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Probing the alkylidene carbene–strained alkyne equilibrium in polycyclic systems via the Fritsch–Buttenberg–Wiechell rearrangement

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Strained cycloalkynes are valuable building blocks in synthetic chemistry due to their high degree of reactivity and ability to form structurally complex scaffolds, common features of many pharmaceuticals and natural products. Alkylidene carbenes provide a pathway to the formation of strained cycloalkynes through Fritsch–Buttenberg–Wiechell rearrangements, but this strategy, like other methods of alkyne generation, is believed to depend upon a thermodynamic equilibrium that favors the alkyne over the carbene. Herein three highly strained, polycyclic alkynes, previously thought to be thermodynamically inaccessible, are generated under mild conditions and intercepted through Diels–Alder cycloaddition with a diene trapping agent. The use of a different trapping agent also allows for the interception of the alkylidene carbene, providing the first instance in which both an exocyclic alkylidene carbene and its cycloalkyne Fritsch–Buttenberg–Wiechell rearrangement product have been trapped.

Strained cyclic alkynes are of both theoretical and practical interest in organic chemistry. Incorporation of alkynes into constricted ring structures forces deviation from their ideal linear geometry, allowing chemists to probe the limits of distortion of these chemical bonds. The reactivity associated with the strain of cyclic alkynes has also been a subject of growing synthetic interest, and has been utilized for the generation of a number of complex molecular scaffolds[1,2]. Highly strained cycloalkynes are unstable, transient species, however, making their generation and study difficult under normal laboratory conditions[3].

Alkylidene carbenes **1** undergo 1,2-shifts, known as Fritsch–Buttenberg–Wiechell (FBW) rearrangements, to yield alkynes **2** (Fig. 1A)[4–6]. In the case of exocyclic alkylidene carbenes **3**, FBW rearrangements can provide access to highly reactive, geometrically strained cyclic alkynes **4** that are difficult to generate through other means (Fig. 1B)[7,8]. FBW rearrangements of alkylidene carbenes have been used for the generation of monocyclic alkynes[9,10] such as cyclopentynes[11–13] and cyclohexynes[13–15], as well as a number of polycyclic alkynes[16–18]. Many of these strained alkynes are transient, non-isolable species under ambient temperature, and their formation is inferred through their reaction with various trapping agents[3,12].

The generation of alkynes via FBW rearrangements of alkylidene carbenes is generally considered to depend upon a thermodynamic equilibrium that favors the target alkyne over the corresponding carbene[19–23]. While this is the case for most monocyclic alkynes[10,11,16], with the exceptions of cyclobutyne[20] and cycloheptyne[9,24], the additional geometric constriction present in many polycyclic alkynes can potentially tip equilibrium in favor of the carbene. In such cases, even direct synthesis of the strained alkyne will result in rearrangement to the alkylidene carbene through the reverse 1,2-shift, known as the Roger Brown rearrangement[20,25,26]. Attempts to detect a number of polycyclic alkynes, including **5** and **7**, through the FBW rearrangement of their respective alkylidene carbenes have been unsuccessful, purportedly due to unfavorable differences in the relative stabilities of the two chemical species (Fig. 1B)[19,21–23].

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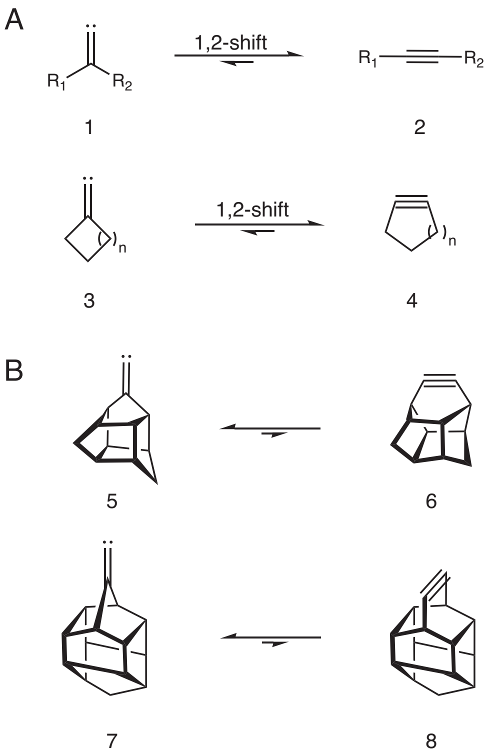

Fig. 1 | The alkylidene carbene–alkyne equilibrium. **A** Fritsch–Buttenberg–Wiechell (FBW) rearrangement of acyclic and exocyclic alkylidene carbenes **1** and **3**, respectively. **B** Polycyclic alkylidene carbenes for which FBW rearrangements are thermodynamically unfavorable. The relative thermodynamic stabilities of **5** and **6**[19] and **7** and **8**[20] have been reported previously, and are in agreement with computational experiments conducted herein (See Supplementary Fig. 1).

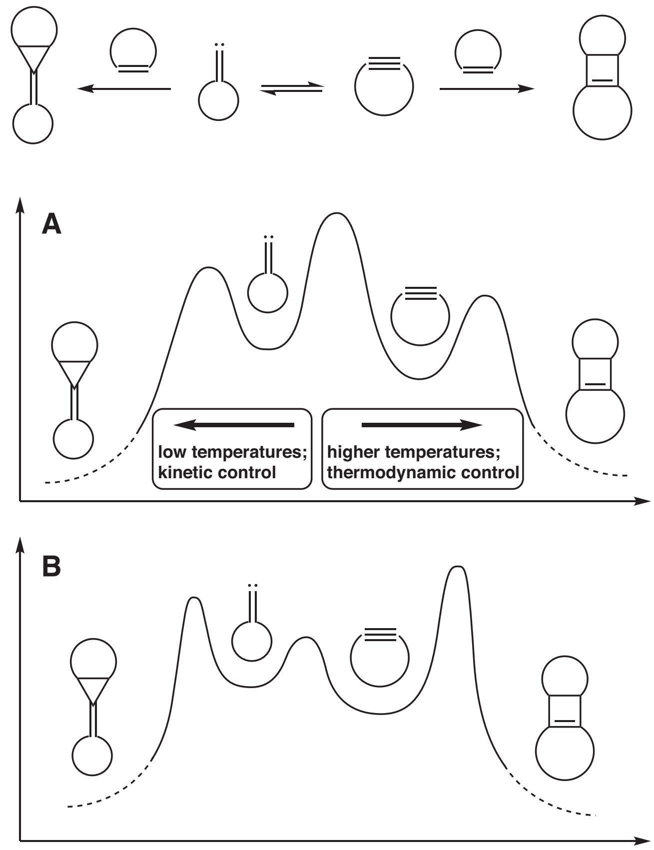

Fig. 2 | Scenarios in which the FBW rearrangement of alkylidene carbene to cycloalkyne is thermodynamically favored, but the cycloalkyne would not be detected through trapping experiments. **A** Low temperatures may prevent establishment of equilibrium between alkylidene carbene and cycloalkyne, resulting in trapping of the alkylidene carbene. **B** If the absolute activation energy for trapping of the alkylidene carbene is lower than that for the alkyne, the carbene will be trapped regardless of the thermodynamic relationship of the two intermediates.

A number of experimental factors affect the successful detection of a cycloalkyne that is in equilibrium with an alkylidene carbene, factors that can confound subsequent interpretations of the relative thermodynamic stabilities of these intermediates. Preparation of alkylidene carbenes for the generation of polycyclic alkynes has primarily involved the deprotonation of bromoethylenecycloalkanes[16–18,27], or the lithiation of dibromomethylenecycloalkanes[19,21–24], both of which initially generate an alkylidenecarbenoid species. Alkylidenecarbenoids exhibit different patterns of reactivity compared to free alkylidene carbenes[28], and can react through unique pathways[4] that involve dimerization[29], decomposition[30–32], and FBW rearrangements[33–35]. This potential for alternative pathways of reactivity makes the use of alkylidenecarbenoids problematic for the study of carbene–alkyne equilibria.

Reaction temperature will also influence the degree to which the carbene–alkyne equilibrium is established. Typical preparations of alkylidene carbenes require either high temperatures in the case of deprotonation of bromoethylenecycloalkenes[16–18,27], or low temperatures in the case of lithiation of dibromomethylenecycloalkanes[19,21–24]. Whereas trapping experiments utilizing high-temperature reactions have typically been successful in detecting the alkyne[16–18,27], a number of attempts under low temperature conditions have been unsuccessful[19,21]. This outcome has generally been attributed to thermodynamic favorability of the carbene over the alkyne, but low temperatures may also place the reaction outcome under kinetic control, thereby favoring trapping of the carbene before thermodynamic equilibrium is established between the carbene and alkyne (Fig. 2A).

An alkyne that is thermodynamically favored over its corresponding carbene can still evade detection, even after establishment of equilibrium, depending on the particular trapping agent in use. The reaction of a carbene or alkyne with a trapping agent may follow a Curtin–Hammett scenario[36], in which the distribution of products is determined not by the thermodynamic stability of the intermediates, but by the relative activation free energies for the trapping of these intermediates. If the absolute activation free energies to reaction between carbene and trap is lower than that between alkyne and trap, the carbene will be preferentially selected regardless of the relative thermodynamic stabilities of the two intermediates (Fig. 2B).

Our laboratory has a developed a photolytic approach to the generation of free alkylidene carbenes that proceeds under mild conditions and ambient temperatures[13,14,37–39]. Herein, we demonstrate the utility of this method toward the generation of highly strained polycyclic alkynes bicyclo[2.2.2]oct-2-yne (**10**), pentacyclo[5.5.0.0^{4,11}.0^{5,9}.0^{8,12}]dodec-2-yne (**13**), and pentacyclo[6.4.0.0^{3,7}.0^{4,12}.0^{6,11}]dodec-9-yne (**6**) via the FBW rearrangement of their respective alkylidene carbenes **9, 12**, and **5** (Fig. 3). All three alkynes have previously been determined to be inaccessible due to unfavorable thermodynamic relationships with their corresponding carbenes[19,21,23]. The choice of trapping agent was found to have a decisive effect on reaction outcome, allowing for either carbene or alkyne to be intercepted, which could be predicted through computational experiments.

The results herein demonstrate that trapping experiments are an inadequate method for the elucidation of thermodynamic relationships between intermediates, and that the nature of these relationships

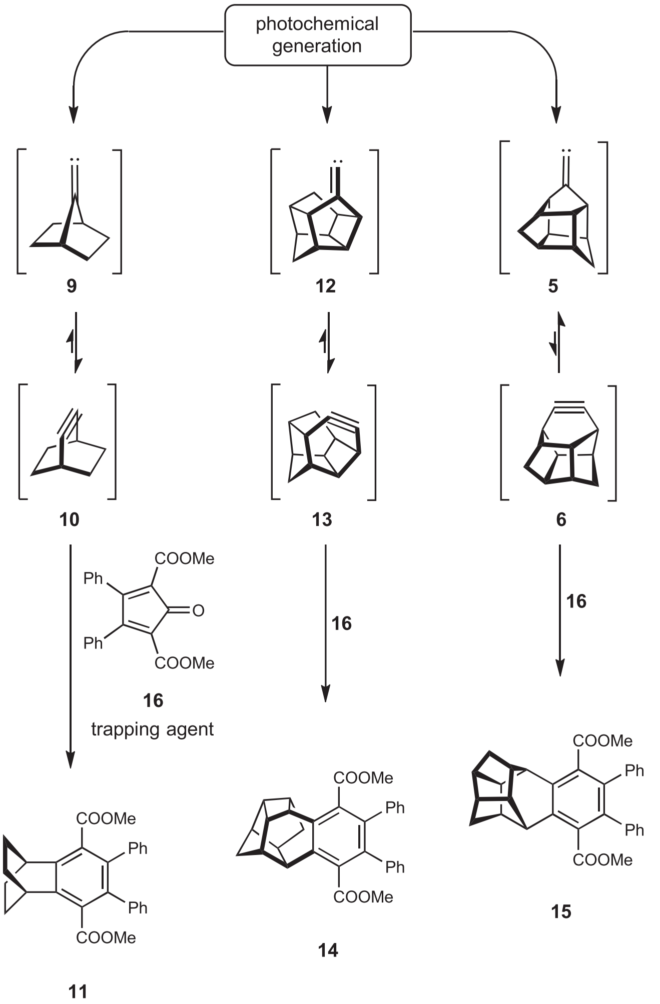

Fig. 3 | Photochemical generation and trapping of the strained polycyclic alkynes. Bicyclo[2.2.2]oct-2-yne (**10**), pentacyclo[5.5.0.0^{4,11}.0^{5,9}.0^{8,12}]dodec-2-yne (**13**), and pentacyclo [6.4.0.0^{3,7}.0^{4,12}.0^{6,11}] dodec-9-yne (**6**) underwent reaction with 2,5-bis(methoxycarbonyl)−3,4-diphenylcyclopentadienone (**16**) to generate trapped products **11, 14**, and **15**, respectively.

is not a limitation to the trapping of unstable intermediates. The use of photolysis moreover allows for the generation of free carbenes under mild conditions that avoid alternative reaction pathways characteristic of alkylidenecarbenoids[4], and enables trapping with a variety of reaction partners. To our knowledge, this is the first report in which both an exocyclic alkylidene carbene and its cycloalkyne FBW rearrangement product have been successfully trapped.

Results and discussion

Synthesis of alkylidene carbene precursors

Our investigation into the generation of strained alkynes via FBW rearrangement of their corresponding alkylidene carbenes was prompted by calculations at the DLPNO-CCSD(T)/CPCM$_{\text{(benzene)}}$/def2-TZVPP//M06/CPCM$_{\text{(benzene)}}$/def2-TZVP[40–47] level of theory, which predicted bicyclo[2.2.2]oct-2-yne (**10**) to be lower in energy than 7-norbornylidene carbene (**9**) by 1.0 kcal/mol (Fig. 4). The activation energy of the rearrangement was predicted to be 8.4 kcal/mol, an activation energy that is comparable to those predicted for previously investigated alkylidene carbenes that undergo FBW rearrangement[15]. Pentacyclo[5.5.0.0^{4,11}.0^{5,9}.0^{8,12}]dodec-2-yne (**13**) was also predicted to be more stable than 8-pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecylidene carbene (**12**) by 2.4 kcal/mol (Fig. 4). The presence of the triple bonds in compounds **10** and **13** is predicted to inflict 51.0 kcal/mol and 41.3 kcal/mol of strain energy, respectively (See Supplementary Fig. 2)[48]. Both polycyclic alkynes have previously been determined to be less thermodynamically stable than their corresponding alkylidene carbenes **9** and **12** based on trapping experiments, using norbornadiene in the case of **9**[21], and cyclohexene in the case of **12**[19].

