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Hyperstable alkenes: are they remarkably unreactive?†

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In 1981, Maier and Schleyer first identified a select number of cage bicyclic olefins (alkenes) as "hyperstable", and predicted them to be "remarkably unreactive", based solely on theoretical methods. Since that time only three *ad hoc* systems meeting the criteria of a hyperstable alkene have been reported in the literature. A one-pot, telescoped synthesis, of four hyperstable alkenes is reported herein, which has uncovered unexpected reactivity towards oxidation. Although, this work represents a new benchmark in hyperstable alkenes, it concomitantly emphasised the need to clarify the definition based on a long-held computational prediction.

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Introduction

Hyperstable olefins (alkenes) were first postulated by Maier and Schleyer in the early 1980s in the course of developing predictive theoretical methods to classify the stability of cage bicyclic bridgehead alkenes[1,2] *i.e.*, in an effort to better define Bredt's Rule.[3]

Utilising Allinger's MM1 empirical force field program, a vast array of cage bicyclic systems were evaluated, and subsequently ranked using olefin strain energy (OSE) values. This molecular mechanics-based approach led to the posit that "Hyperstable olefins should be remarkably unreactive".[1a] Given, for example, that the anti-cancer agent, taxol, contains a cage bridgehead alkene, this research endeavor was also of particular importance to rationalise bridgehead double bond stability[4] and that of an increasing number of related natural products being reported in the modern era.[3]

Five theoretical bicyclo[*m.n.o*] (**1**) hyperstable systems were initially identified in 1981 (*e.g.*, **2**–**5**, Fig. 1), which led to a further prediction that bicyclo[4.4.4]tetradec-1-ene (**5**) "may even resist hydrogenation".[1a] In a later study by McEwen and Schleyer, the list of examples was expanded to include additional cases that compared *E*-(*e.g.*, **6**) and *Z*-alkene (*e.g.*, **7**) configurations, and pyramidalisation through homeomorphic isomerisation (*e.g.*, *in*-**8**) (Fig. 1).[6] A decade later Kim performed a more systematic investigation of over 70 bicyclo[*m.n.o*] bridgehead alkenes, and ranked 15 of the top hyperstable predictions, which ranged from bicyclo[4.4.3]tridec-11-ene (**9**) through to bicyclo[4.4.4]tetradec-1-ene (**5**) (Fig. 1).[5,7] Although larger ring systems were identified through the studies undertaken by Kim (*e.g.*, bicyclo[7.4.4] and [8.3.3]), both Schleyer and Kim recognised that a hyperstability optimal zone existed, which preferred medium-sized rings (*e.g.*, the bicyclo[4.4.4] (**5**),

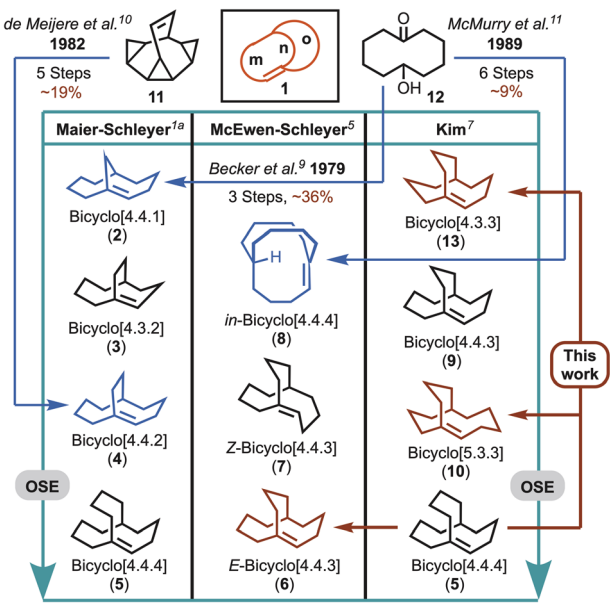

Fig. 1 Hyperstable bicyclo[*m.n.o*] bridgehead alkenes ranked according to olefin strain energy (OSE). Note: alkenes listed in order of increasing stability as predicted in three separate bodies of work using different theoretical methods to determine OSE values.[5] The systems highlighted in dark red are the focus of this work, and those in blue have previously been synthesised *ad hoc*.

