

RESEARCH ARTICLE

View Article Online

View Journal | View Issue

Cite this: *Org. Chem. Front.*, 2024, **11**, 472Received 5th November 2023,
Accepted 30th November 2023

DOI: 10.1039/d3qo01841e

rsc.li/frontiers-organic

Total synthesis of (±)-villosin C and (±)-teuvinenone B†

Jin-Xin Zhou,^{a,c} Ming-Jie Yan,^{b,a} Xiao-Yu Shi,^{b,a} Yue-Qi Wang,^{b,a} Hong-Yan Shen,^a Xu-Dong Mao^{*a} and Jie Wang^{ID} ^{*a,b,c}

Herein, we report the first total synthesis of 17(15 → 16)-abeo-abietane diterpenoids (±)-villosin C (**5**) and (±)-teuvinenone B (**4**) in 11 steps. The A/B/C ring system was assembled via a modified three-step sequence on gram-scale, while the D ring was constructed by intramolecular iodoetherification. This synthesis relied largely on the rational design of the order for oxidation state escalation (C6/11/14 → C7 → C12 → C17), which was realized through sequential benzylic iodination/Kornblum oxidation, Siegel–Tomkinson C–H oxidation and iodoetherification. In addition, villosin C (**5**) and its epimer (**5a**) were found to have indistinguishable NMR data and the correct configuration for villosin C was elucidated by comparing HPLC trace with a natural sample.

Introduction

Abietanes represent a rich array of naturally occurring diterpenoids isolated from a variety of terrestrial plant sources.¹ Skeleton rearrangements were frequently observed in this family, where 17(15 → 16)-abeo-abietane is amongst the most common one, as was found in various natural products (Fig. 1).² Villosin C (**5**), characterized by this framework, was first isolated by Ulubelen in 1994 from *Teucrium divaricatum* subsp. *Villosum*.³ In the past decade, this natural product was reisolated from several other plant sources independently, including *Teucrium polium*,⁴ the Chinese medicinal plants *Clerodendrum trichotomum*⁵ and *Clerodendrum bungei*,⁶ and *Akebia quinata*.⁷ Multiple biological activities such as antioxidative,⁴ NO production inhibitory^{5c} and antitumor activities^{5d} were reported for villosin C (**5**), which could partly account for the therapeutic effects of *Clerodendrum trichotomum* (known as “Chou-Wu-Tong”) in traditional Chinese medicine. Teuvinenone B was first isolated from the root of *Teucrium polium*⁸ and was later found to exhibit antioxidant⁴ and antitumor activities.^{5d} Nonetheless, these natural products are rather scarce from natural sources, with less than 1 mg kg^{−1} isolated

from the corresponding dried plants. Thus, the development of a synthetic strategy allowing the access to teuvinenone B (**4**), villosin C (**5**), and their natural and unnatural analogs would be highly desired. Herein, we present our study on the total synthesis of (±)-villosin C (**5**) and (±)-teuvinenone B (**4**) by a convergent approach.

Structurally, villosin C (**5**) and teuvinenone B (**4**) were characterized by a 6/6/6/5 tetracyclic ring system with an aromatized C ring and a dihydrofuran D ring. The synthetic challenge is mainly embedded in the highly oxidized nature (9 out of 10 carbons of the B/C ring are unsaturated and 5 are directly