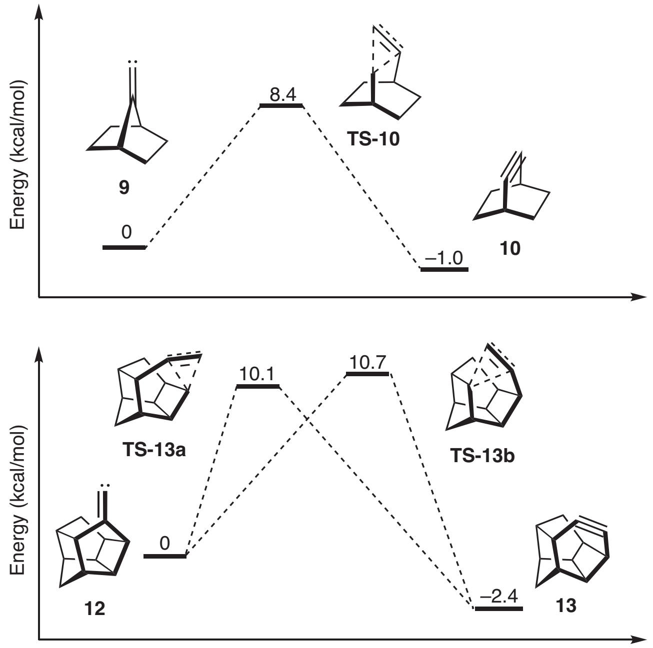

Fig. 4 | FBW rearrangement is thermodynamically favorable for alkylidene carbenes 9 and 12. Potential energy surface for the FBW rearrangement of 7-norbornylidene carbene (**9**) to bicyclo[2.2.2]oct-2-yne (**10**) and 8-pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecylidene carbene (**12**) to pentacyclo[5.5.0.0^{4,11}.0^{5,9}.0^{8,12}]dodec-2-yne (**13**), computed at DLPNO-CCSD(T)/CPCM$_{\text{(benzene)}}$/ def2-TZVPP//M06/CPCM$_{\text{(benzene)}}$/def2-TZVP. See Supplementary Data 1 for the cartesian coordinates of the optimized structures.

Precursor **22**, from which 7-norbornylidene carbene (**9**) can be photochemically generated, was synthesized from 7-norbornanone (**21**)[49–51] and dichlorocyclopropyl phenanthrene derivative **23**[52] by adapting a procedure previously reported by Takeda et al.[53] (Fig. 5). The synthesis of 7-norbornanone (**21**) was achieved in four steps starting from norbornadiene (**17**) following previously reported procedures[49–51]. Precursor **29** was synthesized using 8-pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecan-8-one **(28)**, made from 8-pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}] undecan-8,11-dione (**24**) in four steps, and **23**.

Trapping studies

The strained alkyne bicyclo[2.2.2]oct-2-yne (**10**) was successfully generated following irradiation of precursor **22** in benzene (280–400 nm, 6 h) and intercepted with cyclopentadienone **16** as the trapping agent (Fig. 6). Photolysis of **22** is expected to initially extrude 7-norbornylidene carbene (**9**) with the concomitant release of phenanthrene (**30**, Fig. 6)[14,15,54]. Subsequent FBW rearrangement of **9** generates bicyclo[2.2.2]oct-2-yne (**10**), which can then undergo a Diels–Alder cycloaddition with diene **16**, yielding the adduct **33.** Loss of carbon monoxide from **33** leads to the observed product **11**, the structure of which was confirmed by X-ray crystallography (Fig. 6). Compound **32**, which likely arises from a 1,5-alkyl shift within precursor **22** followed by electrocyclic ring opening, was also identified as a major product of the photolysis reaction. Similar isomerization reactions have previously been reported in the photochemical generation of carbenes[55–57]. A small amount of allene **31** was also detected, the product of dimerization of alkylidene carbene **9** (Fig. 6). Using the yield

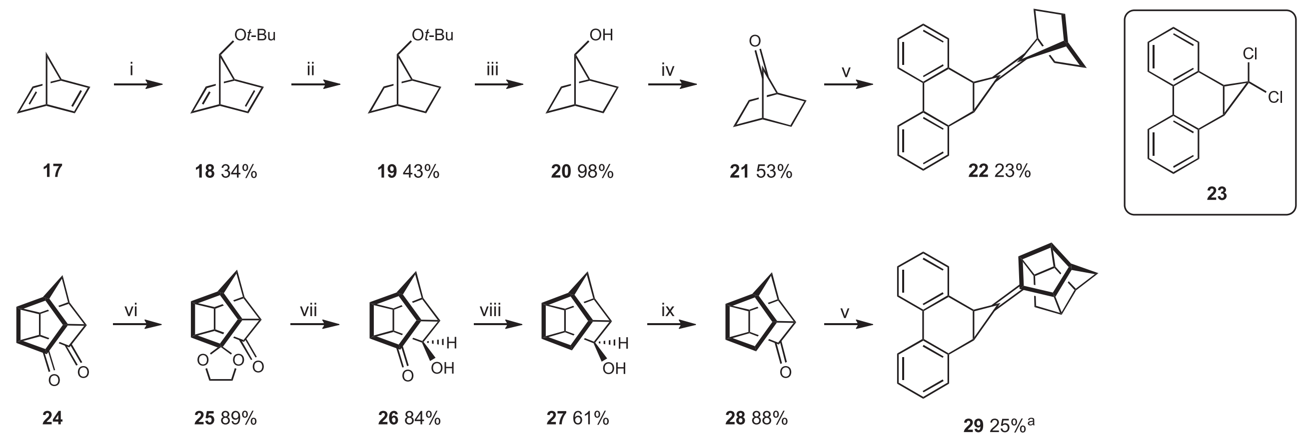

Fig. 5 | Synthesis of alkylidene carbene precursors 22 and 29. Yields reported represent isolated yields. Reagents and conditions: i) TBPB, CuBr, benzene, reflux, ii) $Pd(OAc)_2/C$, H_2, MeOH, iii) TMS-I, $CHCl_3$, $NaHCO_3$, MeOH, iv) PCC, CH_2Cl_2, v) **23**, Cp_2TiCl_2, Mg, $P(OEt)_3$, 4 Å mol. sieves, THF, RT vi) ethylene glycol, pTsOH, benzene vii) $LiAlH_4$, Et_2O, reflux, HCl, H_2O, viii) $NH_2NH_2 \cdot H_2O$, diethylene glycol, Δ, KOH, reflux, ix) CrO_3, H_2O, AcOH, Δ. ^{a}Mixture of *exo* and *endo* diastereomers.

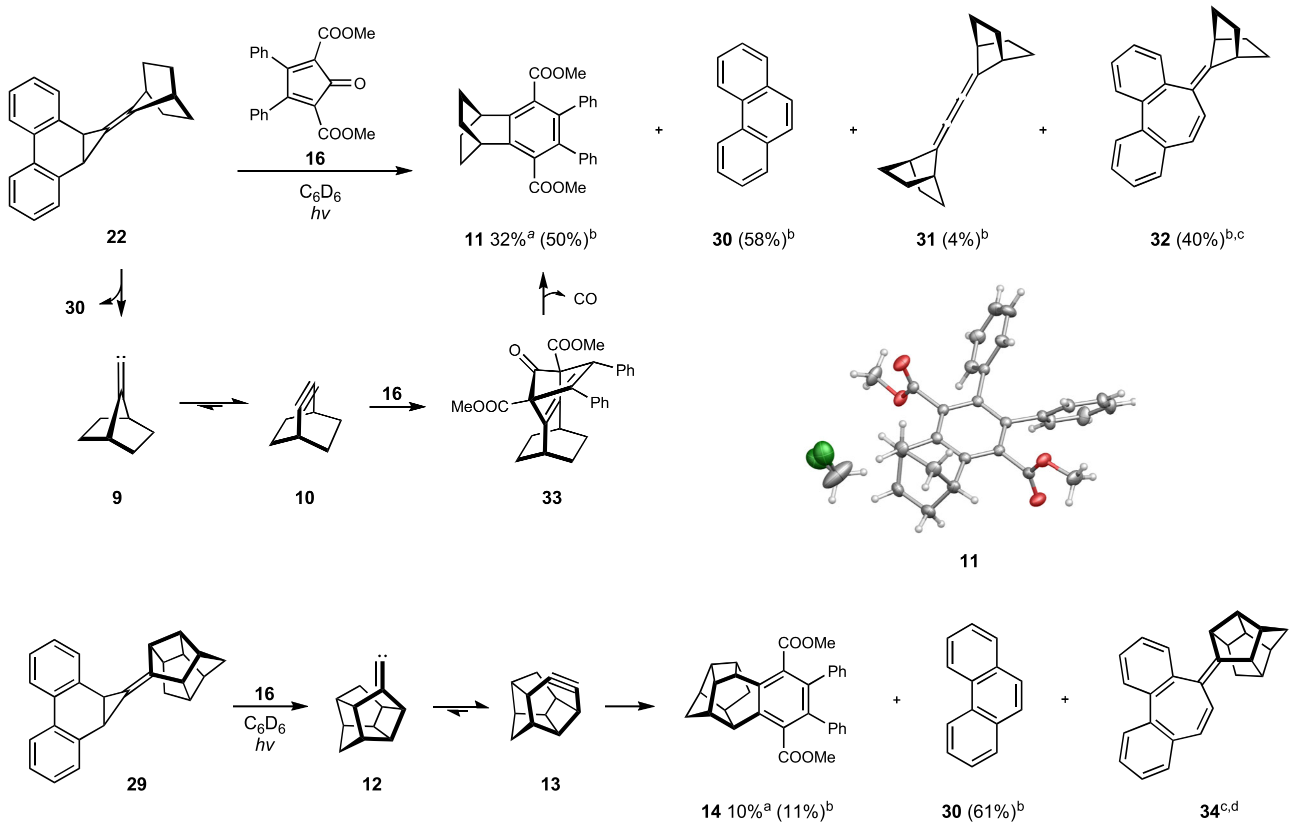

Fig. 6 | Trapping of strained alkynes 10 and 13. Photolysis of precursor **22** in the presence of diene **16** resulted in the formation of adduct **11**, the expected product of reaction between bicyclo[2.2.2]oct-2-yne (**10**) and **16**. Photolysis of precursor **29** in the presence of **16** resulted in the formation of adduct **14**, indicating the reaction of pentacyclo[5.5.0.0^{4,11}.0^{5,9}.0^{8,12}]dodec-2-yne (**13**) and **16**. ^{a}Isolated yield. ^{b}Yield determined by NMR spectroscopy of the unpurified reaction mixture. ^{c}Mixture of two diastereomers. ^{d}Identity determined by GC/MS analysis of the unpurified reaction mixture.

of phenanthrene in the unpurified reaction mixture as an indication of the amount of carbene released in the photolysis reaction, approximately 86% of the carbene **11** released from precursor **22** was trapped as alkyne **10** to yield **11**.

Photolysis of precursor **29** (280–400 nm, 10 h) proceeded to yield the Diels–Alder adduct **14** as the major product, in addition to a complex mixture of other minor products (Fig. 6). ^{1}H NMR spectroscopy of the unpurified reaction mixture indicated that phenanthrene was released, and likewise 8-pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecylidene carbene (**12**) was generated, in 61% yield. The remaining precursor likely underwent isomerization to **34**, similarly to the photolysis of precursor **22**. Although adduct **14** accounts for only 18% of the alkylidene carbene generated, there are no other major products of reaction with diene **16**. The peaks corresponding to the methyl ester protons of unreacted diene **16** and adduct **14** are the largest signals within the 3.0–4.0 ppm range in the ^{1}H NMR spectrum of the unpurified reaction mixture, indicating that **14** is the major product of reaction with diene **16** (See Supplementary Fig. 3). A number of much smaller peaks are evident within the 3.0–4.0 ppm range, indicating that much of the diene that is consumed, either in reaction with carbene **12** or alkyne **13**, reacts to form a multitude of different products in minor amounts.

The use of cyclopentadienone **16** as a trapping agent was expected to preferentially detect alkynes **10** and **13**, which can undergo Diels–Alder cycloaddition, over carbenes **9** and **12**, which can only undergo a [1 + 2] cyclopropanation reaction. Irradiation of precursors **22** and **29** in the presence of cyclohexene (**35**, 280–400 nm, 6 h), which is expected to be capable of trapping both carbene and alkyne[11,19,23], yielded the cyclopropanation products **36** and **39** exclusively (Fig. 7). The identities of **36** and **39** were determined by derivatization to spirocyclopropanes **37** and **40**, respectively, and subsequent characterization by X-ray crystallography (Fig. 7). Photolysis of **22** yielded **36** selectively both when the reagents were diluted in benzene (0.1 M or 0.01 M), or when cyclohexene (**35**) was used as solvent, indicating that bicyclo[2.2.2]oct-2-yne (**10**) could not be intercepted with cyclohexene regardless of the concentration of this trapping agent. Together, the data indicate that the outcome of the trapping experiments are primarily dependent on the identity of the trapping agent, rather than the thermodynamic relationship between the alkyne and alkylidene carbene.

Computational Studies

The differences in product specificity when cyclopentadienone **16** or cyclohexene **35** are used as trapping agents are consistent with calculations at the DLPNO-CCSD(T)/CPCM$_{(\text{benzene})}$/def2-TZVPP//M06/CPCM$_{(\text{benzene})}$/def2-TZVP[40–47] level of theory (Fig. 8). [Comparable results were obtained using DLPNO-CCSD(T)/CPCM$_{(\text{benzene})}$/def2-TZVPP//M06-2X/CPCM$_{(\text{benzene})}$/def2-TZVP model chemistry. See Supplementary Fig. 7] Upon generation of 7-norbornylidene carbene (**9**), at least three pathways of reactivity are possible: dimerization, addition to the trapping agent, or FBW rearrangement. Dimerization, a pathway generally associated with carbenoids[4,21], has also been observed following the photochemical generation of free 2-adamantylidenecarbene[57]. In the case of 7-norbornylidene carbene (**9**), dimerization to triene **31** is predicted to be an energetically barrierless process (Fig. 8), similar to the dimerization of methylenecarbene[58–60]. Dimer **31** was the only product detected besides the isomerization product **32** following photolysis of precursor **22** in the absence of trapping agent (See Supplementary Fig. 4), indicating that this pathway is largely outcompeted by trapping when diene **16** or cyclohexene (**35**) is present.