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bicyclo[4.4.3] (**6**), and bicyclo[5.3.3] (**10**) systems). In fact, the major contribution to polycyclic alkene stability is suggested to arise from sp^2 flattening at the bridgehead carbon, which provides significant reductions in angle and torsional strain and in non-bonded interactions (*e.g.*, van der Waals forces), all controlled by changes in ring size.[7,8] That is, combinations of much larger rings (or bicyclic bridges) do not provide additional stabilisation, while smaller ring sizes give rise to unstable bridgehead double bonds and/or anti-Bredt systems.[3,4]

Despite putative hyperstable systems being identified through Maier–Schleyer–Kim *in silico* studies, a substantial limitation preventing the interrogation of alkene hyperstability has been an inability to readily synthesise the computationally predicted targets. To highlight this point only three examples that lie in the hyperstability optimal zone have been synthesised previously (*i.e.*, **2**, **4** and **8**). In 1979, Becker *et al.*[9] reported the synthesis of bicyclo[4.4.1]undec-1-ene (**2**), but it predated the hyperstability hypothesis by two years, and was detected as a serendipitous side product in pursuit of anti-Bredt systems. Similarly, a few years later de Meijere *et al.*[10] reported having unexpectedly obtained bicyclo[4.4.2]dodeca-1-ene (**4**), while working with *exo*,*exo*-bishomobullvalene **11**, but subsequently demonstrated **4** was a hyperstable alkene system. Lastly, in the course of pursuing stable three-center, two-electron C–H–C bonds McMurry *et al.* reported the synthesis of hyperstable bridgehead alkene, *in*-bicyclo[4.4.4]tetradec-1-ene (**8**), in 6 steps commencing from 6-hydroxy-cyclodecan-1-one (**12**).[11,12] Interestingly, in the case of **2**, **4** and **8**, all could be hydrogenated, but conditions ranged from mild to forcing.[9,10,11b] Unfortunately, however, in the intervening years there have been no attempts to access the systems with even greater predicted stability,[13] *i.e.*, **5**, **6** and **10** (Fig. 1).

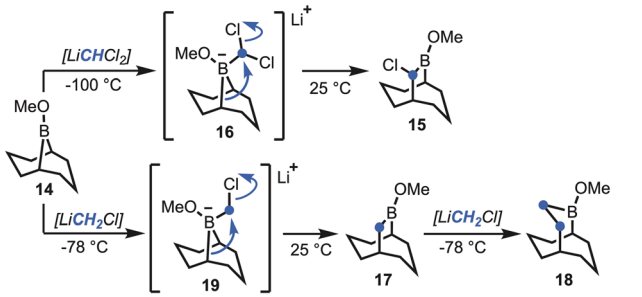
Disclosed herein are efficient methods to access these cage bicyclic systems, which has enabled refinement of the "unreactive" definition, and determination of whether the term hyperstable alkene is more broadly applicable.

