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Article

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Four-step access to the sesquiterpene natural product presilphiperfolan-1β-ol and unnatural derivatives via supramolecular catalysis

Leonidas-Dimitrios Syntrivanis,[†] Ivana Némethová,[†] Dario Schmid,[†] Shani Levi,[§] Alessandro Prescimone,[†] Fabian Bissegger,[†] Dan T. Major,[§] Konrad Tiefenbacher*[,†,‡]

[†] Department of Chemistry, University of Basel, Mattenstrasse 24a, 4058 Basel, Switzerland

[‡] Department of Biosystems Science and Engineering, ETH Zurich, Mattenstrasse 24, 4058 Basel, Switzerland

[§] Department of Chemistry, Bar-Ilan University, Ramat-Gan 52900, Israel

Supporting Information Placeholder

ABSTRACT: Terpenes constitute one of the most structurally varied classes of natural products. A wide range of these structures are produced in nature by type I terpene cyclase enzymes from one single substrate. However, such reactivity has proven difficult to reproduce in solution with man-made systems. Herein we report the shortest synthesis of the tricyclic sesquiterpene presilphiperfolan-1β-ol to date, utilizing the supramolecular resorcinarene capsule as catalyst for the key step. This synthetic approach also allows access to unnatural derivatives of the natural product, which would not be accessible through the biosynthetic machinery. Additionally, this study provides useful insight into the biosynthesis of the presilphiperfolanol natural products, including the first experimental evidence consistent with the proposed biosynthetic connection between caryophyllene and the presilphiperfolanols.

INTRODUCTION

The tail-to-head terpene (THT) cyclization is one of the most complex reactions observed in nature, giving rise to a vast amount of complex terpene structures starting from a handful of linear precursors.[1] Despite its great synthetic potential, the THT cyclization has proven very difficult to reproduce in solution, as premature quenching of reactive intermediates, for instance by the cleaved leaving group, gives rise to complex mixtures mainly favoring monocyclic products.[2] The Shenvi group succeeded in forming a few polycyclic sesquiterpene structures by covalently linking the leaving group to the molecule.[3] Our group employed a different approach, by using the hexameric resorcinarene capsule **I**,[4,5] formed from the assembly of monomers **1**, as a reaction chamber (Figure 1a). This supramolecular container is able to catalyse the THT cyclization, likely via the stabilization of cationic transition states within its cavity.[6] We also demonstrated that the limited selectivity encountered in the capsule-catalysed cyclizations of linear sesquiterpene precursors could be overcome through the use of a conformationally restricted substrate, in this way achieving the selective preparation of the natural product isolongifolene.[7] However, isolongifolene is a commercially available compound, and it is not known to possess any biological activity. Identifying capsule-catalyzed cyclizations that lead to complex, biologically active terpenes, hard to synthesize by other means, would be highly desirable and showcase the applicability of supramolecular catalysis.

Cyclase enzymes exercise control over the terpene cyclization pathway via their cavity shape, which facilitates specific substrate folding,[8] as well as via specific interactions with active site amino acid residues and cofactors.[9] However, as recently argued by Tantillo,[10] evidence from gas-phase computational studies indicates that not every step is enzyme catalysed, as the intrinsic gas-phase reactivity of the cation itself can dictate the reaction outcome in some cases. We recognized that the resorcinarene capsule **I** could be utilized to exploit this inherent reactivity: identifying a key cationic intermediate and generating it within its confines should enable the downstream reactions, while preventing premature quenching of the reactive intermediates. To probe this possibility in practice, we chose to investigate the postulated biosynthetic connection between caryophyllene and the presilphiperfolanol family of natural products.[11] Three members of this family have been isolated to date: (−)-presilphiperfolan-9α-ol [(−)-**2**],[12] (−)-presilphiperfolan-8α-ol [(−)-**3**],[13] and (−)-presilphiperfolan-1β-ol [(−)-**4**] (Figure 1 b).[14,15] These natural products hold significant importance in the study of terpene biosynthesis, as their strained framework[16] is believed to represent a branching point that links together a number of different biosynthetic pathways.[11] They also exhibit interesting biological activities like antimycobacterial and insect antifeedant properties.[17,18] Their complex tricyclic skeleton has proven to be a challenging target for total synthesis; hitherto reported total syntheses of the presilphiperfolanols have required 13-17 linear steps from commercially available materials.[15,19,20]