With the use of diene **16** as a trapping agent, the activation energy for the FBW rearrangement of 7-norbornylidene carbene (**9**) to bicyclo[2.2.2]oct-2-yne (**10**) is predicted to be lower than that for trapping of the carbene **9** to form cyclopropylidene **42** (Fig. 8A). The first-order, intramolecular FBW rearrangement of 7-norbornylidene carbene (**9**) also largely outcompetes the second-order, intermolecular dimerization reaction, as evidenced by the minimal amount of dimer product in the reaction mixture (Fig. 6)[61]. Bicyclo[2.2.2]oct-2-yne (**10**) exhibits a lower absolute and relative activation free energy to trapping with diene **16** compared to that of **9**, and would thereby be favored in the trapping experiment, resulting in formation of adduct **33**, then adduct **11** via decarbonylation.

Generation of 7-norbornylidene carbene (**9**) in the presence of cyclohexene (**35**) results in trapping of **9** due to a prohibitively high activation free energy of reaction for the addition of cyclohexene to bicyclo[2.2.2]oct-2-yne (**10**, Fig. 8B). The FBW rearrangement of carbene **9** to alkyne **10** may be expected to outcompete the addition of **9** to cyclohexene (**35**) due to a lower activation free energy and a lesser dependence on the concentration of reactants. The strained alkyne **10** faces a substantially larger activation free energy to trapping, however, compared to that of alkylidene carbene **9** (18.9 kcal/mol vs 11.1 kcal/mol). Computational experiments indicate that bicyclo[2.2.2]oct-2-yne (**10**) does not exhibit a substantial amount of biradical character, and predict similar activation energies for the addition of **10** to cyclohexene via dicarbene and biradical intermediates (See Supplementary Table 1 and Supplementary Fig. 6). Previous investigations into the reactivity of other strained alkynes indicate that cycloaddition reactions typically occur through a dicarbene pathway[62–65]. Due to the high activation free energy for reaction between cyclohexene (**35**) and alkyne **10**, and a substantially lower activation energy for the rearrangement of alkyne **10** back to carbene **9** (9.4 vs 18.9 kcal/mol), trapping of 7-norbornylidene carbene (**9**) will be

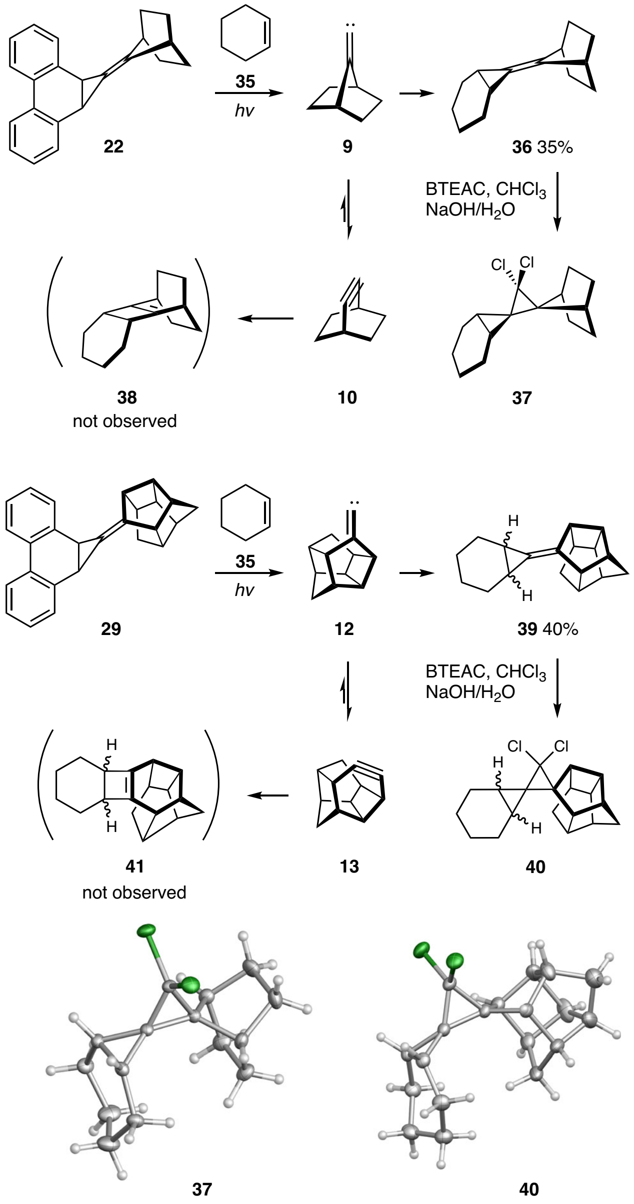

Fig. 7 | Trapping of alkylidene carbenes 9 and 12. Photolysis of precursor **22** in the presence of cyclohexene (**35**) resulted in the formation of adduct **36**, the expected product of reaction between 7-norbornylidene carbene (**9**) and **35**. Photolysis of precursor **29** in the presence of **35** resulted in the formation of **39**, indicating the reaction of 8-pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecylidene carbene (**12**) and **35**. The identities of adducts **36** and **39** were determined by derivatization to spirocyclopropanes **37** and **40**, respectively, and characterization by X-ray crystallography.

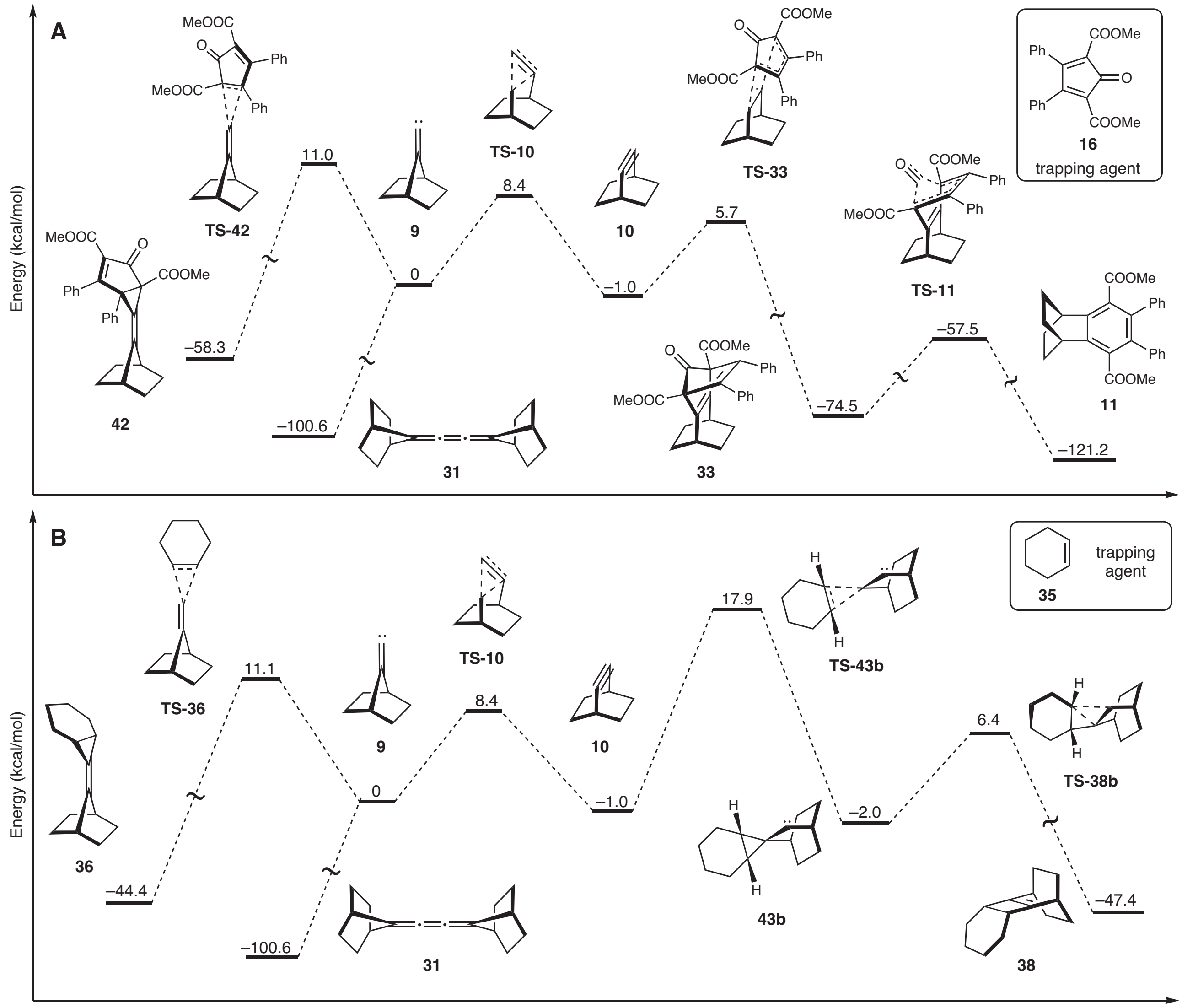

Fig. 8 | Potential energy surface for the reactions of 7-norbornylidene carbene (9) and bicyclo[2.2.2]oct-2-yne (10). A In the presence of cyclopentadiene **16**. **B** In the presence of cyclohexene (**35**). See Supplementary Figs. 5 and 6 for a comprehensive analysis of the addition of cyclohexene (**35**) to bicyclo[2.2.2]oct-2-yne (**10**). Computed at DLPNO-CCSD(T)/CPCM$_{\text{(benzene)}}$/ def2-TZVPP//M06/CPCM$_{\text{(benzene)}}$/ def2-TZVP. See Supplementary Data 1 for the cartesian coordinates of the optimized structures.

favored despite its lower concentration at equilibrium. The cyclobutylated product **38**, and likewise the presence of bicyclo[2.2.2]oct-2-yne (**10**), will thus not be detected under these experimental conditions, regardless of the relative thermodynamic stabilities of the two intermediates (Fig. 8B).

Computational experiments indicate that the complex mixture of products observed following generation of 8-pentacyclo [5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecylidene carbene (**12**) is likely due to a relatively high activation free energy for FBW rearrangement (Fig. 9). The activation energies for trapping of carbene **12** and alkyne **13** with diene **16** (10.6 and 6.6 kcal/mol, Fig. 9A) are comparable to those of 7-norbornylidene carbene (**9**) and bicyclo[2.2.2]oct-2-yne (**10**, 11.0 and 6.7 kcal/mol, Fig. 8A). Despite these similar activation energies for trapping, the yield of adduct **11** following the photolysis of **22** is significantly higher than that of adduct **14** following the photolysis of **29** (50% and 11%, Fig. 6). This discrepancy in the yields of adducts **11** and **14** may be attributable to a larger activation energy for FBW rearrangement of undecylidene carbene **12** than for that of 7-norbornylidene carbene (**9**, 10.1 kcal/mol and 8.4 kcal/mol, Fig. 8A and Fig. 9A). The relatively slow rate of both rearrangement and trapping of undecylidene carbene **12** likely leaves this intermediate more susceptible to alternative pathways of reactivity and decomposition, as is indicated by the ^{1}H NMR spectrum of the unpurified reaction mixture (See Supplementary Fig. 3).

Generation of undecylidene carbene **12** in the presence of cyclohexene (**35**) results in a Curtin–Hammett scenario in which trapping of the carbene is favored over that of the alkyne (Fig. 9B). While equilibration of undecylidene carbene **12** and pentacyclo[5.5.0.0^{4,11}.0^{5,9}.0^{8,12}] dodec-2-yne (**13**) via FBW rearrangement is expected to result in a substantially higher concentration of alkyne **13**, the free activation energy for reaction of **13** with cyclohexene is prohibitively high (23.3 kcal/mol). Thus, cyclohexene will react with carbene **12** selectively, driving the rearrangement of alkyne **13** back to carbene **12**. Similarly to alkyne **10**, the addition of pentacyclo[5.5.0.0^{4,11}.0^{5,9}.0^{8,12}] dodec-2-yne (**13**) to cyclohexene (**35**) is predicted to proceed through a dicarbene, rather than biradical, intermediate (See Supplementary Table 1 and Supplementary Figs. 12 and 13).

