was allowed to warm up to room temperature and stirred for 1 h. The mixture was quenched with 5% solution of NH_4Cl (20 mL), extracted with diethyl ether (2×30 mL), and dried over $MgSO_4$. The solvent was removed under reduced pressure and the crude product was purified by vacuum distillation (bp=45–47 °C, 1 mmHg).

4.3.1. [3-(Allylthio)prop-1-yn-1-yl](trimethyl)silane. Yield: 1.4 g, 87%, as a colorless oil. [Found: C, 58.85; H, 8.86. $C_9H_{16}SSi$ requires C, 58.63; H, 8.75%]. IR (neat) ν_{max}=3084, 2963, 2175, 1635, 1408, 1253, 846, 639 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.23 (s, 9H, TMS), 3.26 (s, 2H, CH_2), 3.34 (d, 2H, CH_2, J=7.3 Hz), 5.13–5.29 (m, 2H, CH_{2allyl}), 5.72–5.91 (m, 1H, CH_{allyl}). ^{13}C NMR (75 MHz, $CDCl_3$) δ 0.2, 18.7, 33.5, 87.7, 101.3, 117.5, 132.8.

*4.3.2. Methyl 2-(trifluoromethyl)-2-{[3-(trimethylsilyl)prop-2-yn-1-yl]thio}pent-4-enoate (**9a**).* Yield (2.6 g, 68%) as a light-yellow oil. [Found: C, 48.32; H, 6.02. $C_{13}H_{19}F_3O_2SSi$ requires C, 48.13; H, 5.90%]. R_f (EtOAc/hexane=1/15) 0.6. IR (neat) ν_{max}=3088, 2962–2855 (br), 2180, 1748, 1643, 1439, 1360, 1254, 1127, 847 cm^{-1}. ^{1}H NMR (300 MHz, $CDCl_3$) δ 0.21 (s, 9H, TMS), 2.74–3.01 (m, 2H, CH_2), 3.52–3.69 (m, 2H, CH_2), 3.89 (s, 3H, OCH_3), 5.19–5.31 (m, 2H,

CH_{2allyl}), 5.73–5.97 (m, 1H, CH_{allyl}). ^{19}F NMR (282 MHz, $CDCl_3$) δ 10.06 (s, 3F, CF_3). ^{13}C NMR (75 MHz, $CDCl_3$) δ −0.4, 20.3 (q, J=2.5 Hz), 36.9, 53.1, 58.9 (q, J=26.5 Hz), 88.9, 99.5, 120.0, 125.2 (q, J=283.5 Hz), 130.3, 165.9.

*4.3.3. Diethyl (1-(trifluoromethyl)-1-{[3-(trimethylsilyl)prop-2-yn-1-yl]thio}but-3-en-1-yl)phosphonate (**9b**).* Yield (2.45 g, 75%) as a light-yellow oil. [Found: C, 44.89; H, 6.93. $C_{15}H_{26}F_3O_3PSSi$ requires C, 44.76; H, 6.51%]. R_f(EtOAc/hexane=1/3) 0.55. IR (neat) ν_{max}=3086, 2985–2914 (br), 2179, 1642, 1441, 1369, 1266, 1250, 1142, 1055, 1026, 848 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$) δ 0.19 (s, 9H, TMS), 1.28–1.51 (m, 6H, 2 CH_3), 2.68–2.99 (m, 2H, CH_2), 3.78 (d, 1H, CH_2, J=13.4 Hz), 4.09 (d, 1H, CH_2, J=13.4 Hz), 4.21–4.51 (m, 4H, $2OCH_2$), 5.16–5.33 (m, 2H, CH_{2allyl}), 5.93–6.11 (m, 1H, CH_{allyl}). ^{19}F NMR (282 MHz, $CDCl_3$) δ 14.92 (d, 3F, CF_3, J=3.4 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 15.09 (br s). ^{13}C NMR (75 MHz, $CDCl_3$) δ −0.5, 16.1 (dd, J=11.9, 5.4 Hz), 20.3, 35.9, 53.1 (dq, J=146.5, 25.7 Hz), 64.0 (dd, J=107.2, 7.0 Hz), 89.0, 99.7, 119.4, 125.2 (q, J=284.2 Hz), 130.4 (d, J=6.6 Hz).