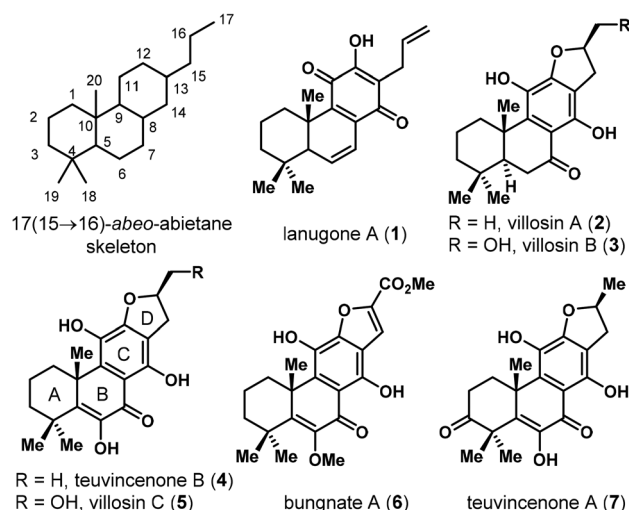


Fig. 1 Representative natural products bearing 17(15 → 16)-abeo-abietane skeleton.

^aState Key Laboratory of Chemical Biology, Shanghai Institute of Materia Medica, Chinese Academy of Sciences, Shanghai 201203, China.

E-mail: maod1993@163.com, jiewang@simm.ac.cn

^bSchool of Chinese Materia Medica, Nanjing University of Chinese Medicine, Nanjing 210023, China

^cUniversity of Chinese Academy of Sciences, Beijing 100049, China

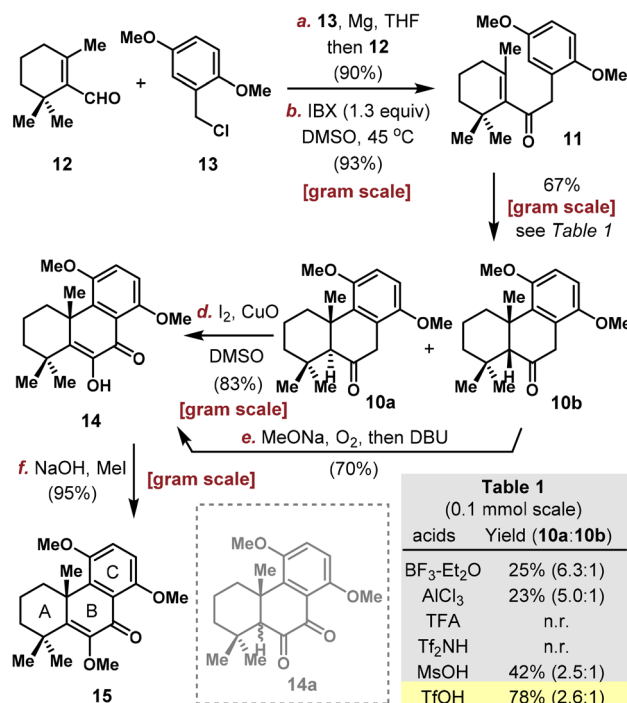
† Electronic supplementary information (ESI) available. CCDC 2305767. For ESI and crystallographic data in CIF or other electronic format see DOI: <https://doi.org/10.1039/d3qo01841e>



attached to oxygen) and that the C ring is a fully substituted benzene moiety. Although there is a plethora of synthetic studies on C ring aromatized abietane diterpenoids,⁹ seldom has targeted those with high oxidation states and fully substituted benzene in this family,¹⁰ and the total synthesis of villosin C (5) and teuvincenone B (4) are yet to be reported. In an initial synthetic study, one of us (Mao) obtained an elaborated intermediate (8) with fully established carbon skeleton and ring system. Unfortunately, the late stage oxidation of the C6/C7 sites proved unsuccessful (Scheme 1A). Instead, oxidative cleavage of the strong electron rich benzene ring was observed. These results prompted us to sketch a new retrosynthetic design, where the α -hydroxy enone moiety in the B ring was constructed prior to installation of the C12 oxidation state (Scheme 1B). Thus, the D ring of 4/5 was envisaged to be built *via* a Claisen rearrangement/iodoetherification sequence from phenol 9. The C12 and C7 oxidation states could be introduced *via* sequential C–H oxidations from ketone 10, which was then disconnected to commercially available β -cyclocitral 12 and a known benzyl chloride 13.