Alkynes that are less thermodynamically stable than their corresponding alkylidene carbenes can also be trapped with the use of an appropriate reaction partner. Calculations at the DLPNO-CCSD(T)/

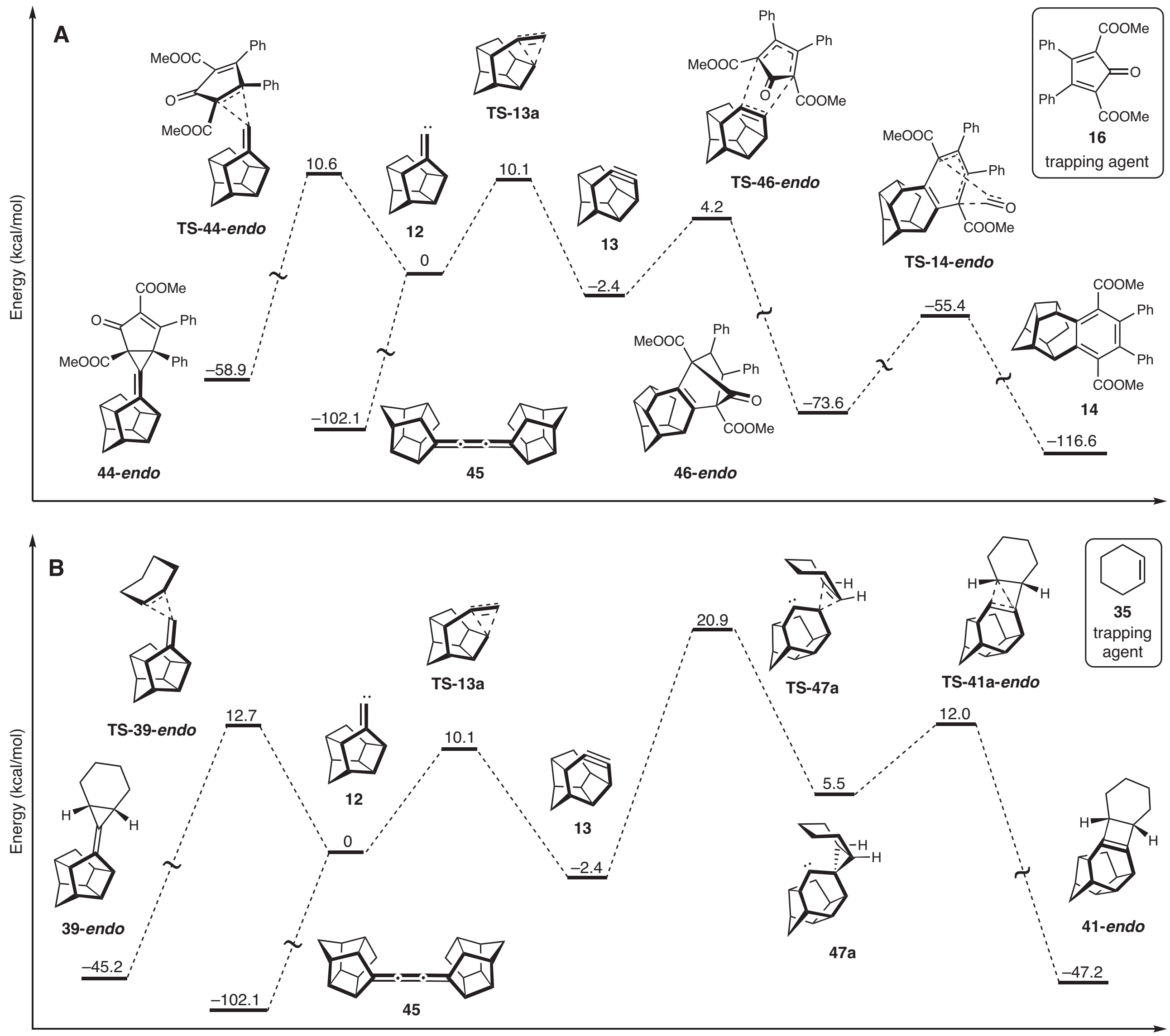

Fig. 9 | Potential energy surface for the reactions of 8-pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecylidene carbene (12) and pentacyclo[5.5.0.0^{4,11}.0^{5,9}.0^{8,12}]dodec-2-yne (13). **A** In the presence of diene **16**. **B** In the presence of cyclohexene (**35**). See Supplementary Fig. 8 for a comprehensive analysis of the addition of diene **16** to alkylidene carbene **11** and alkyne **13**, and Supplementary Fig. 9–13 for the addition of cyclohexene (**35**) to alkylidene carbene **11** and alkyne **13**. Computed at DLPNO-CCSD(T)/CPCM$_{\text{(benzene)}}$/def2-TZVPP//M06/CPCM$_{\text{(benzene)}}$/def2-TZVP. See Supplementary Data 1 for the cartesian coordinates of the optimized structures.

CPCM$_{\text{(benzene)}}$/def2-TZVPP//M06/CPCM$_{\text{(benzene)}}$/def2-TZVP[40–47] level of theory predict pentacyclo[6.4.0.0^{3,7}.0^{4,12}.0^{6,11}]dodec-9-yne (**6**) to be less stable than 2-pentacyclo[6.3.0.0^{3,7}.0^{4,11}.0^{6,10}]undecylidene carbene (**5**) by 4.5 kcal/mol, with a free activation energy of rearrangement of 12.3 kcal/mol (Fig. 10A). The presence of the triple bond is moreover predicted to incur 52.1 kcal/mol of strain energy to alkyne **6** (See Supplementary Fig. 2). Nevertheless, the intramolecular rearrangement of alkylidene carbene **5** to alkyne **6** may potentially outcompete the intermolecular trapping of the carbene, processes which have similar activation energies (10.5 and 12.3 kcal/mol, Fig. 10A). Once alkyne **6** is formed, its reaction with diene **16** becomes the energetically favorable pathway. Precursor **50** was therefore synthesized, using methods similar to those employed for the synthesis of **22** and **29** (See Synthetic Procedures), with the aim of trapping pentacyclo[6.4.0.0^{3,7}.0^{4,12}.0^{6,11}]dodec-9-yne (**6**).

Despite the large free activation energy for the formation of pentacyclo[6.4.0.0^{3,7}.0^{4,12}.0^{6,11}]dodec-9-yne (**6**), and an equilibrium that predicts **6** to exist at a concentration less than 0.05% that of undecylidene carbene **5**, the cycloalkyne **6** was successfully trapped with diene **16** following the photolysis of precursor **50** (Fig. 10B). Based on the yields of phenanthrene (**30**) and rearrangement product **51**, 18% of the undecylidene carbene **5** generated during photolysis was trapped as cycloalkyne **6** via reaction with diene **16**. The yield of Diels–Alder adduct **15** is comparable to that of **14** following the photolysis of **29** (Fig. 6), despite the different thermodynamic relationships between alkylidene carbene and alkyne within the two reactions (Fig. 9A, Fig. 10A). The comparable yields of **14** and **15** indicate that the activation energies for FBW rearrangement, which are similarly high for undecylidene carbenes **12** and **5**, may be a large determinant of yield in these reactions.

In conclusion, we have demonstrated that the photochemical generation of exocyclic alkylidene carbenes provides a useful strategy for generating highly strained caged alkynes, and have employed this method for the generation of bicyclo[2.2.2]oct-2-yne (**10**), pentacyclo[5.5.0.0^{4,11}.0^{5,9}.0^{8,12}]dodec-2-yne (**13**), and pentacyclo[6.4.0.0^{3,7}.0^{4,12}.0^{6,11}]dodec-9-yne (**6**) all of which were previously considered to be

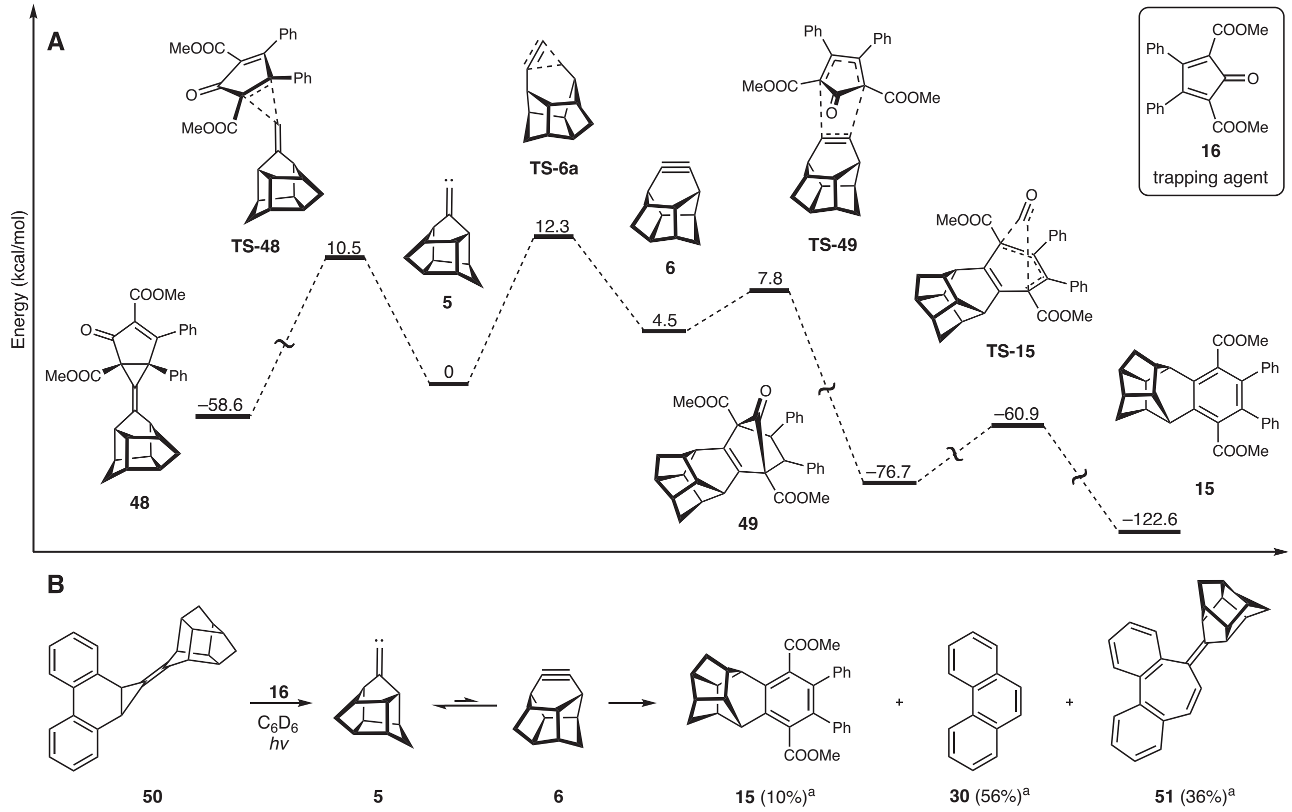

Fig. 10 | Trapping of pentacyclo[6.4.0.0^{3,7}.0^{4,12}.0^{6,11}]dodec-9-yne (6). **A** Potential energy surface for the reactions of 2-pentacyclo[6.3.0.0^{3,7}.0^{4,11}.0^{6,10}]undecylidene carbene (**5**) and pentacyclo[6.4.0.0^{3,7}.0^{4,12}.0^{6,11}]dodec-9-yne (**6**) with diene **16**, computed at DLPNO-CCSD(T)/CPCM$_{(\text{benzene})}$/def2-TZVPP//M06/CPCM$_{(\text{benzene})}$/def2-TZVP. See Supplementary Data 1 for the cartesian coordinates of the optimized structures. **B** Photolysis of precursor **50** in the presence of diene **16** resulted in the formation of adduct **15**, the expected product of reaction between **6** and **16**.

thermodynamically inaccessible[21]. While computational experiments predicted **10** and **13** to be more stable than their corresponding alkylidene carbenes, **6** is expected to be less stable than undecylidene carbene **5**. Alkyne **6** can still be trapped, however, with an appropriate reaction partner. The results herein demonstrate that the use of chemical trapping experiments for the investigation of alkyne–carbene equilibria in FBW rearrangements is a problematic approach. The results of trapping experiments reflect the differences in the absolute free activation energies for the trapping of the two intermediates, in addition to the activation energies of FBW rearrangement, rather than the thermodynamic relationships of the intermediates themselves. With the use of different trapping agents, alkylidene carbenes **9** and **12** as well as their corresponding cycloalkynes **10** and **13** could all be intercepted in the present work. The relative stabilities of the alkylidene carbene and alkyne is less consequential, in regards both to their trapping and their potential synthetic utility, than the reactive partner used and the activation energy for FBW rearrangement.

Methods

General notes

Tetrahydrofuran was degassed by purging with nitrogen, and dried by passage through two activated alumina columns (2 ft × 4 in). Other solvents and reagents were used as obtained from commercial sources. Medium-pressure flash chromatography was performed on an automated system using prepacked silica gel columns (70–230 mesh), or by hand using Sorbtech silica gel 60 A (35 × 70 mesh) with the indicated eluents. $AgNO_3$-treated silica gel was prepared as follows: To a solution of $AgNO_3$ (12.0 g) in acetonitrile (100 mL) was added silica gel (40 g). The mixture was stirred, and the resulting slurry was heated at 80 °C in vacuo on a rotary evaporator for 2 h, then allowed to cool to room temperature and stored in a foil-covered flask. Proton (^{1}H) and proton-decoupled carbon ^{13}C{^{1}H} NMR spectra were recorded in $CDCl_3$ and C_6D_6 at 500 and 126 MHz, respectively. The data are reported as follows: chemical shift in ppm referenced to residual solvent (^{1}H NMR: $CDCl_3$ δ 7.26; ^{13}C NMR: $CDCl_3$ δ 77.2, multiplicity, coupling constants (Hz), and integration. Structures were determined using COSY, HSQC, and HMBC experiments. Overlapping carbon peaks were identified using HSQC experiments and the integration of ^{13}C NMR spectra. Product yields in unpurified reaction mixtures were determined by ^{1}H NMR spectroscopy using 1,3-benzodioxole and p-xylene as internal standards. High-resolution mass spectra (HRMS) data were obtained on an Agilent 6230 TOF Mass Spectrometer. Infrared spectra (resolution 4.0 cm^{-1}) were acquired on solid samples with an FTIR instrument equipped with an attenuated total reflectance (ATR) accessory. Photolysis experiments were conducted with a Newport 200 W Xe-Hg arc lamp (model # 6290; horizontal intensity 600 cd) with a Newport 280–400 dichroic mirror (model # 66245) fitted in a Newport 67005 Housing with a Newport 69907 Universal Arc Lamp Power Supply. All photolysis reactions were conducted in quartz glassware positioned 30 cm away from the light source. All reactions were performed under an atmosphere of argon in glassware that had been dried in an oven at 120 °C unless otherwise stated.

Synthetic procedures

7-*tert*-butoxynorbornadiene (18). Following the procedure of Kozel et al.[50], to a refluxing mixture of norbornadiene (**17**, 45.3 g, 492 mmol) and cuprous bromide (0.109 g, 0.756 mmol) in benzene (150 mL) under argon atmosphere was added a solution of *tert*-butylperoxybenzoate

(36.0 mL, 189 mmol) in benzene (30 mL) over 20 min. The reaction mixture was stirred an additional 30 min, then cooled to room temperature and washed with 10% aqueous sodium carbonate (3 × 100 mL), followed by H_2O (2 ×100 mL). The organic phase was then dried (Na_2SO_4), and the benzene was removed *in vacuo*. Distillation under reduced pressure afforded 7-*tert*-butoxynorbornadiene (**18**) as a colorless oil (10.5 g, 34%). The spectroscopic data are in agreement with those previously reported[66]: ^1H NMR (500 MHz, $CDCl_3$) δ 6.54 (t, *J* = 2.2 Hz, 2H), 6.49 (t, *J* = 2.2 Hz, 2H), 6.50–6.48 (m, 2H), 3.68 (s, 1H), 3.32–3.28 (m, 2H), 1.04 (s, 9H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 139.9, 137.4, 104.4, 73.7, 55.6, 28.4. HRMS (ESI) *m/z*: [M• − *t*-Bu]$^+$ Calcd for $C_{11}H_{16}O$ 107.0497; Found 107.0499.