Results and discussion

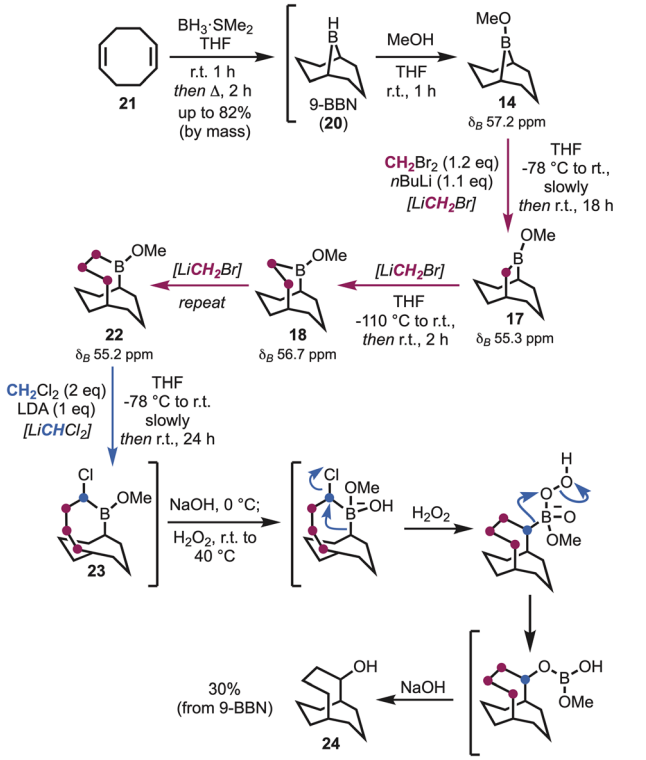
Alkene synthesis

Brown *et al.* demonstrated that boracyclanes (*e.g.*, *B*-methoxy-9-borabicylo[3.3.1]nonane, **14**) (Scheme 1) undergo facile ring enlargement.[14] Expanding upon the methodology of Matteson,[15] treatment with (dichloromethyl)lithium (*i.e.*, $LiCHCl_2$) was shown to give the corresponding (α-haloalkyl)borinic ester homologue (**15**), *via* boronate **16**. Subsequently, Brown *et al.* developed a procedure utilising (chloromethyl)lithium (*i.e.*, $LiCH_2Cl$),[16] which enabled sequential formation of the unsubstituted *B*-methoxy-9-borabicyclo[3.3.2]decane (**17**), *via* boronate **19**, or *B*-methoxy-2-borabicyclo[3.3.3]undecane (**18**) on addition of a second equivalent (Scheme 1). Only in the case of **17** was the boracyclane used synthetically, whereas the other borabicycles have remained unexplored. Inspired by the boracyclane chemistry, synthesis of the proposed hyperstable alkenes bicyclo[5.3.3] tridec-1-ene (**10**) and bicyclo[4.3.3]dodec-1-ene (**13**) (Fig. 1), were attempted using this synthetic methodological approach.

In the course of preparing fresh 9-BBN (**20**), *via* cyclooctadiene (**21**) (Scheme 2),[17] to investigate the first homologation, it soon became apparent that the entire process to access the desired carbocycles might be feasible through a one-pot sequence.[18] That is, synthesis of 9-BBN provided a clean precipitate that could be used directly to afford the borinic ester **14** (δ_B 57.2 ppm). In pursuit of the first ring expansion, (bromomethyl)lithium was selected as the α-halomethyllithium nucleophile of choice, leveraging the widespread availability of dibromomethane and straightforward lithium–halogen exchange.[19] Homologation was achieved through addition of *n*-butyllithium to a solution of dibromomethane and **14** at −78 °C, with formation of the ring-expanded borinic ester **17** visible by ^{11}B NMR (δ_B 55.3 ppm) upon warming. Essential to maintaining the one-pot procedure was adjustment for the growing



Scheme 1 The Matteson homologation-based boracyclane homologation methodology developed by Brown *et al.*[16]



Scheme 2 One-pot synthesis of bicyclo[4.3.3]docecan-2-ol (**24**).

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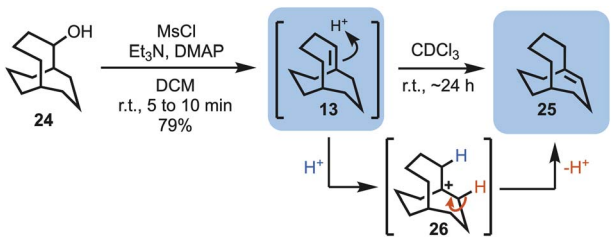
volume of the solution (*i.e.*, all depending on reaction scale). However, the hexanes introduced alongside the *n*-butyllithium could be carefully removed under reduced pressure, in addition to a small quantity of tetrahydrofuran (THF), whereupon the solution was diluted to approximately 1 M by the addition of anhydrous THF.