Results and discussion

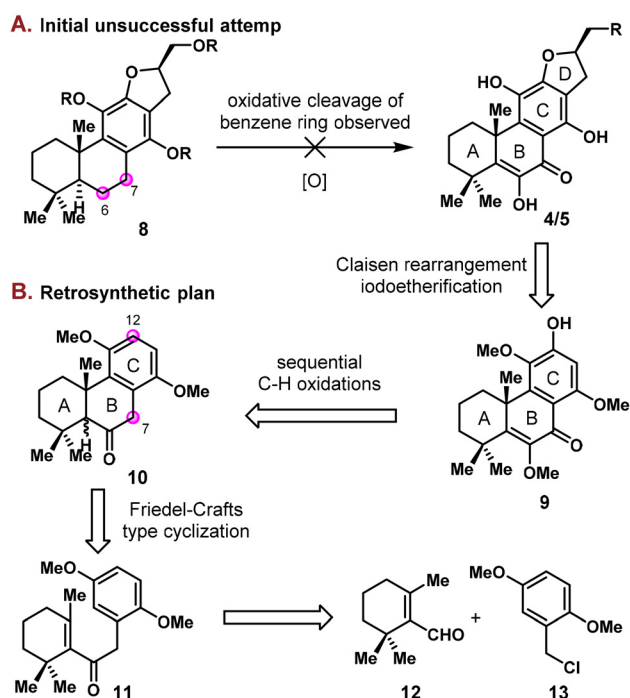
Our synthesis commenced from the assembly of aldehyde 12 and benzyl chloride 13 through a similar three-step sequence previously utilized in other abietane natural product and analog synthesis (Scheme 2).¹¹ In these studies, stoichiometric Li/naphthalene was used unexceptionally to activate benzyl chloride, which is problematic for scale-up. Here, the union of



Scheme 2 Synthesis of tricyclic α -methoxy enone 15.

12 and 13 through Grignard addition afforded 90% yield on multigram-scale. After oxidation with IBX, enone 11 was obtained in 93% yield. Friedel–Crafts cyclization of a similar type was previously reported for either enone¹¹ or unconjugated alkene substrates¹² under Lewis and Brønsted acid conditions. In our case, condition screening on 0.1 mmol scale revealed that AlCl₃ and BF₃·Et₂O delivered cyclized products 10a and 10b in poor yields while TFA and Tf₂NH proved ineffective (Table S1, see the ESI† for more details). The optimum result was obtained with 3 equivalents of TfOH in DCE at 0 °C on 0.1 mmol scale, furnishing 10a and 10b in 78% combined yield with 2.6/1 dr as determined by crude ¹H NMR, and the efficiency could be well maintained on gram-scale (67% isolated yield).¹³

Both diastereoisomers could be used in the subsequent synthesis, however, under different conditions. Jones oxidation and O₂ under basic conditions are two common methods reported in literature for converting ketone to the corresponding α -diketone or α -hydroxy enone moiety in abietane natural product synthesis.^{14,11c,12a} In our attempt to oxidize ketone 10a, while the Jones oxidation was messy, base/O₂ provided variable 30–70% yields depending on reaction scale. After optimization, a one-pot benzylic iodination/Kornblum oxidation using CuO and I₂ in DMSO was found to deliver α -hydroxy enone 14 efficiently in 83% yield on gram-scale.¹⁵ Surprisingly, application of this condition to the other diastereomer 10b gave a messy reaction. Interestingly, this diastereomer was found to be easily oxidized by air, even when placed on bench without any reagent. MeONa/O₂ was then used to achieve the desired oxidation in high conversion, however,



Scheme 1 (A) Initial unsuccessful attempt and (B) Retrosynthetic plan.