The current proposal for the presilphiperfolanol biosynthesis (Figure 1b)[21,22] posits that the initial cyclization of farnesyl pyrophosphate, according to density functional theory (DFT) calculations via its allylic isomer nerolidyl pyrophosphate,[23] leads to the humulenyl cation **5**. After cyclization to the caryophyllenyl cation **6**, a concerted 1,2-alkyl shift/cyclization cascade leads to structure **8**, the direct precursor to presilphiperfolan-9α-ol (**2**). From here, isotopic labelling[22] and computational studies[23] support a 1,3-hydride shift (path a, red) as the path that leads to cation **11**; capture of this intermediate by water leads to presilphiperfolan-8α-ol (**3**), while further rearrangements are believed to generate a number of other sesquiterpene classes.[13,21,24] The reassignment of

the C9 methyl configuration by Stoltz et al.[15] allowed an alternative 1,2-hydride shift (path b, blue) to be proposed as the pathway that leads to presilphiperfolan-1β-ol (**4**), however so far no further evidence to support this has appeared in the literature.

The proposed intermediacy of the caryophyllenyl cation **6**[24c,25] in the biosynthesis of the presilphiperfolanols has led to a number of studies aimed at their biomimetic synthesis from caryophyllene and related compounds in solution; however no such approach has so far provided a natural presilphiperfolanol. Coates et al. carried out solvolysis studies of caryophyllenyl alcohol derivatives.[26] These were only successful when performed on the simplified system **12** (Scheme 1a) lacking the methyl group present on C4 of the natural product. The main product formed was compound **13**, a derivative of presilphiperfolan-9α-ol (**2**). When the solvolysis was attempted on derivatized caryophyllenyl alcohol **14**, the main product (caryophyllene, **15**), resulted from a simple elimination, while no presilphiperfolanol structures were formed. Acidic treatment of caryophyllene (**15**) itself has been shown to lead to unrelated compounds.[27] For instance, treatment with sulphuric acid furnished β-caryolanol (**16**) as the main product (Scheme 1b).[27g] Rearrangement of isocaryophyllene (**17**), containing a *Z*-alkene instead of the *E*-isomer, in acidic media has also been studied and has only led to stereochemical isomers of the presilphiperfolanol skeleton. Specifically, Robertson and coworkers reported the formation of compound **18** in 35% yield as part of a mixture of products by using sulfuric acid in diethyl ether (Scheme 1c); this compound bears the opposite configuration on C1 to that observed in the natural products.[28] Collado et al. improved the yield to 60% by employing $FeCl_3/SiO_2$ instead.[29] Khomenko and coworkers reported the formation of alcohol **19**, bearing the opposite configuration on C9 to that observed in the natural product, in 16% yield by using superacid conditions (Scheme 1d).[30]

With this context in mind, we theorized that generation of the caryophyllenyl cation **6** within the stabilizing environment of the resorcinarene capsule may allow the reproduction of the so far elusive natural cyclization cascade in a non-enzymatic setting. However, the exact reaction product was not predictable at the outset. This supramolecular approach led to several important results, which are all reported in this article: (1) The shortest synthesis of the sesquiterpene natural product presilphiperfolan-1β-ol (**4**) to date (four steps), (2) the isolation and identification of a novel hydrocarbon skeleton, (3) the facile access to presilphiperfolan-1β-ol derivatives not available via the biomachinery.