7-(*tert*-butoxy)bicyclo[2.2.1]heptane (19). Following the procedure of Felpin and Fouquet[49], to a stirring solution of 7-*tert*-butoxynorbornadiene (**18**, 9.50 g, 58.0 mmol) in methanol (75 mL) was added a mixture of palladium acetate (0.013 g, 0.058 mmol) and charcoal (0.117 g). The reaction mixture was flushed with hydrogen gas, then stirred under an atmosphere of hydrogen until diene **18** was fully consumed, as determined by GC-MS. The reaction mixture was then filtered through a plug of Celite, and the solvent was removed *in vacuo*. Purification by flash column chromatography (3:97 Et_2O:pentane) afforded 7-(*tert*-butoxy)bicyclo[2.2.1]heptane (**19**) as a colorless oil (4.09 g, 43%). The spectroscopic data are in agreement with those previously reported[49]: ^1H NMR (500 MHz, $CDCl_3$) δ 3.69 (s, 1H), 1.89–1.80 (m, 4H), 1.56–1.49 (m, 2H), 1.21–1.15 (m, 11H), 1.13–1.09 (m, 2H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 79.4, 72.8, 40.2, 28.6, 27.4, 26.5. HRMS (ESI) *m/z*: [M• − *t*-Bu]$^+$ Calcd for $C_{11}H_{20}O$ 111.0810; Found 111.0808.

7-norbornol (20). Following the procedure of Rosenkoetter et al.[51], iodotrimethylsilane (3.7 mL, 26 mmol) was added to a solution of 7-(*tert*-butoxy)bicyclo[2.2.1]heptane (**19**, 5.2 g, 26 mmol) in chloroform (45 mL).The reaction mixture was stirred 20 min at room temperature, then poured into a slurry of sodium carbonate (7.4 g) in methanol (150 mL) and stirred an additional 10 min. The suspension was then filtered, and the filtered solid was washed with methanol (150 mL). The combined filtrates were concentrated *in vacuo*, then suspended in 10% aqueous sodium thiosulfate (185 mL) and stirred 1 h. The mixture was then extracted with diethyl ether (3 ×100 mL), and the combined organic phases were dried (Na_2SO_4), filtered, and concentrated *in vacuo* to afford 7-norbornol (**20**) as an orange waxy solid (2.20 g, 98%). The spectroscopic data are in agreement with those previously reported[51]: ^1H NMR (500 MHz, $CDCl_3$) δ 3.99 (s, 1H), 3.75–3.67 (m, 1H), 1.96–1.93 (m, 2H), 1.88–1.83 (m, 2H), 1.58–1.53 (m, 2H), 1.30–1.25 (m, 2H), 1.19–1.14 (m, 2H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 79.9, 40.4, 26.9, 26.7. HRMS (ESI) *m/z*: [M• − H]$^+$ Calcd for $C_7H_{12}O$ 111.0810; Found 111.0810.

7-norbornone (21). Following the procedure of Rosenkoetter et al.[51], to a suspension of pyridinium chlorochromate (5.39 g, 25.0 mmol) in dichloromethane (300 mL) was added a solution of 7-norbornol (**20**, 1.12 g, 10.0 mmol) in dichloromethane (150 mL). The reaction mixture was stirred until 7-norbornol (**20**) was completely consumed, as determined by GC-MS. Diethyl ether (150 mL) was then added and the mixture was stirred 30 min, then transferred to a separatory funnel and extracted with diethyl ether (150 mL). The organic phase was washed with H_2O (3 ×400 mL), dried (Na_2SO_4), filtered, and concentrated *in vacuo*. Purification by column chromatography (Et_2O) yielded 7-norbornone (**21**) as a pale oil (0.588 g, 53%). The spectroscopic data are in agreement with those previously reported[51]: ^1H NMR (500 MHz, $CDCl_3$) δ 1.96–1.89 (m, 4H), 1.87–1.84 (m, 2H), 1.60–1.54 (m, 4H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 217.9, 38.1, 24.3. HRMS (ESI) *m/z*: [M• − H]$^+$ Calcd for $C_7H_{10}O$ 109.0653, Found 109.0652.

Precursor 22. Following the procedure of Takeda et al.[53], to a round-bottom flask charged with magnesium turnings (0.729 g, 30.0 mmol) and 4 Å molecular sieves (1.50 g) was added bis(cyclopentadienyl) titanium(IV) dichloride (7.47 g, 30.0 mmol) followed by anhydrous THF (60 mL). Triethyl phosphite (10.3 mL, 60.0 mmol) was added and the reaction mixture was stirred for 3 h, during which the color of the mixture turned from red to dark green. A solution of dichlorocyclopropyl phenanthrene **23** (2.62 g, 10.0 mmol) dissolved in THF (20 mL) was added and the reaction mixture was stirred for an additional 30 min. 7-Norbornone (**21**, 0.55 g, 5.0 mmol) in THF (5 mL) was then added, and the reaction mixture was stirred for an additional 16 h. Hexanes (200 mL) was added, and the resulting suspension was transferred to a plug of silica and eluted with hexanes (100 mL) followed by a solution of hexanes and ethyl acetate (10:90, 100 mL). The elution was concentrated *in vacuo*. Purification of the resulting residue by flash chromatography with silica gel (hexanes) followed by flash column chromatography with $AgNO_3$-treated silica gel (30% $AgNO_3$, 2:98→20:80 ethyl acetate:hexanes) afforded precursor **22** (0.330 g, 23%) as a white solid: mp = 130–133 °C. ^1H NMR (500 MHz, $CDCl_3$) δ 7.97–7.90 (m, 2H), 7.41–7.35 (m, 2H), 7.26–7.19 (m, 4H), 3.16 (s, 2H), 2.41 (s, 2H), 1.73–1.65 (m, 2H), 1.37–1.30 (m, 2H), 1.11–0.97 (m, 4H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 139.2, 134.8, 129.2, 128.6, 127.7, 125.8, 123.3, 108.1, 38.4, 29.3, 28.7, 22.3. IR (ATR) 2954, 2862, 1486, 1441, 763, 730, 615 cm^{-1}. HRMS (ESI) *m/z*: [M• − H]$^+$ Calcd for $C_{22}H_{20}$ 283.1487; Found 283.1499.

8-pentacyclo[5.4.0.0^{2,6}.^{03,10}.0^{5,9}]undecan-8,11-dione (24). Following the procedure of Gaidai et al.[67], racemic (1*R*,4*S*,4a*R*,8a*S*)-1,4,4a,8a-tetrahydro-1,4-methanonaphthalene-5,8-dione (**54**, 7.05 g, 40.5 mmol) was dissolved in ethyl acetate (50 mL) in a quartz cuvette, positioned in front of a mercury-xenon lamp and irradiated for 36 h. The solvent was then removed *in vacuo*, and purification of the resulting solid by flash chromatography (1:1 ethyl acetate:hexanes) afforded 8-pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecan-8,11-dione (**24**) as white crystals (6.29 g, 89%). The spectroscopic data are in agreement with those previously reported[67]: ^1H NMR (500 MHz, $CDCl_3$) δ 3.20–3.15 (m, 2H), 2.96–2.92 (m, 2H), 2.84–2.80 (m, 2H), 2.71 (s, 2H), 2.07–2.03 (m, 1H), 1.91–1.87 (m, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 212.3, 54.9, 44.8, 43.9, 40.6, 38.9. HRMS (ESI) *m/z*: [M + Na]$^+$ Calcd for $C_{11}H_{10}O_2$ 197.0573; Found 197.0575.

Caged acetal 25. Following the procedure of Eaton et al.[68], a mixture of 8-pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecan-8,11-dione (**24**, 10.0 g, 57.5 mmol), ethylene glycol (3.95 g, 63.6 mmol), and *p*-toluene sulfonic acid (0.125 g, 0.726 mmol) in benzene (50 mL) was heated under reflux (85 °C) in a heating mantle for 14 h. The reaction mixture was then cooled to room temperature and slowly poured into ice-cold 10% aqueous sodium bicarbonate (50 mL). The organic phase was separated and the aqueous phase was extracted with dichloromethane (2 ×50 mL). The combined organic layers were dried over Na_2SO_4, filtered, and concentrated *in vacuo*. Recrystallization of the resulting solid from ether-hexane (1:1) afforded caged acetal **25** as a white solid (11.18 g, 89%). The spectroscopic data are in agreement with those previously reported[68]: ^1H NMR (500 MHz, $CDCl_3$) δ 3.97–3.82 (m, 4H), 3.00–2.93 (m, 1H), 2.84–2.78 (m, 2H), 2.69–2.52 (m, 3H), 2.53–2.41 (m, 2H), 1.87 (d, *J* = 11.0 Hz, 1H), 1.58 (d, *J* = 11.0 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 215.4, 114.1, 65.9, 64.8, 53.2, 50.9, 46.0, 43.0, 42.5, 41.6, 41.5, 38.9, 36.5. HRMS (ESI) *m/z*: [M + H]$^+$ Calcd for $C_{13}H_{14}O_3$ 219.1016; Found 219.1006.

Caged hydroxy-ketone 26. Following the procedure of Dekker and Oliver[69], caged acetal **25** (9.00 g, 41.3 mmol) was added via solid addition funnel to a suspension of lithium aluminum hydride (0.788 g, 20.8 mmol) in dry diethyl ether (50 mL) over 10 min. The reaction mixture was heated under reflux (35 °C) for 2 h, then cooled to 0 °C in an ice bath. Saturated aqueous ammonium chloride (20 mL) was added slowly, then the organic layer was separated and concentrated *in vacuo*. 6% Aqueous HCl (180 mL) was added to the resulting solid, and the mixture was stirred for 2 h. The solution was then neutralized with 10% aqueous NaOH, then extracted with dichloromethane (3 ×100 mL). The combined organic phases were dried over Na_2SO_4, filtered, and concentrated *in vacuo* to afford caged hydroxy-ketone **26** as a white solid (6.11 g, 84%). The spectroscopic data are in agreement with those previously reported[69]: ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.64 (t, *J* = 5.2 Hz, 0.5 H, H_A), 4.15–4.01 (m, 0.5 H, H_A), 3.82–3.68 (m, 0.5 H, H_B), 3.05–2.36 (m, 8H), 2.32–2.19 (m, 0.5 H, H_B), 1.89 (t, *J* = 12.2 Hz, 1H), 1.56 (d, *J* = 10.5 Hz, 0.5 H), 1.50 (d, *J* = 11.0 Hz, 0.5 H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 219.3, 119.4, 81.8, 72.4, 56.4, 55.1, 54.3, 50.0, 46.1, 45.4, 45.0, 44.8, 43.6, 43.4, 43.2, 42.2, 42.0, 41.8, 41.7, 40.8, 38.5, 37.0. HRMS (ESI) *m/z*: [M + H]$^+$ Calcd for $C_{11}H_{12}O_2$ 177.0910; Found 177.0902.

8-pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecan-8-ol (27). Following the procedure of Dekker and Oliver[69], a mixture of caged hydroxy-ketone **26** (3.00 g, 17.0 mmol) and hydrazine monohydrate (4.97 mL, 102 mmol) in diethylene glycol (60 mL) was heated at 120 °C in a heating mantle for 1.5 h. Potassium hydroxide (2.34 g, 41.7 mmol) was then added and the excess hydrazine and H_2O were distilled off until the temperature reached 190 °C. The reaction mixture was heated under reflux at 190 °C for 3 h and then steam distilled. Extraction of the distillate with dichloromethane afforded caged 8-pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecan-8-ol (**27**, 1.68 g, 61%) as a white solid. The spectroscopic data are in agreement with those previously reported[69]: ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.96–3.91 (m, 1H), 2.76–2.70 (m, 1H), 2.65–2.59 (m, 1H), 2.58–2.52 (m, 1H), 2.46–2.38 (m, 2H), 2.31–2.19 (m, 4H), 1.72–1.67 (m, 1H), 1.44–1.41 (m, 1H), 1.19–1.14 (m, 1H), 1.08 (dt, *J* = 11.9, 3.9 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 74.5, 47.2, 45.9, 43.2, 42.15, 42.14, 40.0, 39.0, 36.0, 35.3, 28.9. HRMS (ESI) *m/z*: [M + H − H_2O]$^+$ Calcd for $C_{11}H_{14}O$ 145.1017; found 145.1015.

8-pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecan-8-one (28). Following the procedure of Dekker and Oliver[69], chromium trioxide (1.60 g, 16.0 mmol) in H_2O (2.4 mL) was added to caged alcohol **28** (1.30 g, 8.00 mmol) in 94% aqueous acetic acid (26 mL). The suspension was heated at 90 °C for 4 h, then cooled to room temperature and diluted with H_2O (120 mL). The mixture was extracted with dichloromethane (3 ×20 mL), and the combined organic phases were washed with H_2O (2 ×40 mL, saturated aqueous $NaHCO_3$ (2 ×40 mL), and again with H_2O (40 mL). The organic layer was then dried over Na_2SO_4, filtered, and concentrated *in vacuo* to yield 8-pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecan-8-one (**28**, 1.13 g, 88%) as a white solid. The spectroscopic data are in agreement with those previously reported[69]: ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.02–2.89 (m, 2H), 2.82–2.67 (m, 2H), 2.61–2.47 (m, 3H), 2.35–2.27 (m, 1H), 1.91–1.84 (m, 1H), 1.56–1.38 (m, 3H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 221.8, 53.2, 48.8, 48.5, 44.7, 43.9, 43.5, 39.7, 37.8, 36.9, 31.3. HRMS (ESI) *m/z*: [M + H]$^+$ Calcd for $C_{11}H_{12}O$ 161.0961; Found 161.0967.