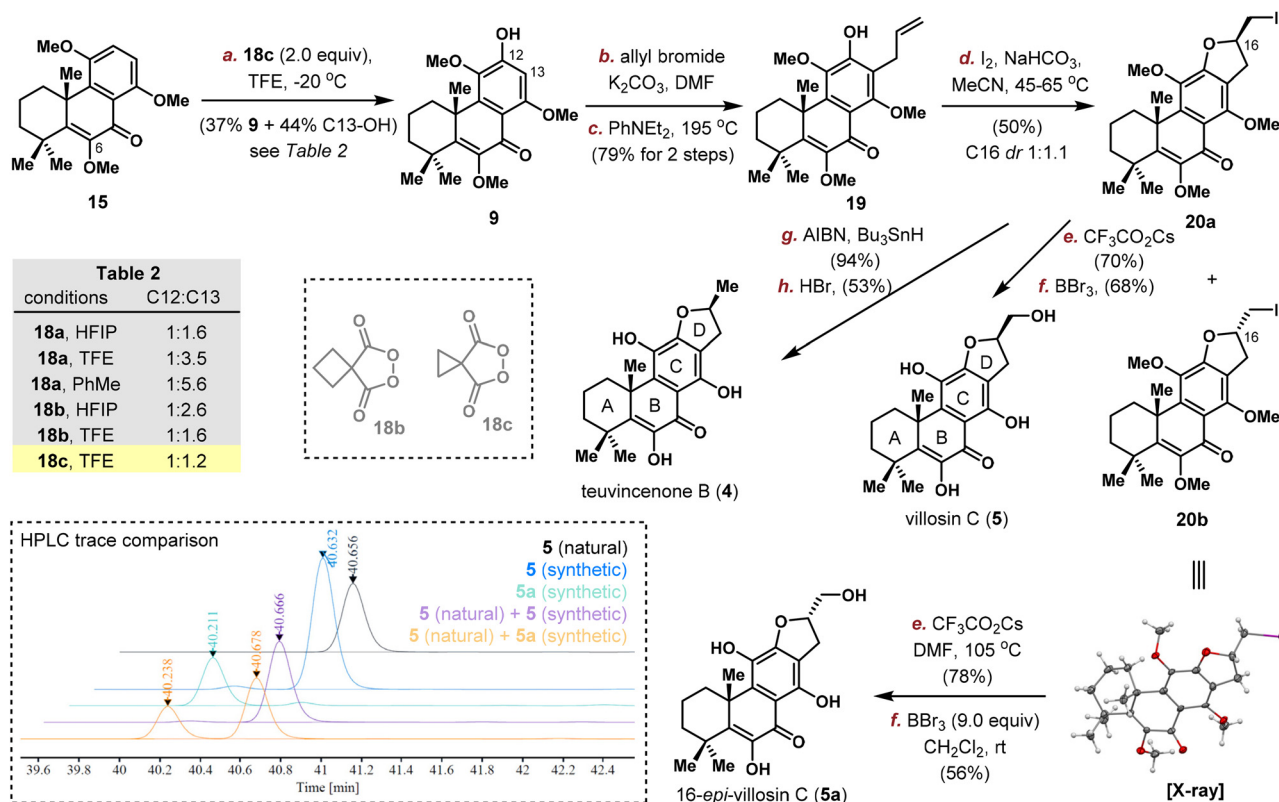
affording a mixture of α -hydroxy enone **14** and α -diketone **14a**. After treating the mixture with DBU, **14** could be obtained in 70% overall yield from **10b**. Protection of the free enol with NaOH/MeI afforded the tricyclic α -methoxy enone **15** in 95% yield.