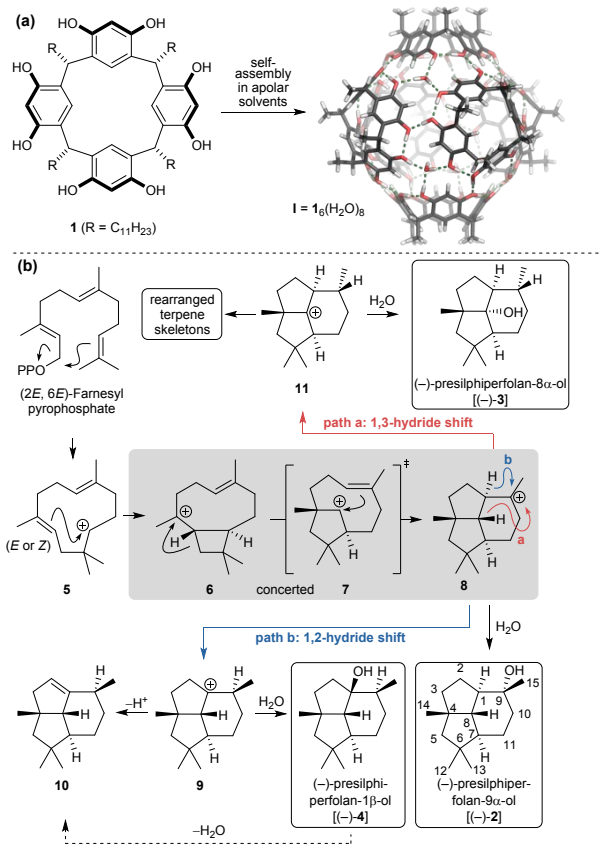
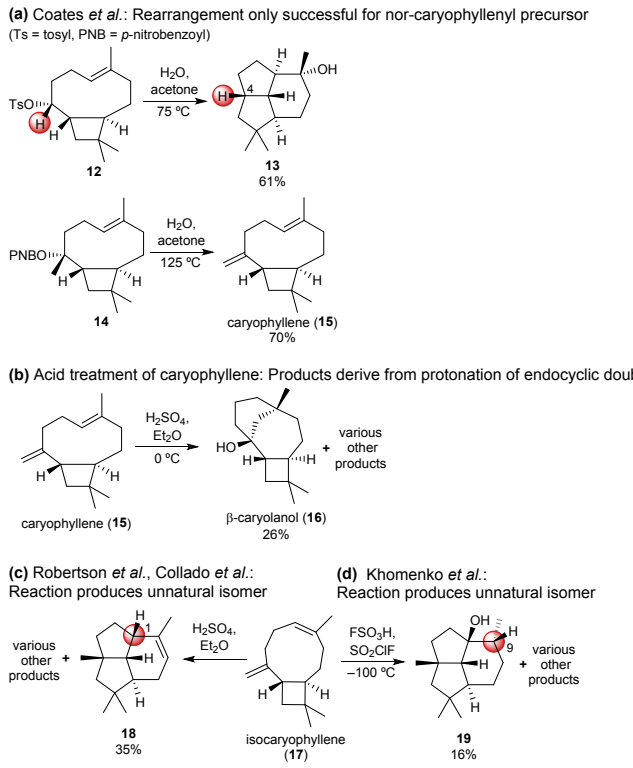


Figure 1. a. Self-assembly of monomer **1** into hexameric capsule **I**; b. Proposed biosynthesis of the presilphiperfolanol family of natural products.

Scheme 1. Overview of the literature on attempted biomimetic synthesis of the presilphiperfolanol framework from caryophyllene or its derivatives.