*4.3.4. Diethyl [1-(allylthio)-1-(trifluoromethyl)buta-2,3-dien-1-yl] phosphonate (**8d**).* Yield (1.6 g, 60%) as a light-yellow oil. [Found: C, 43.46; H, 5.33. $C_{12}H_{18}F_3O_3PS$ requires C, 43.64; H, 5.49%]. R_f (EtOAc/hexane=1/3) 0.36. IR (neat) ν_{max}=3053, 2985, 1954, 1645, 1445, 1362, 1259, 1247, 1138, 1043, 1027, 863 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$) δ 1.42 (t, 6H, 2 CH_3, J=6.9 Hz), 3.52–3.76 (m, 2H, CH_{2allyl}), 4.23–4.44 (m, 4H, $2CH_2$), 5.10–5.35 (m, 4H, CH_{2allyl}+-$CH_{2allene}$), 5.50 (dd, 1H, CH_{allene}, J=14.6, 7 Hz), 5.78–6.00 (m, 1H, CH_{allyl}). ^{19}F NMR (282 MHz, $CDCl_3$) δ 12.60 (d, 3F, CF_3, J=4.1 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 13.54 (s). ^{13}C NMR (75 MHz, $CDCl_3$) δ 16.1 (dd, J=5.5, 3.4 Hz), 33.9, 53.8 (dq, J=145.2, 27.2 Hz), 64.8 (m), 79.8, 84.8, 118.9, 127.2 (q, J=246.8 Hz), 132.1, 209.5 (d, J=10.0 Hz).

4.4. Typical procedure for the removal of TMS-group

A solution of TBAF (4.4 mmol, 4.4 mL of 1 M solution in THF) was added dropwise to a solution of sulfide **9a** (1.29 g, 4 mmol) in a mixture (15 mL) of THF/H_2O (15:1). The resulting mixture was allowed to warm up to room temperature and stirred for additional 30 min. After addition of water (50 mL) the crude product was extracted with ether (2×50 mL), dried over $MgSO_4$, concentrated in vacuum, and purified by column chromatography on silica gel.

*4.4.1. Methyl 2-(prop-2-yn-1-ylthio)-2-(trifluoromethyl)pent-4-enoate (**7c**).* Yield (0.41 g, 55%) as a light-yellow oil. [Found: C, 47.71; H, 4.58. $C_{10}H_{11}F_3O_2S$ requires C, 47.62; H, 4.40%]. R_f (EtOAc/hexane=1/15) 0.36. IR (neat) ν_{max}=3310–3252 (br), 3080, 2985, 2124, 1755, 1645, 1445, 1392, 1169 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$) δ 2.31 (t, 1H, $CH_{propargyl}$, J=2.7 Hz), 2.77–2.97 (m, 2H, CH_2), 3.50–3.68 (m, 2H, CH_2), 3.91 (s, 3H, OCH_3), 5.17–5.37 (m, 2H, CH_{2allyl}), 5.75–5.93 (m, 1H, CH_{allyl}). ^{19}F NMR (282 MHz, $CDCl_3$) δ 10.06 (s, 3F, CF_3). ^{13}C NMR (75 MHz, $CDCl_3$) δ 19.0 (q, J=2.7 Hz), 36.9, 53.0, 58.6 (q, J=26.5 Hz), 71.8, 78.1, 120.1, 125.1 (q, J=283.4 Hz), 130.4, 165.9.

*4.4.2. Diethyl [1-(prop-2-yn-1-ylthio)-1-(trifluoromethyl)but-3-en-1-yl] phosphonate (**7d**).* Yield (0.26 g, 40%) as a light-yellow oil. [Found: C, 44.01; H, 5.11. $C_{12}H_{18}F_3O_3PS$ requires C, 43.64; H, 5.49%]. R_f (EtOAc/hexane=1/3) 0.3. IR (neat) ν_{max}=3315–3241 (br), 3091, 2993, 2126, 1642, 1440, 1395, 1265, 1173, 1054, 1027 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$) δ 1.37–1.50 (m, 6H, 2 CH_3), 2.30 (t, 1H, $CH_{propargyl}$, J=2.7 Hz), 2.64–2.98 (m, 2H, CH_2), 3.76 (dd, 1H, CH_2, J=15.5, 2.6 Hz), 4.06 (dd, 1H, CH_2, J=15.5, 2.6 Hz), 4.21–4.47 (m, 4H, $2OCH_2$), 5.18–5.31 (m, 2H, CH_{2allyl}), 5.90–6.09 (m, 1H, CH_{allyl}). ^{19}F NMR (282 MHz, $CDCl_3$) δ 14.93 (d, 3F, CF_3, J=4.3 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 19.03 (q, J=4.3 Hz). ^{13}C NMR (75 MHz, $CDCl_3$) δ 16.1 (dd, J=9.9, 5.8 Hz), 19.0, 35.8, 52.9 (dq, J=147.2, 26.5 Hz), 64.1 (dd, J=87.2, 7.4 Hz), 72.1, 78.1, 119.5, 125.2 (qd, J=283.9, 6.4 Hz), 130.2 (d, J=7.1 Hz).