Quantities of **15** was produced through the implementation of the above-mentioned sequence on gram-scale and the stage

is now setting for the introduction of C12/C13 substituents. Electronic analysis pointed C13 position as the more electron rich site, which was confirmed by exclusive electrophilic bromination at C13.¹⁶ Thus, we planned to first install an allyl group on C13 and then an oxygen atom at C12. Selective removal of 1 methyl group out of 3 was realized using AlCl₃ in PhMe (Scheme 3). Allylation provided **16** in 91% yield, with the location of allyl group confirmed by NOESY spectrum analysis. Claisen rearrangement took place efficiently to position the allyl group on C13, and **17** was obtained after methyl protection. Unfortunately, the subsequent C(12)-H oxidation proved problematic. While electrophilic bromination/iodination were unsuccessful, radical based arene C-H oxidation developed by Siegel using **18a** yielded the desired phenol **19** in very low productivity (8–16% yield under various solvents/temperatures), probably due to steric hindrance and incompatibility with the terminal alkene group.¹⁷

In an optimized protocol, we tried to switch the order of C(12)-H oxidation and C13 allylation (Scheme 4, upper left). Direct oxidation of **15** with **18a** provided a mixture of C12-OH (**9**) and C13-OH products in 1:1.6 ratio. After optimization (Table S2†), cyclopropane malonyl peroxide **18c** in TFE delivered the desired phenol **9** in 37% isolated yield along with the C13-OH isomer in 1:1.2 ratio.^{18,19} Subsequent allylation and Claisen rearrangement proceeded smoothly to provide phenol **19** in 79% yield.

Scheme 3 Synthesis of the fully substituted C ring intermediate **19**.



Scheme 4 Modified synthesis of **19** and total synthesis of (+)-villosin C (**5**), (+)-teuvinenone B (**4**), and (+)-16-*epi*-villosin C (**5a**).



Next, the D ring was constructed through iodoetherification uneventfully to give **20a** and **20b** in 50% combined yield with almost no selectivity at the newly generated stereocenter (1 : 1.1 dr at C16). The two diastereomers were isolated by flash column chromatography and the structure of the undesired isomer **20b** was confirmed by X-ray crystallographic analysis unambiguously. Thus, the conversion of the primary iodide in **20a** to alcohol was achieved using CF₃CO₂CS in DMF at elevated temperature. After global deprotection with BBr₃, (±)-villosin C (**5**) was obtained in 68% yield. In addition, iodide **20a** was reduced with AIBN/Bu₃SnH and globally deprotected with HBr in HOAc to afford (±)-teuvinenone B (**4**) in 50% yield over two steps. The spectroscopic data for **5** and **4** are all in good agreement with those reported from the isolation literature.

The same two-step sequence (hydroxylation, global deprotection) was also applied to **20b** to deliver 16-*epi*-villosin C (**5a**) in 44% yield (Scheme 4). Surprisingly, the ¹H and ¹³C NMR spectra of synthetic **5a** and **5** were almost identical, and could not distinguish with the reported data in the isolation literature (C11–OH represented the only large difference: 5.12, 4.98 and 4.99 ppm for natural **5**, synthetic **5** and **5a** respectively, see the ESI† for detailed comparison).^{5b} Although the C10/C16 relative stereochemistry of some 17(15 → 16)-*abeo*-abietane diterpenoids was elucidated by X-ray crystallographic analysis to be *cis* as drawn in **5**, it is still uncertain in the case of villosin C. Therefore, we requested a sample of natural villosin C from Yang, and the HPLC trace of which was compared to that of synthetic **5** and **5a**, confirming that the true structure of villosin C (**5**) was indeed as originally proposed (Scheme 4, left bottom).^{5c} While the C16 stereochemistry in some 17(15 → 16)-*abeo*-abietane diterpenoids was proposed by comparing the chemical shifts and coupling constant values in NMR around C15–C17 to known ones, our work suggests that NMR data might not be sufficient to make a definite conclusion, at least in the category of 17(15 → 16)-*abeo*-abietane natural products.