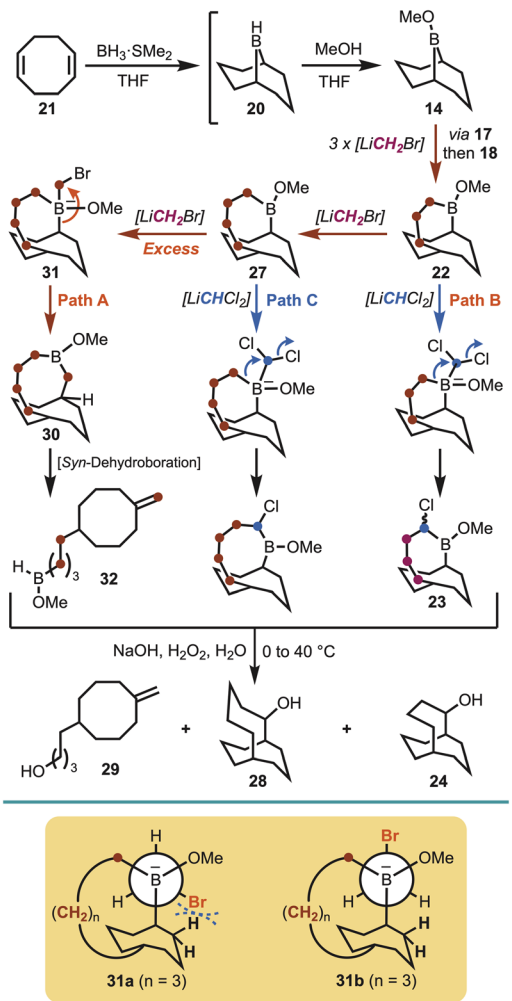
Following the formation of **17**, further homologation could be achieved utilising (bromomethyl)lithium, but this transformation required significantly reduced temperatures to prevent over-homologation, suggesting that the 1,2-migration responsible for ring expansion occurs at temperatures as low as −78 °C within this system (Scheme 2). Formation of (bromomethyl)lithium at −110 °C saw significantly improved selectivity during the second homologation, with formation of the ring-expanded borinic ester **18** observed within 2 hours of stirring at room temperature (δ_B 56.7 ppm). Formation of the trihomologated *B*-methoxy-2-borabicyclo[4.3.3]dodecane (**22**) was achieved on repetition of this procedure (δ_B 55.2 ppm), however formation of the all-carbon framework necessitated the use of $LiCHCl_2$, in order to facilitate migration of the boron atom out of the ring. Lithium *N*,*N*-diisopropylamide (LDA) was the optimum base in this regard and was added to a solution of **22** and dichloromethane (DCM) at −78 °C [Note: typically prompting a slow colour change on, or when, approaching the completion of addition]. Workup of the α-chloroborane (**23**), on sequential treatment with aqueous sodium hydroxide and hydrogen peroxide, furnished the secondary alcohol bicyclo[4.3.3]dodecan-2-ol (**24**) in 30% overall yield (~80% yield for each step following methanolysis) (Scheme 2).

With alcohol **24** in hand, elimination reactions could be explored in an attempt to access the first target, *i.e.*, bicyclo[4.3.3]dodec-1-ene (**13**). Simple treatment of the alcohol with mesyl chloride (MsCl) in the presence of base at room temperature gave bridgehead alkene **13**, and traces of **25**. However, while dissolved in deuterated chloroform **13** fully converted into the bridgehead alkene, bicyclo[4.3.3]dodec-6-ene (**25**), within 24 hours, suggesting a more stable system. This unexpected transformation likely occurs *via* carbocation formation (*i.e.*, **26**), mediated by the presence of traces of acid in the $CDCl_3$ (Scheme 3).

With an iterative homologation strategy in place, further ring expansion was explored in an effort to access the larger bicyclo[5.3.3]tridecane system, and to determine the upper limit of the methodology. Therefore, the same homologation sequence was utilised to access the previously generated boracyclane **22** [*i.e.*, starting from cyclooctadiene (**21**)], whereupon further treatment with (bromomethyl)lithium was expected to give the ring enlarged boracyclane (**27**). Interestingly, on subsequent treatment with (dichloromethyl)lithium, followed by oxidative workup, not only was the desired bicyclo[5.3.3]tridecan-2-ol (**28**) obtained, but also bicyclo[4.3.3]dodecan-2-ol (**24**) and cyclooctanol derivative **29** in an inseparable 2 : 1 : 3 ratio, respectively (Scheme 4). This observation suggested that controlling the formation of boracyclane **27** is more difficult compared with the preceding boracyclanes **17**, **18** and **22**, especially given the developing excess of (bromomethyl)lithium through each iterative homologation. This was particularly evident through the isolation of the ring-opened cyclooctanol **29**, which is a result of undesired over-homologation of boracyclane **27** giving boracyclane **30** (Path A, Scheme 4). However, in this case the preference for the carbon–boron bond migration switched to the bridgehead carbon of boronate complex **31**, which then underwent dehydroboration[20] to afford **32**, and subsequently **29** on oxidation. Brown has suggested that increasing ring size within medium-ring boracyclanes can encroach the strain limits of the labile carbon–boron bond.[16a] This notion is supported by conformational analysis of **31** whereby conformer **31a**, required for the desired homologation *via* a staggered conformation, shows that the bromine atom approaches the bicyclic ring hydrogens as the ring



Scheme 3 Elimination of bicyclo[4.3.3]dodecan-2-ol (**24**) to give bicyclo[4.3.3]dodec-1-ene (**13**) and bicyclo[4.3.3]dodec-6-ene (**25**).



Scheme 4 One-pot synthesis of bicyclo[5.3.3]tridecan-2-ol (**28**).