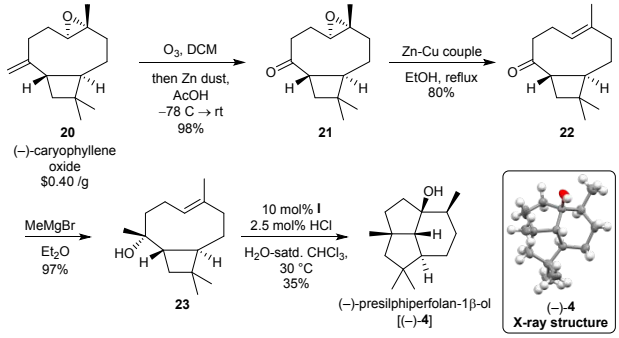


RESULTS AND DISCUSSION

Initial cyclization studies

Alcohol **23** (Scheme 2) was chosen as the substrate for our experiments. This was prepared in three steps from inexpensive ($0.4 /g)[31] commercially available (−)-caryophyllene oxide (**20**) following literature procedures;[26] multigram quantities of this alcohol can be readily accessed. In a first experiment, **23** was subjected to reaction with 10 mol% of capsule **I** and 3 mol% of HCl in $CDCl_3$, conditions previously identified by us as optimal for the capsule-catalyzed THT cyclization of sesquiterpenes.[6a-d] Gratifyingly the formation of presilphiperfolan-1β-ol (**4**) as a major product (13% GC yield after 4 days) was observed, along with rearranged alkene **26** (11% GC yield, Figure 2a). The latter is presumably formed through a 1,3-hydride shift of cation **9** (Figure 2c), followed by a methyl shift and elimination. To confirm the structure of the rearranged alkene **26**, a sample isolated after preparative scale reaction (see SI) was subjected to allylic oxidation; further oxidation to the aldehyde and formation of the corresponding semicarbazone gave a crystalline derivative **28**, which provided further proof of the compound's structure via X-ray crystallography (Figure 2c). Interestingly, this compound presents, to our knowledge, a novel hydrocarbon skeleton. It remains to be seen if it also occurs in nature. Other components of the reaction mixture were identified as elimination product **10** and caryophyllene (**15**), the latter presumably deriving from dehydration of the starting material.

Scheme 2. Synthesis of (−)-presilphiperfolan-1β-ol utilizing the capsule-catalysed cyclization cascade as the key step.



Optimization of the reaction conditions

We next sought to identify optimal conditions for the formation of presilphiperfolan-1β-ol (**4**) and its derivatives. Pleasingly, it was found that carrying out the reaction in H_2O-saturated $CDCl_3$ slowed down the formation of rearranged alkene **26**, while at the same time increasing the yield of desired presilphiperfolan-1β-ol (**4**) to synthetically very useful 42% (Figure 2b). The reaction rate was slower than with untreated $CDCl_3$, with conversion reaching a plateau at ~85%; addition of further HCl at this point was ineffective as it increased the rate of formation of rearranged alkene **26**. Carrying out the reaction with higher amounts of HCl favoured formation of the rearranged alkene **26** and of caryophyllene (**15**). Aromatic media (benzene and toluene) were also assayed but proved inferior to $CDCl_3$. Interestingly when H_2O-saturated DCM was used, the main byproduct observed was the elimination product **10**; only traces of rearrangement product **26** were formed, while the yield of presilphiperfolan-1β-ol was comparable to that observed in the reaction in $CDCl_3$. Under these conditions, prolonging the reaction time eventually led to complete conversion of presilphiperfolan-1β-ol into elimination product **10** (39% GC yield after 20 d). Lastly, rearranged alkene **26** could be obtained as the main product by prolonging the reaction time when using untreated $CDCl_3$ as the solvent, with complete conversion observed after 15 days at room temperature (21% GC yield) or 2 days at 50 °C (29% GC yield).