Conclusions

In summary, total synthesis of 17(15 → 16)-*abeo*-abietane diterpenoids (±)-villosin C (**5**) and (±)-teuvinenone B (**4**) was accomplished for the first time employing a convergent approach. The synthesis features (i) five-step gram-scale assembly of A/B/C ring system with oxidation state of B ring fully positioned through one-pot benzylic iodination/Kornblum oxidation, (ii) Siegel–Tomkinson C–H oxidation and Claisen rearrangement to install all substituents required on C ring, and (iii) iodoetherification to construct D ring. The successful implementation of this route also relied largely on the rational design of the order for oxidation state escalation (C6/11/14 → C7 → C12 → C17). In addition, our finding that villosin C (**5**) and 16-*epi*-villosin C (**5a**) showed indistinguishable NMR spectroscopy called for more prudence during structural characterization of the 17(15 → 16)-*abeo*-abietane family.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We thank Professor Li Yang for providing the natural sample of villosin C isolated from *Clerodendrum trichotomum*. Financial support for this work was provided by the National Natural Science Foundation of China (Grant No. 22101290), Chinese Academy of Sciences and the State Key Laboratory of Chemical Biology, Shanghai Institute of Materia Medica.

References

- (a) M. Gaborova, K. Smejkal and R. Kubinova, Abietane Diterpenes of the Genus *Plectranthus* sensu lato, *Molecules*, 2022, **27**, 166; (b) L. Kuzma and J. Gomulski, Biologically Active Diterpenoids in the *Clerodendrum* Genus—A Review, *Int. J. Mol. Sci.*, 2022, **23**, 11001; (c) A. Ulubelen, G. Topcu and U. Sonmez, Chemical and biological evaluation of genus *teucrium*, *Stud. Nat. Prod. Chem.*, 2000, **23**, 591–648.
- (a) M. J. S. Cuadrado, M. Bruno, M. C. De La Torre, F. Piozzi, G. Savona and B. Rodríguez, Rearranged Abietane Diterpenoids from the Root of Two *Teucrium* Species, *Phytochemistry*, 1992, **31**, 1697–1701; (b) J. M. Schmid, P. Rüedi and C. H. Eugster, Diterpenoid Leaf-gland Pigments from Labiatae: 22 Novel Coleons and Royleanones from *Plectranthus lanuginosus*, *Helv. Chim. Acta*, 2004, **65**, 2136–2163; (c) B. Rodríguez, A. Robledo and M. J. Pascual-Villalobos, Rearranged Abietane Diterpenoids from the Root of *Teucrium lanigerum*, *Biochem. Syst. Ecol.*, 2009, **37**, 76–79; (d) M. Xu, L. Shen, K. Wang and Q. Du, Two New Abietane Diterpenoids from the Stems of *Clerodendrum kaichianum* P. S. Hsu, *Helv. Chim. Acta*, 2011, **94**, 539–544; (e) D. B. Pu, T. Wang, X. J. Zhang, J. B. Gao, R. H. Zhang, X. N. Li, Y. M. Wang, X. L. Li, H. Y. Wang and W. L. Xiao, Isolation, Identification and Bioactivities of Abietane Diterpenoids from *Premna szechuanensis*, *RSC Adv.*, 2018, **8**, 6425–6435; (f) B. Zhou, Y. H. Ren, Y. S. Han, T. Mesplede and J. M. Yue, Diverse Types of Diterpenoids with an Aromatized C Ring from the Twigs of *Podocarpus imbricatus*, *J. Nat. Prod.*, 2020, **83**, 2416–2424; (g) J. Qi, Y. Zhang, Q. Liu, H. Liu, Y. Fan and J. Yue, Clerodendroids A–F: C-ring Aromatized and/or Rearranged Abietane Diterpenoids from *Clerodendrum chinense* var. *simplex*, *Chin. J. Chem.*, 2021, **39**, 1891–1897.
- A. Ulubelen, G. Topcu and S. Olçal, Rearranged abietane diterpenes from *Teucrium divaricatum* subsp. *Villosum*, *Phytochemistry*, 1994, **37**, 1371–1375.
- A. Fiorentino, B. D'Abrosca, S. Pacifico, M. Scognamiglio, G. D'Angelo and P. Monaco, *abeo*-Abietanes from *Teucrium polium* Roots as Protective Factors against Oxidative Stress, *Bioorg. Med. Chem.*, 2010, **18**, 8530–8536.