4.5. Typical procedure for Rh-catalyzed cyclopropenation of allyl(propargyl) ethers

Diazocompound **1** (1.0 g, 5.9 mmol) was added dropwise to a solution of allylpropargylether (0.5 g, 5.3 mmol) and $Rh_2(OAc)_4$ (0.051 g, 0.12 mmol) in 20 mL of methylene chloride at room temperature. Nitrogen evolution started after the addition of one third of **1**. The reaction mixture was stirred for 1 h, then the solvent was removed under reduced pressure and the product was purified by column chromatography on silica gel (eluent: hexanes–ethyl acetate).

*4.5.1. Methyl 2-[(allyloxy)methyl]-1-(trifluoromethyl)cycloprop-2-ene-1-carboxylate (**10**).* Yield (0.32 g, 26%) as a colorless oil. [Found: C, 51.12; H, 4.52. $C_{10}H_{11}F_3O_3$ requires C, 50.85; H, 4.69%]. R_f (EtOAc/hexane=1/6) 0.45. IR (neat) ν_{max}=2982, 2123, 1747, 1660, 1648, 1444, 1172, 1130 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$) δ 3.80 (s, 3H, OCH_3), 4.13 (dd, 2H, CH_2, J=5.7, 1.3 Hz), 4.56 (d, 2H, CH_2, J=1.4 Hz), 5.23–5.43 (m, 2H, CH_2), 5.85–6.08 (m, 1H, CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 12.32 (s, 3F, CF_3). ^{13}C NMR (75 MHz, $CDCl_3$) δ 31.6 (q, J=36.9 Hz), 52.4, 61.8, 71.6, 95.0, 110.4, 118.1, 124.2 (q, J=276.0 Hz), 133.4.

*4.5.2. Methyl 2-[(prop-2-yn-1-yloxy)methyl]-1-(trifluoromethyl)cycloprop-2-ene-1-carboxylate (**11**).* Yield: 61% as a colorless oil. [Found: C, 51.47; H, 3.48. $C_{10}H_9F_3O_3$ requires C, 51.29; H, 3.87%]. R_f (EtOAc/hexane=1/3) 0.5. IR (neat) ν_{max}=3304, 2962, 2125, 1750, 1660, 1442, 1362, 1130 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$) δ 2.55 (t, 1H, $CH_{propargyl}$, J=2.4 Hz), 3.80 (s, 3H, OCH_3), 4.30 (d, 2H, CH_2, J=2.4 Hz), 4.67 (d, 2H, CH_2, J=1.5 Hz), 6.73 (q, 1H, CH, J=1.3 Hz). ^{19}F NMR (282 MHz, $CDCl_3$) δ 12.32 (s, 3F, CF_3). ^{13}C NMR (151 MHz, $CDCl_3$) δ 31.7 (q, J=36.7 Hz), 52.5, 57.8, 61.3, 75.7, 78.3, 95.8, 109.8, 124.2 (q, J=276 Hz), 169.5.

*4.5.3. Dimethyl 2,2′-[oxydi(methylene)]bis[1-(trifluoromethyl)cycloprop-2-ene-1-carboxylate] (**12**).* Yield: 8% as a colorless oil. [Found: C, 45.10; H, 3.34. $C_{14}H_{12}F_6O_5$ requires C, 44.93; H, 3.23%]. R_f (EtOAc/hexane=1/3) 0.28. IR (neat) ν_{max}=3310, 2968, 1753, 1662, 1445, 1167 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$) δ 3.82 (s, 6H, $2OCH_3$), 4.67 (d, 4H, $2CH_2$, J=1.5 Hz), 6.77 (s, 2H, 2CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 12.32 (s, 3F, CF_3). ^{13}C NMR (75 MHz, $CDCl_3$) δ 31.5 (q, J=36.8 Hz), 52.5, 62.5, 96.1, 109.5, 124.0 (q, J=276.1 Hz), 169.2.

4.6. Typical procedure for metathesis

To a solution of diolefin **5a** (0.25 g, 1 mmol) in anhydrous methylene chloride (5 mL) was added Grubbs II catalyst (0.038 g, 5 mol %) under an inert atmosphere at room temperature. The reaction mixture was stirred at room temperature until full completion (TLC, ^{19}F NMR-monitoring). The solvent was removed, and the crude product was purified by flash column chromatography on silica gel (eluent: hexanes–ethyl acetate).