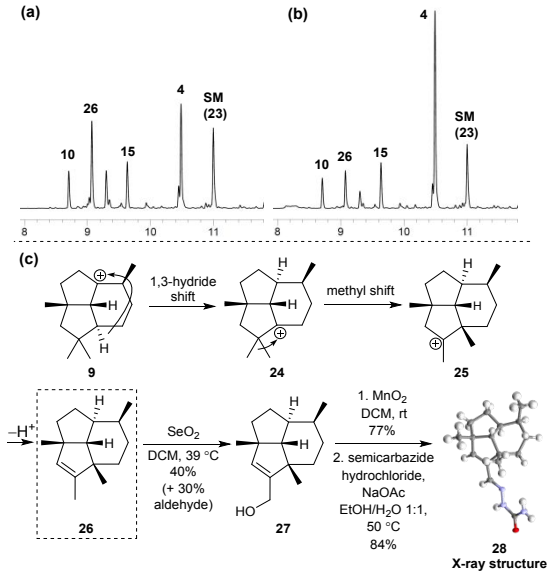


Figure 2. a. Gas chromatogram of reaction in untreated $CDCl_3$ after 4 d; b. Gas chromatogram of reaction in H_2O-satd. $CDCl_3$ after 7 d; c. Proposed mechanism for the formation of rearranged alkene **26**, and synthesis of the crystalline derivative **28**.

Total synthesis on preparative scale

To demonstrate the applicability of this approach to a total synthesis of the natural product, a preparative scale reaction was carried out, using optimized conditions (Scheme 2). A slightly lower (2.5 mol%) loading of HCl was used as this was found to provide a better reaction profile with regards to formation of rearranged alkene **26** on this scale. H_2O-saturated $CHCl_3$ was chosen as the solvent over H_2O-saturated DCM since it provided a less complex reaction mixture. However, concerning reaction time DCM is clearly superior. The reaction was stopped after 7 days (approximately 90% conversion), providing presilphiperfolan-1β-ol in 35% isolated yield. Optical rotation measurement was consistent with the literature value[15] (within experimental error), as expected given enantiomerically pure starting material was utilized. This constitutes the shortest synthesis of (−)-presilphiperfolan-1β-ol to date, in four steps from inexpensive commercially available caryophyllene oxide. Additionally, X-ray crystallographic analysis of crystals of the natural product thus obtained (Scheme 2) confirmed that its structure is identical to that of 9-*epi*-presilphiperfolan-1-ol reported by Joseph-Nathan et al.,[14c] therefore supporting Stoltz's structural reassignment.[15]

Control experiments

Control experiments were carried out to confirm that the reaction was taking place inside the cavity of capsule **I**. No product formation was observed when the reaction was carried out in the absence of capsule, or without any added HCl. Similarly, no reaction was observed when the cavity of the capsule was blocked with a strong-binding guest (Bu_4NBr, 1.5 eq with respect to capsule). Taken together, these results indicate that the synergistic action between capsule and acid is essential for the catalytic activity, in accordance with what was observed in our previous studies.[6a-d] Interestingly, conversion of presilphiperfolan-1β-ol (**4**) to either **10** or **26** also failed to take place in the absence of capsule, indicating that these are also capsule catalysed processes.

In order to better judge the importance of the supramolecular catalyst (Figure 3a), further control experiments with a variety of acidic conditions were tested. Emphasis was put on conditions previously employed for the cyclization of caryophyllene or its derivatives. A small selection of control experiments is displayed in Figure 3 (the whole selection is displayed in Fig. S-3 – S-4). For instance, BX_3 Lewis acids[29b,32] did not form any traces of the natural product **4** (entries b-d). The same holds true for Bronsted acids under a variety of conditions (entries e and g, see also Fig-S-3 – S-4).[33] Only in one case (H_2SO_4, DCM, 1:4) a minor peak close in retention time to the one of the natural product **4** was formed (entry f). However, NMR analysis (see SI Fig. S-5), did not indicate formation of the natural product. These control experiments highlight the extraordinary chemical environment present inside the supramolecular catalyst system.