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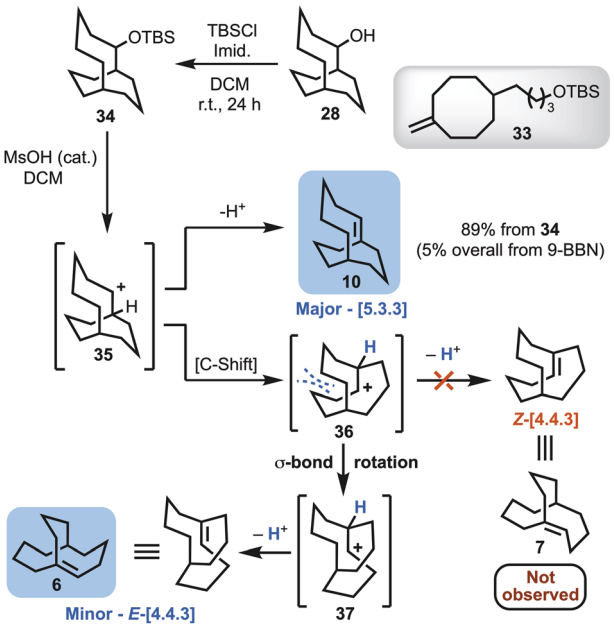


Scheme 5 Synthetic route affording bicyclo[5.3.3]tridec-1-ene (**10**) and *E*-bicyclo[4.4.3]tridec-1-ene (**6**) and proposed mechanistic pathway of formation.

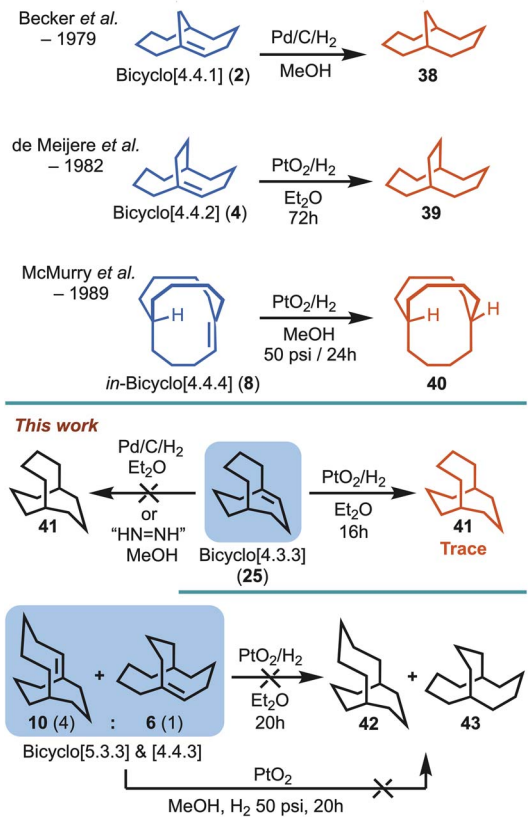
expands. To avoid the ensuing steric clash the alternate anti-periplanar conformer **31b** is adopted, and this change in conformation facilitates the observed bridgehead carbon-boron migration to give boracyclane **30** (Scheme 4). The formation of undesired bicyclo[4.3.3]dodecan-2-ol (**24**) arose from under homologation of boracyclane **22** (Path B, Scheme 4), whereas desired product bicyclo[5.3.3]tridecan-2-ol (**28**) was obtained *via* boracyclane **27** (Path C, Scheme 4).

Treating the mixture of **24**, **28** and **29** with *t*-butyldimethylsilyl chloride (TBSCl) enabled removal of the corresponding bicyclo[4.3.3]dodecan-2-yl (not shown) and cyclooctanyl silyl ethers (**33**), to deliver the desired TBS-protected bicyclo[5.3.3]tridecane **34** (Scheme 5). Exposure of **34** to a catalytic amount of methanesulfonic acid (MsOH) afforded a mixture of the bicyclo[5.3.3] alkene (**10**), and unexpectedly the rearranged bicyclo[4.4.3] alkene **6** as a minor product (Scheme 5). The ratio of alkene isomers could be improved from a ratio ~4 : 1 to ~9 : 1 in favour of **10** by lowering the temperature of the reaction from room temperature to −78 °C. The competing elimination and rearrangement pathways can be envisaged as arising from carbocation **35** (Scheme 5). The major product is derived from elimination of a proton to afford the Kim system, *i.e.*, bicyclo[5.3.3]tridec-1-ene (**10**). Carbocation **35** also undergoes a Wagner–Meerwein rearrangement to **36**. This is followed by a conformational change to give **37**, that relieves steric clashing, and then loss of a proton to afford the McEwen–Schleyer system *i.e.*, *E*-bicyclo[4.4.3]tridec-1-ene (**6**) (Scheme 5).