- 5 (a) W. X. Wang, J. Xiong, Y. Tang, J. J. Zhu, M. Li, Y. Zhao, G. X. Yang, G. Xia and J. F. Hu, Rearranged Abietane Diterpenoids from the Roots of *Clerodendrum trichotomum* and Their Cytotoxicities against Human Tumor Cells, *Phytochemistry*, 2013, **89**, 89–95; (b) L. Li, L. Wu, M. Wang, J. Sun and J. Liang, Abietane Diterpenoids from *Clerodendrum trichotomum* and Correction of NMR Data of Villosin C and B, *Nat. Prod. Commun.*, 2014, **9**, 907–910; (c) H. J. Hu, Y. Zhou, Z. Z. Han, Y. H. Shi, S. S. Zhang, Z. T. Wang and L. Yang, Abietane Diterpenoids from the Roots of *Clerodendrum trichotomum* and Their Nitric Oxide Inhibitory Activities, *J. Nat. Prod.*, 2018, **81**, 1508–1516; (d) L. Li, Y. Zhang, L. Chen, Y. Cen, Y. Tu, X. Yang and Y. Li, Chemical Constituents of the *n*-Butanol Fraction from the Stems of *Clerodendrum trichotomum* and Their Antitumor Activities *in vitro*, *China Pharm.*, 2022, **33**, 2578–2583, DOI: [10.6039/j.issn.1001-0408.2022.21.04](https://doi.org/10.6039/j.issn.1001-0408.2022.21.04).
- 6 Q. Liu, H. J. Hu, P. F. Li, Y. B. Yang, L. H. Wu, G. X. Chou and Z. T. Wang, Diterpenoids and Phenylethanoid Glycosides from the Toots of *Clerodendrum bungei* and Their Inhibitory Effects against Angiotensin Converting Enzyme and Alpha-glucosidase, *Phytochemistry*, 2014, **103**, 196–202.
- 7 J. P. An, T. K. Ha, J. Kim, T. O. Cho and W. K. Oh, Protein Tyrosine Phosphatase 1B Inhibitors from the Stems of *Akebia quinata*, *Molecules*, 2016, **21**, 1091.
- 8 M. C. Carreiras, B. Rodriguez, M. C. de la Torre, A. Perales, M. R. Torres, G. Savona and F. Piozzi, Rearranged Abietane Diterpenoids from the Root of *Teucrium polium* subsp. *vincentinum*, *Tetrahedron*, 1990, **46**, 847–860.
- 9 For seletcted reviews, see: (a) M. A. Gonzalez, Synthetic Derivatives of Aromatic Abietane Diterpenoids and Their Biological Activities, *Eur. J. Med. Chem.*, 2014, **87**, 834–842; (b) M. A. Gonzalez, Aromatic Abietane Diterpenoids: Their Biological Activity and Synthesis, *Nat. Prod. Rep.*, 2015, **32**, 684–704; (c) M. A. González, Aromatic Abietane Diterpenoids: Total Syntheses and Synthetic Studies, *Tetrahedron*, 2015, **71**, 1883–1908; (d) J. Kang, T. Quynh Le and C. H. Oh, Recent Advances in Abietane/Icetexane Synthesis, *Tetrahedron Lett.*, 2022, **108**, 154133.