Precursor 29. Following the procedure for the synthesis of **22**, magnesium turnings (0.365 g, 15.0 mmol), 4 Å molecular sieves (0.750 g), bis(cyclopentadienyl)titanium(IV) dichloride (3.73 g, 15.0 mmol), triethyl phosphite (5.14 mL, 30.0 mmol), dichlorocyclopropyl phenanthrene **23** (1.31 g, 5.00 mmol, in 10 mL THF), and caged ketone **28** (0.400 mL, 2.50 mmol, in 10 mL THF) were combined in THF (30 mL) to yield **29** as a mixture of diastereomers in a 1.0:0.8 ratio. Purification of the resulting residue by flash chromatography with silica gel (hexanes) followed by flash column chromatography with $AgNO_3$-treated silica gel (30% $AgNO_3$, 2:98→20:80 ethyl acetate:hexanes) afforded precursor **29** (0.213 g, 25%) as a mixture of diastereomers in a 1.0:1.0 ratio as a white solid: mp = 104–110 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.96–7.89 (m, 4H), 7.41–7.31 (m, 4H), 7.27–7.19 (m, 8H), 3.17–3.13 (m, 2H), 3.13–3.09 (m, 2H), 2.95–2.90 (m, 1H), 2.85–2.80 (m, 1H), 2.78–2.61 (m, 4H), 2.56–2.42 (m, 3H), 2.42–2.35 (m, 2H), 2.35–2.30 (m, 1H), 2.28–2.24 (m, 1H), 2.16–2.11 (m, 1H), 2.11–2.05 (m, 1H), 1.81–1.78 (m, 1H), 1.64 (d, *J* = 10.5 Hz, 1H), 1.56 (d, *J* = 10.5 Hz, 1H), 1.35 (d, *J* = 11.8 Hz, 1H), 1.25 (d, *J* = 10.5 Hz, 1H), 1.20–1.12 (m, 2H), 0.62 (dt, *J* = 11.9, 3.8 Hz, 1H), 0.45 (d, *J* = 11.9 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 135.6, 135.1, 135.0, 134.9, 134.53, 134.52, 129.33, 129.32, 129.30, 129.2, 128.9, 128.8, 128.58, 128.55, 127.74, 127.73, 127.71, 127.66, 125.80, 125.78 (2 C), 125.75, 123.4, 123.31, 123.30, 123.29, 114.1, 113.6, 48.3, 48.0, 46.93, 46.91, 46.86, 46.15, 45.8, 45.4, 43.1, 42.9 (2 C), 42.8, 41.1, 40.8, 39.3, 38.8, 35.3, 35.2, 30.4, 29.4, 22.29, 22.26, 22.1, 22.0. IR (ATR) 2954, 1485, 1440, 768, 730, 616 cm^{-1}. HRMS (ESI) *m/z*: [M + H]$^+$ Calcd for $C_{26}H_{22}$ 335.1794; Found 335.1802.

Photolysis of precursor 22 with diene 16. Precursor **22** (0.135 g, 0.475 mmol) and 2-oxo-4,5-diphenyl-cyclopenta-3,5-diene-1,3-dicarboxylic acid dimethylester (**16**, 0.188 g, 0.540 mmol) were combined in deuterated benzene (5 mL) in a quartz cuvette. The reaction mixture was placed in front of a mercury-xenon lamp and irradiated for 6 h, at which point precursor **22** had been consumed, as determined by ^{1}H NMR spectroscopy. The solvent was removed *in vacuo*, and purification by flash column chromatography (0:100→10:90 ethyl acetate:hexanes) afforded adduct **11** as a white solid (0.065 g, 32%): mp = 193–195 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.14–7.07 (m, 6H), 7.04–6.99 (m, 4H), 3.49 (s, 6H), 3.14 (s, 2H), 1.90–1.77 (m, 4H), 1.57–1.48 (m, 4H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 169.5, 140.9, 138.9, 136.2, 131.5, 130.2, 127.5, 126.8, 52.0, 31.8, 25.7. IR (ATR) 2948, 1726, 1233, 1197, 1077, 699 cm^{-1}. HRMS (ESI) *m/z*: [M + H]$^+$ Calcd for $C_{28}H_{26}O_4$ 427.1904; Found 427.1911

Photolysis of precursor 22. Precursor **22** (0.114 g, 0.40 mmol) was dissolved in benzene (4 mL) in a quartz cuvette, positioned in front of a mercury–xenon lamp, and irradiated for 16 h. The solvent was removed *in vacuo*, and purification of the resulting residue by flash chromatography with silica gel (hexanes) followed by flash column chromatography with $AgNO_3$-treated silica gel (30% $AgNO_3$, 1:99→10:90 ethyl acetate: hexanes) afforded allene **31** as a white solid (0.023 g, 54%) and rearrangement product **32** as a colorless oil (0.047 g, 41%): Allene **31**: ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.67–2.62 (m, 4H), 1.81–1.74 (m, 8H), 1.47–1.41 (m, 8H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 147.1, 152.4, 42.5, 29.5. IR (ATR) 2945, 2862, 1450, 1297, 1120, 733 cm^{-1}. HRMS (ESI) *m/z*: [2 M + H]$^+$ Calcd for $C_{16}H_{20}$ 425.3203; Found 425.3202. Rearrangement product **32**: 7.65–7.60 (m, 1H), 7.53–7.48 (m, 1H), 7.37–7.29 (m, 4H), 7.25–7.20 (m, 1H), 7.13–7.09 (m, 1H), 6.60 (d, *J* = 11.2 Hz, 1H), 6.48 (d, *J* = 11.2 Hz, 1H), 2.73 (t, *J* = 4.0 Hz, 1H), 2.60 (t, *J* = 4.0 Hz, 1H), 1.92–1.78 (m, 2H), 1.53–1.23 (m, 6H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 151.9, 143.7, 139.9, 138.5, 136.6, 134.6, 130.5, 130.4, 129.5, 129.4, 128.9, 127.5, 127.0, 126.9, 126.7, 121.5, 36.8, 36.3, 29.8, 29.3, 28.9, 28.2. IR (ATR) 2947, 2864, 1482, 1436, 907, 760, 728 cm^{-1}. HRMS (ESI) *m/z*: [M + H]$^+$ Calcd for $C_{22}H_{20}$ 285.1638; Found 285.1617.

Photolysis of precursor 29 with diene 16. Following the procedure for the photolysis of **22**, Precursor **29** (0.167 g, 0.500 mmol) and 2-oxo-4,5-diphenyl-cyclopenta-3,5-diene-1,3-dicarboxylic acid dimethylester (**16**, 0.174 g, 0.500 mmol) in deuterated benzene (5 mL) were irradiated for 10 h, at which point precursor **29** had been consumed, as determined by ^{1}H NMR spectroscopy. Purification of the resulting residue by flash chromatography (0:100→10:90 ethyl acetate:hexanes) afforded adduct **14** as a white solid (0.241 g, 10%): Upon heating for melting point analysis, **29** turned from a white crystalline solid to a waxy yellow solid at 70–76 °C. The waxy solid melted at 181–184 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.18–6.87 (m, 10H), 3.69 (t, *J* = 8.5 Hz, 1H), 3.49–3.46 (m, 6H), 3.12 (ddd, *J* = 10.1, 3.4, 2.1 Hz, 1H), 2.91–2.80 (m, 2H), 2.74–2.66 (m, 1H), 2.62–2.57 (m, 1H), 2.47 (dt, *J* = 10.1, 4.5 Hz, 1H), 2.09–2.04 (m, 1H), 1.74 (d, *J* = 10.1 Hz, 1H), 1.47 (d, *J* = 10.1 Hz, 1H), 1.40

(dt. J = 13.2, 5.4 Hz, 1H), 0.97 (d, J = 13.2 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 169.9, 169.7, 138.69, 138.65, 137.5, 136.8, 136.6, 134.6, 134.4, 133.3, 130.2, 129.9, 127.5 (2 C), 126.83, 126.82, 51.97, 51.96, 48.9, 45.6, 44.7, 43.1, 40.2, 39.1, 37.0, 36.2, 34.6, 31.4. IR (ATR) 2948, 1727, 1339, 1200, 1141, 699 cm^{-1}. HRMS (ESI) *m/z*: [M + H]$^+$ Calcd for $C_{32}H_{28}O_4$ 477.2060; Found 477.2074.

Photolysis of precursor 22 in cyclohexene (35). Precursor **22** (0.172 g, 0.605 mmol) was dissolved in cyclohexene (6 mL) and transferred to a quartz cuvette. The reaction mixture was placed in front of a mercury-xenon lamp and irradiated until the starting material was consumed, as determined by H^1 NMR spectroscopy (4 h). The reaction mixture was concentrated *in vacuo*, and purification by flash chromatography (1:99 ethyl acetate:hexanes) afforded adduct **36** as a colorless oil (0.040 g, 35%): ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.54–2.49, (m, 2H), 1.80–1.72 (m, 2H), 1.70–1.60 (m, 6H), 1.59–1.53 (m, 2H), 1.40–1.34 (m, 4H), 1.24–1.17 (m, 4H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 137.3, 113.4, 38.4, 29.5, 29.4, 23.4, 21.6, 12.8. IR (ATR) 2924, 2856, 1490, 1546, 745, 720 cm^{-1}. HRMS (ESI) *m/z*: [M• – H]$^+$ Calcd for $C_{14}H_{20}$ 187.1487; Found 187.1459.

Dichlorospirocyclopropane 37. To a mixture of adduct **36** (0.40 g, 0.21 mmol) and benzyltriethylammonium chloride (0.001 g, 0.004 mmol) in chloroform (5 mL) was added 50% aqueous sodium hydroxide (5 mL) slowly. The mixture was heated under reflux overnight, then concentrated *in vacuo*. Purification by flash chromatography (1:99 ethyl acetate:hexanes) afforded dichlorospirocyclopropane **37** as a white solid (0.038 g, 66%): mp = 87–89 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.17–2.13 (m, 2H), 2.10–2.05 (m, 2H), 1.98–1.89 (m, 2H), 1.88–1.83 (m, 2H), 1.62–1.54 (m, 4H), 1.49–1.40 (m, 4H), 1.37–1.20 (m, 4H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 70.4, 52.0, 41.0, 37.2, 30.9, 29.0, 21.8, 21.6, 20.4. IR (ATR) 2924, 2851, 1456, 880, 812, 791 cm^{-1}. HRMS (ESI) *m/z*: [M – Cl]$^+$ Calcd for $C_{15}H_{20}Cl_2$ 235.1253; Found 235.1235.

Photolysis of precursor 29 in cyclohexene (35). Precursor **29** (0.125 g, 0.370 mmol) was dissolved in cyclohexene (5 mL) and transferred to an argon-flushed quartz cuvette. The reaction mixture was placed in front of a mercury-xenon lamp and irradiated until the starting material was consumed, as determined by GC/MS (8 h). The reaction mixture was concentrated *in vacuo*, and purification by flash chromatography (1:99 ethyl acetate:hexanes) afforded adduct **39** as a mixture of diastereomers in a 1.0:0.5 ratio as a colorless oil (0.035 g, 40%): ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.00–2.92 (m, 1.5H), 2.82–2.58 (m, 6H), 2.50–2.38 (m, 1.5H), 2.35–2.20 (m, 3H), 1.82–1.64 (m, 6H), 1.63–1.54 (m, 2H), 1.53–1.44 (m, 2.5H), 1.41 (d, J = 11.8 Hz, 1H), 1.34–1.09 (m, 9.5H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 132.7, 132.6, 120.9, 120.3, 48.5, 48.3, 47.2, 47.0, 46.6, 46.3, 45.5, 45.1, 43.17, 43.16, 43.08, 43.06, 41.3, 41.0, 39.1, 38.7, 35.3, 35.2, 30.31, 30.28, 23.81, 23.78, 23.1, 23.0, 21.9, 21.8, 21.6, 21.5, 12.7, 12.6, 12.5, 12.4. IR (ATR) 2925, 2850, 1446 cm^{-1}. HRMS (ESI) *m/z*: [M + K]$^+$ Calcd for $C_{18}H_{22}$ 277.1353; Found 277.1331.

Dichlorospirocyclopropane 40. To a mixture of alkene **39** (0.060 g, 0.252 mmol) and benzyltriethylammonium chloride (0.001 g, 0.004 mmol) in chloroform (5 mL) was added 50% aqueous sodium hydroxide (5 mL) slowly. The mixture was heated under reflux overnight, then concentrated *in vacuo*. Purification by flash chromatography (1:99 ethyl acetate:hexanes) afforded dichlorospirocyclopropane **40** as a white solid (0.080 g, 99%). **40** was characterized as a single diastereomer **40-endo** which was obtained by recrystallization with hexanes: mp = 114–117 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.81–2.70 (m, 2H), 2.69–2.54 (m, 3H), 2.41–2.25 (m, 3H), 2.01–1.88 (m, 2H), 1.78–1.69 (m, 2H), 1.55–1.30 (m, 9H), 1.23 (dt, J = 11.8, 3.9 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 73.8, 47.6, 47.3, 45.3, 42.8, 42.7, 42.4, 42.1, 40.8, 39.0, 36.3, 34.3, 29.2, 21.034, 21.026, 21.21, 21.20, 19.9, 19.7. IR (ATR) 2934, 2854, 1446, 1304, 1023, 600 cm^{-1}. HRMS (ESI) *m/z*: [M – Cl]$^+$ Calcd for $C_{19}H_{22}Cl_2$ 285.1410; Found 285.1417.

Racemic (1*R*,4*S*,4a*R*,8a*S*)-1,4,4a,8a-tetrahydro-1,4-methanonaphthalene-5,8-dione 54. Following the procedure of Gaidai et al.[67], freshly distilled cyclopentanone (7.50 mL, 91.0 mmol) was added to a suspension of 1,4-benzoquinone (**53**, 10.8 g, 100 mmol) in ethanol (22 mL) stirring at 0 °C in an ice bath. The mixture was heated to 70 °C for 15 min, then cooled to 0 °C overnight. The resulting precipitate was filtered, washed with cold ethanol, then dried *in vacuo* to afford adduct **54** as a yellow solid (11.1 g, 70%). The spectroscopic data are in agreement with those previously reported[67]: ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.56 (s, 2H), 6.05 (s, 2H), 3.56–3.51 (m, 2H), 3.23–3.18 (m, 2H), 1.53 (dt, J = 8.8, 1.8 Hz, 1H), 1.44–1.40 (m, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 199.6, 142.2, 135.4, 48.9, 48.8, 48.5. HRMS (ESI) *m/z*: [M + Na]$^+$ Calcd for $C_{11}H_{10}O_2$ 197.0573; Found 197.0572.