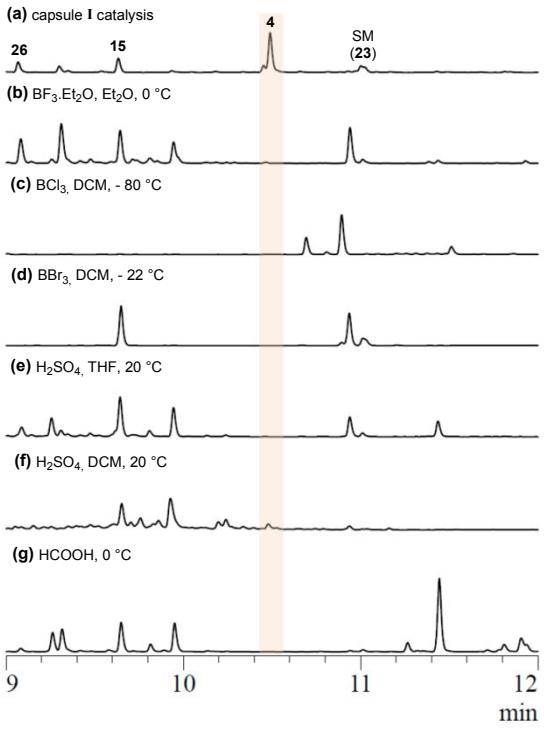
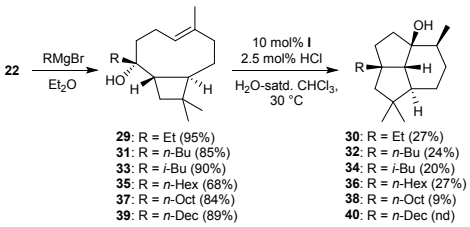


Figure 3. Gas chromatograms for the cyclizations of compound **X** under different conditions. (the full list is depicted in Fig. S-3 – S-5).

Access to unnatural derivatives of presilphiperfolan-1β-ol

One potential advantage of resorcinarene capsule **I** over natural enzymes is its capability to convert unnatural substrates; we therefore decided to also investigate the potential of this methodology to provide unnatural, hitherto unknown presilphiperfolanol analogues. It was found that ethyl substituted precursor **29** (Scheme 3) was tolerated by the supramolecular catalyst system, providing the C4 ethyl analogue of presilphiperfolan-1β-ol **30** in 27% isolated yield (32% GC yield) after 10 days. To probe the limitations of the catalyst with regards to the size of the substituent at C4, we synthesised several cyclisation precursors that varied in the length of the incorporated side-chain. Conversion of the linear butyl and hexyl substituted precursors **31** and **35** proceeded smoothly. The desired derivatives **32** and **36** were isolated in 24% (33% GC yield after 22d) and 27% (35% GC yield after 19d), respectively. However, a decrease in the reaction rate was observed in both cases. For the branched *i*-butyl substrate **33**, the GC-yield dropped significantly (24%). However, the targeted natural product derivative **34** was still isolated in 20% yield. The octyl substrate **37** converted much slower (ca. 60% conversion after two weeks), and product **38** was isolated in only 9% yield (12% GC yield). The decyl substrate **39** failed to convert to an appreciable extent. The observed trend is consistent with a specific size limit for the conversion on the inside of the supramolecular capsule.

Scheme 3. Synthesis of (−)-presilphiperfolan-1β-ol C4-derivatives.



Reaction pathway: Computational study

This study reports the first formation of a presilphiperfolanol natural product from the caryophyllenyl cation **6**, thereby providing experimental evidence that is consistent with its intermediacy in the biosynthesis of this family of natural products. Additionally, we recognized that no presilphiperfolan-8α-ol **3**, or any products presumed to derive from it, were identified in the reaction mixture. This suggests that in the cavity of the capsule, the 1,2-hydride shift that leads to **9** (Figure 1b, path b) is favored over the 1,3-hydride shift that leads to **11** (path a). To our knowledge the 1,2-hydride shift pathway had not been computationally investigated before, in contrast to the 1,3-hydride shift.[23] Therefore, to probe this issue, the relative energies of the two pathways were calculated (Figure 4, Table S-1). In agreement with our experimental observations, transition state **TSb** was found to be lower in free energy to transition state **TSa** by 3.3 kcal/mol, while the resulting carbocation **9** was also found to be more stable than carbocation **11** by 7.8 kcal/mol. Also the final product **4** is more stable than its counterpart **3** from path a (Table S-2). This supports our hypothesis that the resorcinarene capsule can be used to exploit the inherent gas-phase reactivity of terpene frameworks, and in this way find application in the biomimetic synthesis of complex terpenes.