*4.6.1. Methyl 1-methyl-2-(trifluoromethyl)-1,2,3,6-tetrahydropyridine-2-carboxylate (**13a**).* Yield (0.2 g, 91%) as a colorless oil. [Found: C, 48.61; H, 5.29; N, 6.10. $C_9H_{12}F_3NO_2$ requires C, 48.43; H, 5.42; N, 6.28%]. R_f (EtOAc/hexane=1/10) 0.31. IR (neat) ν_{max}=3049, 2960–2825 (br), 1748, 1681, 1463, 1440, 1156 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$) δ 2.55–2.68 (m, 1H, CH), 2.69 (s, 3H, NMe), 2.78–2.84 (m, 1H, CH), 3.40 (d, 1H, CH_2, J=17.5 Hz), 3.53 (d, 1H, CH_2, J=17.2 Hz), 3.84 (s, 3H, OCH_3), 5.69–5.79 (m, 2H, CH_2). ^{19}F NMR (282 MHz, $CDCl_3$) δ 8.64 (s, 3F, CF_3). ^{13}C NMR (75 MHz, $CDCl_3$) δ 29.8

(d, J=1.8 Hz), 39.5, 51.9, 52.3, 67.5 (q, J=18.8 Hz), 120.1, 124.7 (q, J=216.2 Hz), 125.2, 168.4.

*4.6.2. Methyl 2-(trifluoromethyl)-3,6-dihydro-2H-thiopiran-2-carboxylate (**13b**).* Yield (0.39 g, 88%) as a light-yellow oil. [Found: C, 42.20; H, 4.23. $C_8H_9F_3O_2S$ requires C, 42.48; H, 4.01%]. R_f (acetone/hexane=1/8) 0.56. IR (neat) ν_{max}=3039, 2960, 1750, 1692, 1438, 1361, 1189, 669 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$) δ 2.76 (d, 1H, CH_2, J=18.2 Hz), 2.97 (d, 1H, CH_2, J=17.6 Hz), 3.27–3.40 (m, 2H, CH_2), 3.89 (s, 3H, OCH_3), 5.92–6.02 (m, 2H, CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 6.92 (s, 3F, CF_3). ^{13}C NMR (75 MHz, $CDCl_3$) δ 25.3, 27.9, 51.4, 54.4 (q, J=27.8 Hz), 122.9, 124.9 (q, J=283.5 Hz), 124.9, 167.2.

*4.6.3. Diethyl [1-methyl-2-(trifluoromethyl)-1,2,3,6-tetrahydropyridine-2-yl] phosphonate (**13c**).* Yield (0.38 g, 83%) as a colorless oil. [Found: C, 44.01; H, 6.23; N, 5.01. $C_{11}H_{19}F_3NO_3P$ requires C, 43.86; H, 6.36; N, 4.65%]. R_f (EtOAc/hexane=1/1) 0.31. IR (neat) ν_{max}=3048, 2990–2935 (br), 1733, 1443, 1369, 1262, 1162, 1060, 1027 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$) δ 1.34–1.39 (m, 6H, $2CH_3$), 2.43–2.54 (m, 1H, CH), 2.68–2.79 (m, 1H, CH), 2.83 (s, 3H, NMe), 3.27 (d, 1H, CH_2, J=17.2 Hz), 3.39 (d, 1H, CH_2, J=17.2 Hz), 4.12–4.34 (m, 4H, $2OCH_2$), 5.67–5.78 (m, 2H, CH_2). ^{19}F NMR (282 MHz, $CDCl_3$) δ 12.59 (d, 3F, CF_3, J=7 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 20.37 (q, J=7 Hz). ^{13}C NMR (75 MHz, $CDCl_3$) δ 16.2, 28.5, 41.2, 51.5 (d, J=8.2 Hz), 62.9 (dd, J=29.6, 8.2 Hz), 65.4, 120.1 (d, J=6 Hz), 124.6, 126.4 (qd, J=309.5, 4.7 Hz).

*4.6.4. Diethyl [2-(trifluoromethyl)-3,6-dihydro-2H-thiopyran-2-yl] phosphonate (**13d**).* Yield (0.39 g, 86%) as a light-yellow oil. [Found: C, 39.55; H, 5.11. $C_{10}H_{16}F_3O_3PS$ requires C, 39.48; H, 5.30%]. R_f (EtOAc/hexane=1/1) 0.38. IR (neat) ν_{max}=3425–3355, 2991, 1680, 1416, 1270, 1170, 1035, 641 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$) δ 1.36–1.41 (m, 6H, CH_3), 2.65–2.73 (m, 1H, CH_2), 2.84–2.94 (m, 1H, CH_2), 3.18–3.34 (m, 2H, SCH_2), 4.21–4.33 (m, 4H, $2OCH_2$), 5.91–5.93 (m, 1H, CH), 6.06–6.09 (m, 1H, CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 10.58 (d, 3F, CF_3, J=5.1 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 17.17 (q, J=5.5 Hz). ^{13}C NMR (75 MHz, $CDCl_3$) δ 16.1 (d, J=5.7 Hz), 24.3 (d, J=3.5 Hz), 25.1, 64.3 (dd, J=23.8 Hz, 7.5 Hz), 64.8–65.3 (m), 124.2, 124.8, 125.1 (dq, J=283.7, 4.8 Hz).