- 10 (a) M. Li, P. Chen, H. Liu, J. Huang and Y. Chen, Review of Total Synthesis of Aromatic Abietane Diterpenoid: Ferruginol, *Synthesis*, 2023, DOI: [10.1055/a-2186-7983](https://doi.org/10.1055/a-2186-7983); (b) M. Fischer, K. Harms and U. Koert, Total Syntheses of 7,20-Oxa-Bridged Dinorditerpenes: Antihepatitis C Virus Active (+)-Elevenol from *Flueggea virosa* and (+)-Przewalskin, *Org. Lett.*, 2016, **18**, 5692–5695; (c) X. Li and R. G. Carter, Total Syntheses of Aromatic Abietane Diterpenoids Utilizing Advances in the Pummerer Rearrangement, *Org. Lett.*, 2018, **20**, 5546–5549; (d) X.-D. Mao, T.-T. Du, Q. Gu, L. Yang, H.-L. Shi, R. Hong and G.-X. Chou, Synthesis and Bioactivity Evaluation of Nepetaefolin F and Its Analogues, *ACS Omega*, 2023, **8**, 14830–14840.
- 11 (a) T. Matsumoto, S. Usui and T. Morimoto, A Convenient Synthesis of (±)-Taxodione, (±)-Ferruginol, and (±)-Sugiol, *Bull. Chem. Soc. Jpn.*, 1977, **50**, 1575–1579; (b) J. Huang, D. Foyle, X. Lin and J. Yang, Total Synthesis and Biological Evaluation of an Antifungal Tricyclic o-Hydroxy-p-Quinone Methide Diterpenoid, *J. Org. Chem.*, 2013, **78**, 9166–9173; (c) A. Crusco, C. Bordoni, A. Chakroborty, K. C. L. Whatley, H. Whiteland, A. D. Westwell and K. F. Hoffmann, Design, Synthesis and Anthelmintic Activity of 7-keto-Semperviol Analogues, *Eur. J. Med. Chem.*, 2018, **152**, 87–100.
- 12 (a) P. Bie, C. Zhang, A. Li, X. Peng, T. Wu and X. Pan, First Total Synthesis of (±)-Celaphanol A, *J. Chin. Chem. Soc.*, 2002, **49**, 581–583; (b) D. C. Behenna, J. L. Stockdill and B. M. Stoltz, Synthesis of the Carbocyclic Core of Zoanthenol: Implementation of an Unusual Acid-Catalyzed Cyclization, *Angew. Chem., Int. Ed.*, 2007, **46**, 4077–4080.
- 13 Attempt to realize this cyclization with enantioselective control was unsuccessful (see the ESI† for a list of conditions tried).
- 14 T. Matsumoto and S. Takeda, Total Synthesis of Coleons, U and V, *Chem. Lett.*, 1979, **8**, 409–412.
- 15 G. Yin, B. Zhou, X. Meng, A. Wu and Y. Pan, Efficient C-C Double-Bond Formation Reaction via a New Synthetic Strategy: a Self-Sorting Tandem Reaction, *Org. Lett.*, 2006, **8**, 2245–2248.
- 16 Z. Ruan, M. Wang, C. Yang, L. Zhu, Z. Su and R. Hong, Total Synthesis of (+)-Hinckdentine A: Harnessing Noncovalent Interactions for Organocatalytic Bromination, *JACS Au*, 2022, **2**, 793–800.
- 17 C. Yuan, Y. Liang, T. Hernandez, A. Berriochoa, K. N. Houk and D. Siegel, Metal-free Oxidation of Aromatic Carbon-Hydrogen Bonds through a Reverse-Rebound Mechanism, *Nature*, 2013, **499**, 192–196.
- 18 A. Dragan, T. M. Kuczyk, J. H. Rowley, S. Sproules and N. C. Tomkinson, Arene Oxidation with Malonoyl Peroxides, *Org. Lett.*, 2015, **17**, 2618–2621.
- 19 Further screening revealed that with Ts protecting group on C6-OH, 1.3:1 ratio of **9** to C13-OH isomer could be obtained. However, the overall yield was lower (23% for **9**, see the ESI† for details).