8-pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecan-8,11-diol (55). Following the procedure of Gaidai et al.[67], caged diketone **24** (6.27 g, 36.0 mmol) in THF (30 mL) was added dropwise via an addition funnel to stirred suspension of lithium aluminum hydride (2.05 g, 54.0 mmol) in THF (16 mL). The mixture was heated under reflux for 18 h then cooled to room temperature. H_2O (15 mL) was slowly added, then the mixture was neutralized with the addition of 30% aqueous H_2SO_4. The organic layer was separated, and the aqueous layer was extracted with dichloromethane (3 ×10 mL). The combined organic layers were washed with H_2O (2 ×20 mL), dried (Na_2SO_4), and concentrated *in vacuo* to yield 8-pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecan-8,11-diol (**55**) as a white solid, which was used without any further purification (5.32 g, 83%). The spectroscopic data are in agreement with those previously reported[67]: ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.93 (s, 2H), 3.85 (s, 2H), 2.70–2.64 (m, 2H), 2.60–2.54 (m, 2H), 2.38 (s, 2H), 2.35–2.29 (m, 2H), 1.63 (d, J = 10.5 Hz, 1H), 1.05 (d, J = 10.5 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 72.1, 45.7, 43.2, 40.0, 38.5, 34.6. HRMS (ESI) *m/z*: [M + H]$^+$ Calcd for $C_{11}H_{14}O_2$ 179.1067; Found 179.1067.

7-iodo-pentacyclo[6.3.0.0^{2,6}.0^{3,10}.0^{5,9}]undecan-4-ol (56). Following the procedure of Gaidai et al.[67], 8-pentacyclo[5.4.0.0^{2,6}.0^{3,10}.0^{5,9}]undecan-8,11-diol (**55**, 2.67 g, 15.0 mmol) in hydroiodic acid (20 mL) was heated at 100 °C with stirring for 3 h. The reaction mixture was then cooled to room temperature, poured out into H_2O (50 mL), and then extracted with dichloromethane (3 ×20 mL). The combined organic layers were washed with H_2O (50 mL), 10% aqueous NaOH (50 mL), and H_2O (50 mL), then dried (Na_2SO_4). Concentration of the organic layer *in vacuo* afforded 7-iodo-pentacyclo[6.3.0.0^{2,6}.0^{3,10}.0^{5,9}]undecan-4-ol (**56**) as brown solid, which was used without further purification (3.53 g, 82%). The spectroscopic data are in agreement with those previously reported[67]: ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.29–4.20 (m, 1H), 4.08–3.93 (m, 1H), 3.00–1.99 (m, 9H), 1.43–1.38 (m, 2H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 77.3, 75.7, 57.1, 55.3, 54.7, 54.2, 53.6, 53.5, 51.8, 50.7, 48.8, 45.9, 45.1, 43.2, 41.1, 40.6, 40.3, 40.0, 34.0, 32.5, 32.0, 31.5. HRMS (ESI) *m/z*: [M – I]$^+$ Calcd for $C_{11}H_{13}OI$ 161.0966; Found 161.0962.

4-pentacyclo[6.3.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane acetate (57). Following the procedure of Gaidai et al.[67], zinc dust (7.50 g, 115 mmol) was added in portions to a solution of the unpurified mixture of 7-iodo-pentacyclo[6.3.0.0^{2,6}.0^{3,10}.0^{5,9}]undecan-4-ol (**56**, 2.20 g, 7.64 mmol) in acetic acid (22 mL) heated at 60 °C. The mixture was heated under reflux for 3 h, cooled to room temperature, then filtered through a plug of celite into a flask with H_2O (40 mL). The unreacted zinc was washed with H_2O (10 mL) and dichloromethane (10 mL), and the filtrate was extracted with dichloromethane (2 ×20 mL). The combined organic layers were washed with H_2O (40 mL) followed by saturated aqueous $NaHCO_3$ (2 ×20 mL), then dried (Na_2SO_4). Concentration of the organic layer *in vacuo* afforded 4-pentacyclo[6.3.0.0^{2,6}.0^{3,10}.0^{5,9}] undecane acetate (**57**) as a pale oil, which was used without further purification (1.42 g, 91%). The spectroscopic data are in agreement with those previously reported[67]: ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.88 (s, 1H), 2.46 (s, 1H), 2.17–1.91 (m, 10H), 1.45 (d, *J* = 10.0 Hz, 1H), 1.38–1.28 (m, 3H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 171.6, 79.8, 50.8, 49.7, 47.5, 47.3, 44.8, 42.7, 41.3, 40.9, 33.7, 33.1, 21.5. HRMS (ESI) *m/z*: [M − OAc]$^+$ Calcd for $C_{13}H_{16}O_2$ 145.1017; Found 145.1018.

pentacyclo[6.3.0.0^{2,6}.0^{3,10}.0^{5,9}]undecan-4-ol (58). Following the procedure of Gaidai et al.[67], potassium hydroxide (3.12 g, 55.7 mmol) was added to a suspension of 4-pentacyclo[6.3.0.0^{2,6}.0^{3,10}.0^{5,9}]undecane acetate (**57**, 1.90 g, 9.30 mmol) in 50% aqueous ethanol (10 mL). The reaction mixture was heated under reflux for 3 h, then cooled to room temperature. 10% Aqueous H_2SO_4 was then added until the solution became slightly acidic. The mixture was extracted with dichloromethane (3 ×10 mL) and the combined organic layers were dried (Na_2SO_4) and concentrated *in vacuo* to afford pentacyclo[6.3.0.0^{2,6}.0^{4,11}.0^{5,9}]undecan-3-ol (**58**) was a pale solid, which was used without further purification (1.12 g, 74%). The spectroscopic data are in agreement with those previously reported[67]: ^{1}H NMR (500 MHz, $CDCl_3$) δ 4.17 (s, 1H), 2.60–2.56 (m, 1H), 2.18–2.03 (m, 5H), 1.98–1.88 (m, 3H), 1.48 (d, *J* = 10.3 Hz, 1H), 1.37–1.29 (m, 3H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 77.5, 53.6, 52.4, 47.6, 47.3, 44.3, 43.3, 41.4, 40.8, 33.8, 33.1. HRMS (ESI) *m/z*: [M + NH_4]$^+$ Calcd for $C_{11}H_{14}O$ 180.1383; Found 180.1383.

pentacyclo[6.3.0.0^{2,6}.0^{3,10}.0^{5,9}]undecan-4-one (59). Following the procedure of Dekker and Oliver[69], chromium trioxide (1.20 g, 12.0 mmol) in H_2O (2.0 mL) was added to caged pentacyclo[6.3.0.0^{2,6}.0^{4,11}.0^{5,9}]undecan-3-ol (**58**, 1.00 g, 6.00 mmol) in 94% aqueous acetic acid (20 mL). The suspension was heated at 90 °C for 4 h, then cooled to room temperature and diluted with H_2O (100 mL). The mixture was extracted with dichloromethane (3 ×20 mL), and the combined organic phases were washed with H_2O (2 ×40 mL, saturated aqueous $NaHCO_3$ (2 ×40 mL), and again with H_2O (40 mL). The organic layer was then dried over Na_2SO_4, filtered, and concentrated *in vacuo* to yield pentacyclo[6.3.0.0^{2,6}.0^{4,11}.0^{5,9}]undecan-3-one (**59**, 0.951 g, 99%) as a white solid. The spectroscopic data are in agreement with those previously reported[69]: ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.48–2.43 (m, 2H), 2.41–2.35 (m, 4H), 1.80–1.75 (m, 2H), 1.68 (dd, *J* = 10.5, 1.6 Hz, 2H), 1.42 (d, *J* = 10.5 Hz, 2H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 217.6, 50.3, 47.7, 41.2, 41.1, 35.7. HRMS (ESI) *m/z*: [M + H]$^+$ Calcd for $C_{11}H_{12}O$ 161.0961; found 161.0957.

Precursor 50. Following the procedure for the synthesis of **22**, magnesium turnings (0.365 g, 15.0 mmol), 4 Å molecular sieves (0.750 g), bis(cyclopentadienyl)titanium(IV) dichloride (3.73 g, 15.0 mmol), triethyl phosphite (5.14 mL, 30.0 mmol), dichlorocyclopropyl phenanthrene **23** (1.31 g, 5.0 mmol, in 10 mL THF), and caged pentacyclo[6.3.0.0^{2,6}.0^{4,11}.0^{5,9}]undecan-3-one (**59**, 0.400 g, 2.50 mmol, in 5 mL THF) were combined in THF (30 mL). Purification by flash column chromatography with silica gel (2:98 ethyl acetate:hexanes) followed by flash column chromatography with $AgNO_3$-treated silica gel (30% $AgNO_3$, 1:99→20:80 ethyl acetate:hexanes) afforded precursor **50** (0.289 g, 37%) as a white solid: mp = 155–157 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.97–7.91 (m, 2H), 7.41–7.34 (m, 2H), 7.26–7.19 (m, 4H), 3.17–3.12 (m, 2H), 2.28–2.16 (m, 3H), 2.10–2.04 (m, 2H), 2.03–1.98 (m, 1H), 1.74–1.67 (q, *J* = 5.8 Hz, 1H), 1.54–1.52 (m, 1H), 1.42 (d, *J* = 10.0 Hz, 1H), 1.31 (d, *J* = 10.0 Hz, 1H), 1.27–1.24 (m, 1H), 1.19 (d, *J* = 10.0 Hz, 1H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 137.9, 134.92, 134.88, 129.4, 129.3, 128.8, 128.7, 127.8, 127.7, 125.79, 125.76, 123.4, 123.3, 108.3, 50.0, 49.8, 47.4, 47.3, 47.0, 46.2, 42.9, 42.7, 34.2, 34.1, 22.3, 22.2. IR (ATR) 2947, 2865, 1485, 1440, 758, 728, 610 cm^{-1}. HRMS (ESI) *m/z*: [M + H]$^+$ Calcd for $C_{26}H_{22}O$ 335.1794; Found 335.1800.

Photolysis of precursor 50 with diene 16. Following the procedure for the photolysis of **22**, Precursor **50** (0.310 g, 0.927 mmol) and 2-oxo-4,5-diphenyl-cyclopenta-3,5-diene-1,3-dicarboxylic acid dimethylester (**16**, 0.323 g, 0.927 mmol) in deuterated benzene (10 mL) were irradiated for 8 h. Purification of the resulting residue by flash chromatography (0:100→10:90 ethyl acetate:hexanes) afford rearrangement product **51** as a colorless oil (0.111 g, 36%). Subsequent flash column chromatography with $AgNO_3$-treated silica gel (30% $AgNO_3$, 1:99→20:80 ethyl acetate:hexanes) afforded adduct **15** as a white solid (0.003 g, 1%): Rearrangement product **51**: ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.65–7.60 (m, 1H), 7.53–7.48 (m, 1H), 7.37–7.29 (m, 4H), 7.25–7.07 (m, 2H), 6.70–6.60 (m, 1H), 6.51–6.43 (m, 1H), 2.61–2.52 (m, 1H), 2.49–2.31 (m, 2H), 2.26–2.10 (m, 3H), 1.98–1.86 (m, 2H), 1.56–1.50 (m, 1H), 1.45–1.26 (m, 3H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 150.9, 150.8, 143.9, 143.7, 139.99, 139.96, 138.7, 138.6, 136.9, 136.8, 135.17, 135.15, 130.6 (2 C), 130.5 (2 C), 130.1, 129.6, 129.53, 129.47, 128.63, 128.57, 127.44, 127.40, 127.04, 126.97, 126.81, 126.80, 126.64, 126.62, 122.7, 122.6, 48.8, 48.7, 48.13, 48.08, 47.7, 47.6, 47.53, 47.46, 47.4, 46.5, 46.0, 45.6, 43.9, 43.6, 42.5, 42.1, 34.6, 34.34, 34.24, 34.14. IR (ATR) 2950, 2867, 1482, 1435, 1279, 906, 757, 727 cm^{-1}. HRMS (ESI) *m/z*: [M + H]$^+$ Calcd for $C_{26}H_{22}O$ 335.1794; Found 335.1800. Adduct **15:** mp = 62–65 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.17–7.02 (m, 8H), 7.00–6.90 (m, 2H), 3.46 (s, 6H), 2.80 (d, *J* = 6.0 Hz, 2H), 2.45–2.40 (m, 2H), 2.00–2.91 (m, 4H), 1.65–1.62 (m, 2H), 1.49–1.45 (m, 2H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 169.6, 139.0, 137.4, 136.2, 132.2, 129.9, 127.5, 126.7, 52.0, 49.8, 45.9, 45.3, 37.4, 34.3. IR (ATR) 2951, 1723, 1341, 1198, 1174, 1153, 699 cm^{-1}. HRMS (ESI) *m/z*: [M + H]$^+$ Calcd for $C_{32}H_{28}O_4$ 477.2060; Found 447.2028

Data availability

All data generated in this study are provided in the Supplementary Information files. The X-ray crystallographic data generated in this study have been deposited in the Cambridge Crystallographic Data Centre (CCDC) database under the deposition numbers 2301554, 2301553, and 2344429. Data supporting the findings of this manuscript are also available from the authors upon request.

References

1. Anthony, S. M., Wonilowicz, L. G., McVeigh, M. S. & Garg, N. K. Leveraging fleeting strained intermediates to access complex scaffolds. *JACS Au* **1**, 897–912 (2021).
2. Medina, J. M., McMahon, T. C., Jiménez-Osés, G., Houk, K. N. & Garg, N. K. Cycloadditions of cyclohexynes and cyclopentyne. *J. Am. Chem. Soc.* **136**, 14706–14709 (2014).
3. Hopf, H. & Grunenberg, J. in *Strained Hydrocarbons*. (ed. Dodziuk, H.). 375–397 (Wiley-VCH, 2009).
4. Knorr, R. Alkylidene carbenes, alkylidenecarbenoids, and competing species: which is responsible for vinylic nucleophilic substitution, [1 + 2] cycloadditions, 1,5-CH insertions, and the Fritsch –Buttenberg–Wiechell rearrangement? *Chem. Rev.* **104**, 3795–3850 (2004).
5. Jahnke, E. & Tykwinski, R. R. The Fritsch–Buttenberg–Wiechell rearrangement: modern applications for an old reaction. *ChemComm* **46**, 3235–3249 (2010).
6. Roth, A. D. & Thamattoor, D. M. Carbenes from cyclopropanated aromatics. *Org. Biomol. Chem.* **21**, 9482–9506 (2023).
7. Gassman, P. G. & Gennick, I. Synthesis and reactions of 2-lithio-3-chlorobicyclo [2.2.1] hept-2-ene. Generation of the trimer of bicyclo [2.2.1] hept-2-yne. *J. Am. Chem. Soc.* **102**, 6863–6864 (1980).