4.7. General procedure for Pauson–Khand reaction

A solution of the corresponding enyne or allenyne (1.99 mmol) in dichloromethane (10 mL) was added dropwise to a stirred solution of $Co_2(CO)_8$ (0.81 g, 2.30 mmol) in dry dichloromethane (100 mL) at room temperature under argon atmosphere. After stirring at room temperature for 2 h, solid *N*-methylmorpholine *N*-oxide (2.33 g, 19.9 mmol) was added in one portion. The reaction mixture was stirred overnight at room temperature to form a violet Co-precipitate. After filtration through a short pad with SiO_2, the solvent was removed under reduced pressure and the crude product was purified via column chromatography (ethyl acetate–hexanes) to give pure compound.

*4.7.1. Methyl 2-methyl-6-oxo-3-(trifluoromethyl)-2,3,5,6-tetrahydro-1H-cyclopenta[c]pyridine-3-carboxylate (**14a**).* Yield (0.29 g, 52%) as a colorless oil. [Found: C, 52.64; H, 4.77; N, 4.81. $C_{12}H_{12}F_3NO_3$ requires C, 52.37; H, 4.39; N, 5.09%]. R_f (EtOAc/hexane=1/1) 0.6. IR (neat) ν_{max}=2863, 1747, 1714, 1639, 1464, 1169 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$) δ 2.63 (q, 3H, NMe, J=1.5 Hz), 3.04 (s, 2H, CH_2), 3.86 (s, 3H, OCH_3), 3.94–4.14 (m, 2H, CH_2), 5.90 (s, 1H, CH), 6.10 (q, 1H, CH, J=1.6 Hz). ^{19}F NMR (282 MHz, $CDCl_3$) δ 10.78 (s, 3F, CF_3). ^{13}C NMR (75 MHz, $CDCl_3$) δ 37.6, 40.0 (q, J=1.7 Hz), 49.5, 52.2, 69.4 (q, J=25.5 Hz), 116.4 (d, J=2.1 Hz), 124.8 (q, J=292.3 Hz), 128.5, 139.2, 163.3, 167.0, 202.9.

*4.7.2. Methyl 6-oxo-3-(trifluoromethyl)-1,3,5,6-tetrahydrocyclopenta[c] thiopyran-3-carboxylate (**14b**).* Yield (0.03 g, 5%) as a light-yellow unstable oil. R_f (EtOAc/hexane=1/3) 0.27. ^1H NMR (300 MHz, $CDCl_3$) δ 3.18 (s, 2H, CH_2), 3.80 (d, 1H, CH_2, J=16.8 Hz), 3.94 (s, 3H, OCH_3), 4.10 (d, 1H, CH_2, J=16.8 Hz), 6.27 (s, 1H, CH), 6.32 (s, 1H, CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 8.28 (s, 3F, CF_3).

*4.7.3. Diethyl [2-methyl-6-oxo-3-(trifluoromethyl)-2,3,5,6-tetrahydro-1H-cyclopenta[c]pyridin-3-yl]phosphonate (**14c**).* Yield (0.26 g, 48%) as a colorless oil. [Found: C, 47.35; H, 5.52; N, 4.12. $C_{14}H_{19}F_3NO_4P$ requires C, 47.60; H, 5.42; N, 3.96%]. R_f (EtOAc/hexane=1/1) 0.22. IR (neat) ν_{max}=2861, 1712, 1632, 1443, 1259, 1179, 1050, 1035 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$) δ 1.29–1.44 (m, 6H, 2 CH_3), 2.97 (s, 3H, NMe), 3.07–3.15 (m, 2H, CH_2), 3.93 (d, 1H, CH_2, J=17.1 Hz), 4.06 (d, 1H, CH_2, J=17.1 Hz), 4.13–4.36 (m, 4H, 2 CH_2), 6.06 (d, 1H, CH, J=6.1 Hz), 6.08–6.15 (m, 1H, CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 13.28 (d, 3F, CF_3, J=6.5 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 14.84 (q, J=6.5 Hz). ^{13}C NMR (75 MHz, $CDCl_3$) δ 16.4, 37.9, 41.3, 50.3 (d, J=7.8 Hz), 63.4 (d, J=7.6 Hz), 64.5 (d, J=7.3 Hz), 65.9 (dq, J=154.1, 25.4 Hz), 116.8 (m), 125.0 (qd, J=292.4, 11.9 Hz), 127.8 (d, J=1.8 Hz), 138.0 (d, J=9.5 Hz), 163.7 (d, J=3.2 Hz), 203.3.