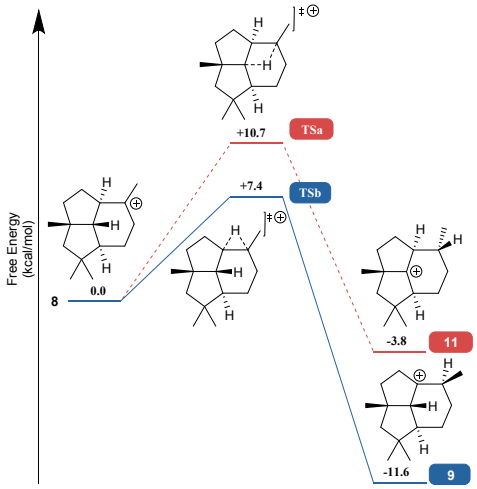


Figure 4. Calculated free energy profile for the pathways leading to presilphiperfolan-8α-ol (path a, red) and presilphiperfolan-1β-ol (path b, blue) [gas phase, M06-2X/6-311++G(2d,p)].

Conclusion

In conclusion, we have shown that the resorcinarene capsule **I** can catalyse the rearrangement of caryophyllenyl alcohol **23** into (−)-presilphiperfolan-1β-ol. This constitutes the shortest synthesis of this natural product to date, in four steps and 26.6% overall yield, while also allowing for the preparation of unnatural analogues. Modification of the reaction conditions leads to the formation of an unnatural presilphiperfolene-like compound bearing a unique substitution pattern. Additionally this study provides the first experimental evidence that is consistent with the biosynthetic connection between caryophyllene and the presilphiperfolanols, and gives useful insight into the pathways that lead to the different members of the presilphiperfolanol family. Computational studies point to the pathway that leads to presilphiperfolan-1β-ol as being energetically preferred in the gas phase over the one that leads to presilphiperfolan-8α-ol. This is in agreement with the observed reactivity in the capsule catalyst. Rightfully, one could ask why the development of man-made terpene cyclase mimics would be required, when natural enzymes could be utilized instead. It is certainly conceivable that if the enzyme that produces presilphiperfolan-1β-ol in nature was identified, it could be used for this purpose. However, access to the hitherto unknown rearranged product **26** and to the unnatural C4 derivatives of presilphiperfolan-1β-ol is only possible via the supramolecular catalyst **I** so far, demonstrating for the first time the potential advantage of supramolecular catalysis over natural enzymes for terpene synthesis. Further work is required to clarify if the concept of mimicking terpene biosynthesis by generating key biosynthetic intermediates inside the capsule can be expanded to other natural products.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website.
Experimental details and NMR spectra of new compounds (PDF)

AUTHOR INFORMATION

Corresponding Author

*konrad.tiefenbacher@unibas.ch; tkonrad@ethz.ch

Notes

The authors declare no competing financial interests.

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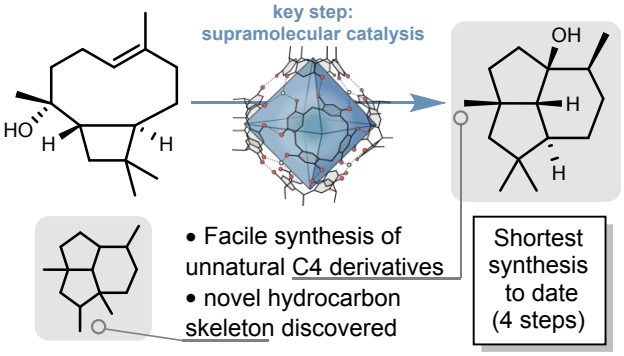
key step:
supramolecular catalysis
HO
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• Facile synthesis of unnatural C4 derivatives
• novel hydrocarbon skeleton discovered
Shortest synthesis to date (4 steps)