8. Guin, A., Bhattacharjee, S. & Biju, A. T. in *Modern Aryne Chemistry*. (ed. Biju, A. T.). 359–406 (Wiley-VCH, 2021).
9. Baxter, G. & Brown, R. Methyleneketenes and methylenecarbenes. XI. Rearrangements of cycloalkylidene carbenes. *Aust. J. Chem.* **31**, 327–339 (1978).
10. Johnson, R. P. & Daoust, K. J. Interconversions of cyclobutyne, cyclopentyne, cyclohexyne, and their corresponding cycloalkylidene carbenes. *J. Am. Chem. Soc.* **117**, 362–367 (1995).
11. Fitjer, L., Kliebisch, U., Wehle, D. & Modaressi, S. 2+2]-cycloadditions of cyclopentyne. *Tetrahedron Lett.* **23**, 1661–1664 (1982).
12. Gilbert, J. C. & Baze, M. E. Symmetry of a reactive intermediate from ring expansion of cyclobutylidenecarbene. *Cyclopentyne. J. Am. Chem. Soc.* **105**, 664–665 (1983).
13. Maurer, D. P., Fan, R. & Thamattoor, D. M. Photochemical generation of strained cycloalkynes from methylenecyclopropanes. *Angew. Chem. Int. Ed. Engl.* **56**, 4499–4501 (2017).
14. Fan, R., Wen, Y. & Thamattoor, D. M. Photochemical generation and trapping of 3-oxacyclohexyne. *Org. Biomol. Chem.* **15**, 8270–8275 (2017).
15. Anderson, T. E., Thamattoor, D. M. & Phillips, D. L. Formation of 3-oxa- and 3-thiacyclohexyne from ring expansion of heterocyclic alkylidene carbenes: a mechanistic study. *Org. Lett.* **25**, 1364–1369 (2023).
16. Erickson, K. L. & Wolinsky, J. Rearrangement of bromomethylenecycloalkanes with potassium *t*-butoxide. *J. Am. Chem. Soc.* **87**, 1142–1143 (1965).
17. Mehta, G. Base-catalyzed rearrangement of. omega.-bromolongifolene. *J. Org. Chem.* **36**, 3455–3456 (1971).
18. Balci, M., Krawiec, M., Ta§kesenligil, Y. & Watson, W. H. Structure of a ring enlarged product from the base induced rearrangement of dibromomethylenebenzonorbornene. *J. Chem. Crystallogr.* **26**, 413–418 (1996).
19. Marchand, A. P., Kumar, K. A., Rajagopal, D., Eckrich, R. & Bott, S. G. Generation and trapping of a caged cyclopentylidenecarbene. *Tetrahedron Lett.* **37**, 467–470 (1996).
20. Baumgart, K.-D. & Szeimies, G. On the intermediacy of bicyclo[3.2.O]hept-6-yne, a cyclobutyne derivative. *Tetrahedron Lett.* **25**, 737–740 (1984).
21. Marchand, A. P. et al. Generation and trapping of 7-norbornylidenecarbene and a heptacyclic analog of this alkylidene carbene. *Tetrahedron* **54**, 13427–13434 (1998).
22. Marchand, A. P., Namboothiri, I. N. N., Ganguly, B. & Bott, S. G. Study of a vinylidenecarbene–cycloalkyne equilibrium in the d3-trishomocubyl ring system. *J. Am. Chem. Soc.* **120**, 6871–6876 (1998).
23. Sahu, B. et al. Generation and trapping of a cage annulated vinylidenecarbene and approaches to its cycloalkyne isomer. *J. Org. Chem.* **77**, 6998–7004 (2012).
24. Xu, L., Lin, G., Tao, F. & Brinker, U. Efficient syntheses of multi-substituted methylenecyclopropanes via novel ultrasonicated reactions of 1,1-dihaloolefins and metals. *Acta Chem. Scand.* **46**, 650–653 (1992).
25. C. Brown, R. F. Some developments in the high temperature gas phase chemistry of alkynes, arynes and aryl radicals. *Eur. J. Org. Chem.* **12**, 3211-3222 (1999).
26. Mabry, J. & Johnson, R. P. Beyond the Roger Brown rearrangement: long-range atom topomerization in conjugated polyynes. *J. Am. Chem. Soc.* **124**, 6497–6501 (2002).
27. Taskesenligil, Y., Kashyap, R. P., Watson, W. H. & Balci, M. Is the intermediate in the reaction of 3-bromo-6,7-benzobicyclo[3.2.1] octa-2,6-diene with potassium *tert*-butoxide an allene or an alkyne? *J. Org. Chem.* **58**, 3216–3218 (1993).
28. Gilbert, J. C., Hou, D.-R. & Grimme, J. W. Pericyclic reactions of free and complexed cyclopentyne. *J. Org. Chem.* **64**, 1529–1534 (1999).
29. Köbrich, G., Heinemann, H. & Zündorf, W. Stabile carbenoide—XXI: oligomere des “isopropylidencarbens”. *Tetrahedron* **23**, 565–584 (1967).
30. Hartzler, H. The synthesis of methylenecyclopropanes via an α-elimination reaction. *J. Am. Chem. Soc.* **86**, 526–527 (1964).
31. Köbrich, G. & Drischel, W. Stabile carbenoide—XX: Über die bildung von tetrabenzylbutatrien aus 1-Chlor-2,2-dibenzylvinyllithium. *Tetrahedron* **22**, 2621–2636 (1966).
32. Köbrich, G. & Ansari, F. Carbenoide reaktionen des α-Chlor-β-methyl-styryllithiums. *Chem. Ber.* **100**, 2011–2020 (1967).
33. Erickson, K. L., Markstein, J. & Kim, K. Base-induced reactions of methylenecyclobutane derivatives. *J. Org. Chem.* **36**, 1024–1030 (1971).
34. Erickson, K. L. Base-induced ring enlargement of halomethylenecyclobutanes. A carbon analog of the Beckmann rearrangement. *J. Org. Chem.* **38**, 1463–1469 (1973).
35. Samuel, S. P., Niu, T. Q. & Erickson, K. L. Carbanionic rearrangements of halomethylenecycloalkanes. *J. Am. Chem. Soc.* **111**, 1429–1436 (1989).
36. Seeman, J. I. Effect of conformational change on reactivity in organic chemistry. Evaluations, applications, and extensions of Curtin-Hammett Winstein-Holness kinetics. *Chem. Rev.* **83**, 83–134 (1983).
37. Yang, X., Languet, K. & Thamattoor, D. M. An experimental and computational investigation of (α-methylbenzylidene)carbene. *J. Org. Chem.* **81**, 8194–8198 (2016).
38. Moore, K. A., Vidaurri-Martinez, J. S. & Thamattoor, D. M. The benzylidenecarbene–phenylacetylene rearrangement: an experimental and computational study. *J. Am. Chem. Soc.* **134**, 20037–20040 (2012).
39. Du, L. et al. Direct observation of an alkylidene carbene by ultrafast transient absorption spectroscopy. *J. Phys. Chem. A* **122**, 6852–6855 (2018).
40. Zhao, Y. & Truhlar, D. G. The M06 suite of density functionals for main group thermochemistry, thermochemical kinetics, noncovalent interactions, excited states, and transition elements: two new functionals and systematic testing of four M06-class functionals and 12 other functionals. *Theor. Chem. Acc.* **120**, 215–241 (2007).
41. Weigend, F. & Ahlrichs, R. Balanced basis sets of split valence, triple zeta valence and quadruple zeta valence quality for H to Rn: design and assessment of accuracy. *Phys. Chem. Chem. Phys.* **7**, 3297–3305 (2005).
42. Weigend, F. Accurate Coulomb-fitting basis sets for H to Rn. *Phys. Chem. Chem. Phys.* **8**, 1057–1065 (2006).
43. Hellweg, A., Hättig, C., Höfener, S. & Klopper, W. Optimized accurate auxiliary basis sets for RI-MP2 and RI-CC2 calculations for the atoms Rb to Rn. *Theor. Chem. Acc.* **117**, 587–597 (2007).
44. Riplinger, C. & Neese, F. An efficient and near linear scaling pair natural orbital based local coupled cluster method. *J. Chem. Phys.* **138**, 034106 (2013).
45. Riplinger, C., Sandhoefer, B., Hansen, A. & Neese, F. Natural triple excitations in local coupled cluster calculations with pair natural orbitals. *J. Chem. Phys.* **139**, 134101 (2013).
46. Riplinger, C., Pinski, P., Becker, U., Valeev, E. F. & Neese, F. Sparse maps–A systematic infrastructure for reduced-scaling electronic structure methods. II. Linear scaling domain based pair natural orbital coupled cluster theory. *J. Chem. Phys.* **144**, 024109 (2016).
47. Chmela, J. & Harding, M. E. Optimized auxiliary basis sets for density fitted post-Hartree–Fock calculations of lanthanide containing molecules. *Mol. Phys.* **116**, 1523–1538 (2018).
48. Bach, R. D. Ring strain energy in the cyclooctyl system. the effect of strain energy on [3 + 2] cycloaddition reactions with azides. *J. Am. Chem. Soc.* **131**, 5233–5243 (2009).

49. Felpin, F.-X. & Fouquet, E. A useful, reliable and safer protocol for hydrogenation and the hydrogenolysis of o-benzyl groups: the in situ preparation of an active Pd^0/C catalyst with well-defined properties. *Chem. Eur. J.* **16**, 12440–12445 (2010).
50. Kozel, V., Daniliuc, C.-G., Kirsch, P. & Haufe, G. C_3-symmetric tricyclo[2.2.1.$0^{2,6}$]heptane-3,5,7-triol. *Angew. Chem. Int. Ed.* **56**, 15456–15460 (2017).
51. Rosenkoetter, K. E., Garrison, M. D., Quintana, R. L. & Harvey, B. G. Synthesis and characterization of a high-temperature thermoset network derived from a multicyclic cage compound functionalized with exocyclic allylidene groups. *ACS Appl. Polym. Mater.* **1**, 2627–2637 (2019).
52. Takeuchi, D., Okada, T., Kuwabara, J. & Osakada, K. Living alternating copolymerization of a methylenecyclopropane derivative with co to afford polyketone with dihydrophenanthrene-1,10-diyl groups. *Macromol. Chem. Phys.* **207**, 1546–1555 (2006).
53. Takeda, T., Sasaki, R. & Fujiwara, T. Carbonyl olefination by means of a *gem*-dichloride–$Cp_2Ti[P(OEt)_3]_2$ system. *J. Org. Chem.* **63**, 7286–7288 (1998).
54. Sarkar, S. K. et al. Detection of ylide formation between an alkylidene carbene and acetonitrile by femtosecond transient absorption spectroscopy. *J. Am. Chem. Soc.* **143**, 17090–17096 (2021).
55. Tobe, Y., Iwasa, N., Umeda, R. & Sonoda, M. Vinylidene to alkyne rearrangement to form polyynes: synthesis and photolysis of dialkynylmethylenebicyclo[4.3.1]deca-1,3,5-triene derivatives. *Tetrahedron Lett.* **42**, 5485–5488 (2001).
56. Hardikar, T. S., Warren, M. A. & Thamattoor, D. M. Photochemistry of 1-(propan-2-ylidene)-1a,9b-dihydro-1*H*-cyclopropa[*l*]phenanthrene. *Tetrahedron Lett.* **56**, 6751–6753 (2015).
57. Roth, A. D., Wamsley, C. E., Haynes, S. M. & Thamattoor, D. M. Adamantylidenecarbene: photochemical generation, trapping, and theoretical studies. *J. Org. Chem.* **88**, 14413–14422 (2023).
58. Hoffmann, R., Gleiter, R. & Mallory, F. B. Non-least-motion potential surfaces. Dimerization of methylenes and nitroso compounds. *J. Am. Chem. Soc.* **92**, 1460–1466 (1970).
59. Cheung, L. M., Sundberg, K. R. & Ruedenberg, K. Dimerization of carbene to ethylene. *J. Am. Chem. Soc.* **100**, 8024–8025 (1978).
60. Ohta, K., Davidson, E. R. & Morokuma, K. Dimerization paths of CH_2 and SiH_2 fragments to ethylene, disilene, and silaethylene: MCSCF and MRCI study of least- and non-least-motion paths. *J. Am. Chem. Soc.* **107**, 3466–3471 (1985).
61. Atkins, P. & de Paula, J. in *Physical Chemistry* 10th edn. 827–832 (Oxford University Press, 2014).
62. Bachrach, S. M., Gilbert, J. C. & Laird, D. W. DFT study of the cycloaddition reactions of strained alkynes. *J. Am. Chem. Soc.* **123**, 6706–6707 (2001).
63. Laird, D. W. & Gilbert, J. C. Norbornyne: a cycloalkyne reacting like a dicarbene. *J. Am. Chem. Soc.* **123**, 6704–6705 (2001).
64. Su, M.-D. The cycloaddition reactions of angle strained cycloalkynes. a theoretical study. *J. Chin. Chem. Soc.* **52**, 599–624 (2005).
65. Kınal, A. & Piecuch, P. Is the mechanism of the [2+2] cycloaddition of cyclopentyne to ethylene concerted or biradical? a completely renormalized coupled cluster study. *J. Phys. Chem. A* **110**, 367–378 (2006).
66. Nagarkar, A. A., Yasir, M., Crochet, A., Fromm, K. M. & Kilbinger, A. F. M. Tandem ring-opening–ring-closing metathesis for functional metathesis catalysts. *Angew. Chem. Int. Ed.* **55**, 12343–12346 (2016).
67. Gaidai, A. V. et al. D3-trishomocubane-4-carboxylic acid as a new chiral building block: synthesis and absolute configuration. *Synthesis* **44**, 810–816 (2012).
68. Eaton, P. E., Cassar, L., Hudson, R. A. & Hwang, D. R. Synthesis of homopentaprismane and homohypostrophene and some comments on the mechanism of metal ion catalyzed rearrangements of polycyclic compounds. *J. Org. Chem.* **41**, 1445–1448 (1976).
69. Dekker, T. G. & Olivier, D. W. Synthesis of (D3)-trishomocuban-4-ol via carbenium ion rearrangement of pentacyclo[5.4.0.$0^{2,6}$.$0^{3,10}$.$0^{5,9}$]undecan-8-ol. *S. Afr. J. Chem.* **32**, 45–48 (1979).

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Author contributions

The manuscript was written through contributions of all authors, who have given approval to the final version of the manuscript. T.E.A. and D.M.T. designed the project, and D.M.T. and D.L.P. supervised the project. T.E.A. carried out the chemical reactions and computational experiments, and analyzed the data. T.E.A. wrote the manuscript and D.M.T. revised the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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