*4.7.4. Diethyl [6-oxo-3-(trifluoromethyl)-1,3,5,6-tetrahydrocyclopenta[c] thiopyran-3-yl]phosphonate (**14d**).* Yield (0.24 g, 45%) as a light-yellow oil. [Found: C, 44.03; H, 4.88. $C_{13}H_{16}F_3O_4PS$ requires C, 43.82; H, 4.53%]. R_f (EtOAc/hexane=1/1) 0.36. IR (neat) ν_{max}=2864, 1715, 1626, 1445, 1325, 1246, 1163, 1045, 1032 cm^{-1}. ^1H NMR (300 MHz, $CDCl_3$) δ 1.37–1.48 (m, 6H, 2 CH_3), 3.07 (s, 2H, CH_2), 3.55 (d, 2H, CH_2, J=10.2 Hz), 4.22–4.46 (m, 4H, $2OCH_2$), 6.15 (q, 1H, CH, J=1.3 Hz), 6.26 (s, 1H, CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 9.76 (d, 3F, CF_3, J=5.1 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 14.41 (q, J=5.1 Hz). ^{13}C NMR (75 MHz, $CDCl_3$) δ 16.4 (m), 27.8, 39.5, 50.2 (dq, J=144.9, 27.7 Hz), 65.0 (m), 144.5 (d, J=4.9 Hz), 125.1 (q, J=284.6 Hz), 130.3, 130.5, 160.5 (d, J=9.1 Hz), 202.9.

*4.7.5. Methyl 2-methyl-6-oxo-3-(trifluoromethyl)-2,3,4,4a,5,6-hexahydro-1H-cyclopenta[c]-pyridine-3-carboxylate (**15a**).* Yield (0.37 g, 68%) as a white solid, mp=51–53 °C; (*syn*/*anti* ratio=83/17 determined by ^{19}F NMR). Diastereomers were separated by column chromatography (ethyl acetate–hexanes: 2/1). [Found: C, 51.75; H, 5.21; N, 5.33. $C_{12}H_{14}F_3NO_3$ requires C, 51.99; H, 5.09; N, 5.05%]. IR (neat) ν_{max}=2961, 2859, 1749, 1711, 1638, 1465, 1378, 1164 cm^{-1}. *syn*-isomer (major): R_f (EtOAc/hexane=1/1) 0.5. ^1H NMR (300 MHz, $CDCl_3$) δ 1.63 (t, 1H, CH_2, J=13.1 Hz), 2.01 (d, 1H, CH_2, J=18.7 Hz), 2.55–2.69 (m, 5H, NMe+CH_2), 2.71–2.82 (m, 1H, CH), 3.79 (d, 1H, CH_2, J=14.6 Hz), 3.85 (s, 3H, OCH_3), 3.93 (d, 1H, CH_2, J=14.6 Hz), 5.94 (s, 1H, CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 8.59 (s, 3F, CF_3). ^{13}C NMR (151 MHz, $CDCl_3$) δ 35.4, 35.9 (q, J=2.2 Hz), 40.2 (q, J=2.2 Hz), 41.0, 52.8, 53.1, 69.6 (q, J=25.8 Hz), 124.3 (q, J=287.3 Hz), 127.5, 168.1, 174.9, 206.9. *anti*-isomer (minor): R_f (EtOAc/hexane=1/1) 0.4. ^1H NMR (300 MHz, $CDCl_3$) δ 1.66 (t, 1H, CH_2, J=13.6 Hz), 1.93 (d, 1H, CH_2, J=18.7 Hz), 2.54 (s, 3H, NMe), 2.58–2.67 (m, 2H, CH_2), 2.97–3.06 (m, 1H, CH), 3.74 (d, 1H, CH_2, J=14.8 Hz), 3.79 (s, 3H, OCH_3), 3.90 (d, 1H, CH_2, J=14.8 Hz), 5.96 (s, 1H, CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 15.52 (s, 3F, CF_3). ^{13}C NMR (151 MHz, $CDCl_3$) δ 34.5, 36.6, 40.7, 41.2, 52.0, 53.2, 69.2 (q, J=23.8 Hz), 126.6 (q, J=296.5 Hz), 128.0, 168.7, 174.4, 206.7.

*4.7.6. Methyl 6-oxo-3-(trifluoromethyl)-1,3,4,4a,5,6-hexahydrocyclopenta[c] thiopyran-3-carboxylate (**15b**).* Yield (0.17 g, 40%) as a light-yellow oil; (*syn*/*anti* ratio=62/38 determined by ^{19}F NMR). [Found: C, 47.31; H, 3.76. $C_{11}H_{11}F_3O_3S$ requires C, 47.14; H, 3.96%]. IR (neat) ν_{max}=2953, 2869, 1753, 1715, 1629, 1445, 1325, 1171 cm^{-1}. *syn*-isomer: R_f (EtOAc/hexane=1/3) 0.4. ^1H NMR (300 MHz, $CDCl_3$) δ 1.95–2.21 (m, 2H, CH_2), 2.76 (dd, 1H, CH_2, J=18.9, 6.7 Hz), 2.98 (dd,

1H, CH_2, J=13.1, 5.2 Hz), 3.08–3.25 (m, 1H, CH), 3.69 (d, 1H, CH_2, J=14.1 Hz), 3.83 (d, 1H, CH_2, J=14.1 Hz), 3.98 (s, 3H, OCH_3), 6.08 (s, 1H, CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 6.87 (s, 3F, CF_3). ^{13}C NMR (151 MHz, $CDCl_3$) δ 28.4, 36.6, 38.6, 42.2, 54.1, 57.4 (q, J=26.9 Hz), 123.8 (q, J=283.8 Hz), 128.5, 167.0, 172.5, 206.0. *anti*-isomer: R_f (EtOAc/hexane=1/3) 0.25. ^{1}H NMR (300 MHz, $CDCl_3$) δ 1.94–2.18 (m, 2H, CH_2), 2.74 (dd, 1H, CH_2, J=18.9, 6.3 Hz), 3.01–3.17 (m, 2H, CH_2+CH), 3.55 (d, 1H, CH_2, J=13.8 Hz), 3.85 (s, 3H, OCH_3), 3.98 (d, 1H, CH_2, J=13.8 Hz), 6.08 (s, 1H, CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 10.89 (s, 3F, CF_3). ^{13}C NMR (151 MHz, $CDCl_3$) δ 28.8, 36.1, 39.7, 42.4, 54.2, 56.0 (q, J=27.9 Hz), 126.1 (q, J=285.4 Hz), 128.9, 166.1, 172.5, 206.0.

*4.7.7. Diethyl [2-methyl-6-oxo-3-(trifluoromethyl)-2,3,4,4a,5,6-hexahydro-1H-cyclopenta[c]-pyridin-3-yl]phosphonate (**15c**).* Yield (0.57 g, 81%) as a colorless oil; (*syn*/*anti* ratio=35/65 determined by ^{19}F NMR and 2D NOESY see Supplementary data). [Found: C, 47.02; H, 6.11; N, 4.21. $C_{14}H_{21}F_3NO_4P$ requires C, 47.33; H, 5.96; N, 3.94%]. R_f (EtOAc/hexane=1/1) 0.3. IR (neat) ν_{max}=2945, 2874, 1711, 1625, 1448, 1259, 1169, 1048, 1027 cm^{-1}. *syn*-isomer: ^{1}H NMR (600 MHz, $CDCl_3$) δ 1.29–1.33 (m, 6H, 2 CH_3), 1.48–1.60 (m, 1H, CH_2), 1.9 (dd, 1H, CH_2, J=18.5, 2.7 Hz), 2.53–2.59 (m, 2H, CH_2), 2.73 (s, 3H, NMe), 3.26–3.35 (m, 1H, CH), 3.81 (d, 1H, CH_2, J=16.8 Hz), 3.90 (d, 1H, CH_2, J=16.8 Hz), 4.06–4.26 (m, 4H, $2OCH_2$), 5.82 (s, 1H, CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 10.83 (d, 3F, CF_3, J=3.9 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 19.39 (q, J=8.3 Hz). ^{13}C NMR (151 MHz, $CDCl_3$) δ 16.3 (m), 33.8, 34.5, 41.0, 41.9, 53.3, 62.7 (d, J=7.5 Hz), 63.5 (d, J=7.5 Hz), 124.0 (dq, J=144.9, 24.1 Hz), 125.9, 126.0 (m), 177.8, 207.0. *anti*-isomer: ^{1}H NMR (600 MHz, $CDCl_3$) δ 1.23–1.28 (m, 6H, 2 CH_3), 1.70–1.80 (m, 1H, CH_2), 1.91 (dd, 1H, CH_2, J=18.7, 2.5 Hz), 2.53–2.66 (m, 2H, CH_2), 2.83 (s, 3H, NMe), 2.92–3.00 (m, 1H, CH), 3.61 (d, 1H, CH_2, J=15.3 Hz), 3.81 (d, 1H, CH_2, J=15.3 Hz), 4.06–4.26 (m, 4H, $2OCH_2$), 5.85 (s, 1H, CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 16.61 (d, 3F, CF_3, J=10.6 Hz). ^{31}P NMR (121 MHz, $CDCl_3$) δ 17.83 (s). ^{13}C NMR (151 MHz, $CDCl_3$) δ 16.3 (m), 34.4, 34.7, 41.1, 41.4, 53.3, 62.9 (d, J=7.5 Hz), 64.1 (d, J=7.5 Hz), 124.0 (dq, J=144.9, 24.1 Hz), 125.9, 126.1 (m), 176.1, 207.1.

*4.7.8. Diethyl [6-oxo-3-(trifluoromethyl)-1,3,4,4a,5,6-hexahydrocyclopenta[c] thiopyran-3-yl]phosphonate (**15d**).* Yield (0.32 g, 59%) as a light-yellow oil; (*syn*/*anti* ratio=75/25 determined by ^{19}F NMR and 2D NOESY see Supplementary data). [Found: C, 43.98; H 5.25. $C_{13}H_{18}F_3O_4PS$ requires C, 43.58; H, 5.06%]. R_f (EtOAc/hexane=2/1) 0.33. IR (neat) ν_{max}=2955, 2864, 1714, 1627, 1441, 1255, 1173, 1050, 1025 cm^{-1}. *syn*-isomer: ^{1}H NMR (600 MHz, $CDCl_3$) δ 1.27 (td, 6H, $2CH_3$, J=7.1, 3.2 Hz), 1.99–1.85 (m, 1H, CH_2), 2.03–2.17 (m, 1H, CH_2), 2.59 (dd, 1H, CH_2, J=18.9, 6.7 Hz), 2.74–2.80 (m, 1H, CH_2), 2.87–3.00 (m, 1H, CH), 3.49 (d, 1H, CH_2, J=13.7 Hz), 3.87 (d, 1H, CH_2, J=13.7 Hz), 4.09–4.22 (m, 4H, $2OCH_2$), 5.97 (s, 1H, CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 14.47 (d, 3F, CF_3, J=8.5 Hz) ppm. ^{31}P NMR (121 MHz, $CDCl_3$) δ=15.04 (q, J=8.3 Hz). ^{13}C NMR (151 MHz, $CDCl_3$) δ 16.2 (m), 28.7 (d, J=6.1 Hz), 35.4 (d, J=11 Hz), 37.1 (d, J=4.2 Hz), 42.2, 50.7 (dq, J=144.9, 27.3 Hz), 64.7 (d, J=7.4 Hz), 64.8 (d, J=7.4 Hz), 124.0 (q, J=284.1 Hz), 129.0, 172.8, 205.9. *anti*-isomer: ^{1}H NMR (600 MHz, $CDCl_3$) δ 1.28–1.35 (m, 6H, 2 CH_3), 1.79 (t, 1H, CH_2, J=13.3 Hz), 1.85–1.99 (m, 1H, CH_2), 2.59 (dd, 1H, CH_2, J=18.9, 6.7 Hz), 2.67–2.76 (m, 1H, CH_2), 3.30–3.41 (m, 1H, CH), 3.47 (d, 1H, CH_2, J=13.5 Hz), 4.22–4.09 (m, 2H, OCH_2), 4.27–4.43 (m, 2H, OCH_2), 4.49 (d, 1H, CH_2, J=13.5 Hz), 5.95 (s, 1H, CH). ^{19}F NMR (282 MHz, $CDCl_3$) δ 9.12 (s, 3F, CF_3). ^{31}P NMR (121 MHz, $CDCl_3$) δ 15.37 (s). ^{13}C NMR (151 MHz, $CDCl_3$) δ=16.3 (m), 28.3, 35.6, 37.2, 42.1, 49.9 (dq, J=144.9, 26.3 Hz), 63.4 (d, J=8.1 Hz), 66.2 (d, J=8.1 Hz), 124.4 (q, J=282.8 Hz), 128.5, 173.7, 206.2.

Crystallographic data for the structure **15a** in this paper have been deposited with the Cambridge Crystallographic Data Center as supplementary publication No CCDC-794426. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK, (fax: +44-(0)1223-336033 or e-mail: deposit@ccdc.cam.ac.Uk).

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Supplementary data

The copies of NMR spectra for compounds **5**–**15** are included in the Supplementary data that can be found. Supplementary data related to this article can be found online at doi:10.1016/j.tet.2011.03.031. These data include MOL files and InChiKeys of the most important compounds described in this article.

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