Hydrogenation

The sole experimental criteria put in place by Maier and Schleyer to determine alkene hyperstability status (*i.e.*, "unreactive") resides on whether the alkene resists catalytic hydrogenation. However, Maier and Schleyer did not detail specific hydrogenation conditions. Simply, the bicyclo[4.4.4] system **5** (Fig. 1) was described as thus: "Therefore, [5] should be an unusually unreactive olefin and may even resist hydrogenation under normal conditions".[1a] Although, it would not be unreasonable to consider normal conditions to consist of palladium suspended on carbon under one atmosphere of hydrogen gas overnight, a variety of conditions could be imagined. With that in mind, previous work by Becker *et al.* demonstrated that bicyclo[4.4.1]undec-1-ene (**2**) could be successfully hydrogenated using palladium on carbon under a hydrogen atmosphere (*i.e.*, say normal conditions) to give **38**,[9] whereas the bicyclo[4.4.2]dodeca-1-ene (**4**) system reported by de Meijere *et al.* required Adam's catalyst (platinum oxide) over a three day duration (*i.e.*, slightly harsher conditions) to afford **39**,[10] and lastly McMurry *et al.*[11] showed that *in*,*out*-bicyclo[4.4.4] tetradec-1-ene (**8**) required more forcing conditions (platinum oxide and 50 psi of pressure) to access **40** (Scheme 6).

Concerning the alkenes investigated herein, the bicyclo[4.3.3] alkene **25** did not undergo hydrogenation using Pd/C/H_2, and only provided trace amounts of the fully saturated alkane **41** when applying slightly harsher conditions (PtO_2/H_2). For the major and minor mixture of bicyclo[5.3.3] (**10**) and bicyclo[4.4.3] (**6**) alkenes (~4 : 1), both of these completely resisted hydrogenation using platinum oxide at atmospheric pressure, but also on hydrogenation under more forcing conditions (PtO_2/H_2 at 50



Scheme 6 Hydrogenation outcomes for known and new bridgehead alkenes.

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psi), with no detection of the corresponding alkanes **42** and **43** by ^{1}H NMR or GC/MS (Scheme 6). Furthermore, when alkene **25** was exposed to *in situ* generated diimide (HN=NH)[21] no reduction was observed.

Computational investigations

Density functional theory[22] calculations with M06-2X/def2-TZVPP[23] were performed to investigate the stabilities and reactivities of the four new alkenes, **6**, **10**, **13**, and **25** (Fig. 2). [Note: calculated heats of hydrogenation are used *in lieu* of experimentally determined values, because the rate of hyperstable alkene hydrogenation is too slow to measure, as reported by Roth.[24]] In the case of the **13**/**25** pair, alkene **25** was found to be 4.3 kcal mol^{-1} lower in energy than **13** (Fig. 2A). The result is consistent with the observed formation of **25** from **13** upon standing in $CDCl_3$.

The original hyperstability predictions proposed by Maier, Schleyer, and Kim, were established on the basis of olefin strain energies (OSE) as calculated with molecular mechanics. In the present study, however, DFT-computed free energies of hydrogenation (ΔG_{hydrog}, Fig. 2B) were used as a direct measure of the propensities of the alkenes to undergo hydrogenation. For comparison, OSEs were also calculated, using Rablen's recently reported quantum mechanical group increment method[25] (see ESI†). The ΔG_{hydrog} and OSE values were found to be linearly correlated ($R^2 = 0.98$). A linear correlation was also detected between OSE and the enthalpy of hydrogenation, ΔH_{hydrog}, a quantity considered by Maier and Schleyer in their original study[1a] (see ESI†).

The two simple alkenes **44** and **45** represent relatively strain-free trisubstituted systems lacking a bicyclic ring system. Their hydrogenation energies (both −18 kcal mol^{-1}) provide reference values against which the new and previously synthesised bridgehead alkenes can be compared (Fig. 2). In general, a hyperstable alkene would be expected to release less energy upon hydrogenation than a strain-free reference alkene, and its ΔG_{hydrog} would therefore be expected to be less negative than those of **44** and **45**. This was observed to be the case with all three of the previously synthesised hyperstable alkenes, for which the hydrogenation energies range from −15 kcal mol^{-1} (**2**) to −9 kcal mol^{-1} (**4**) to −7 kcal mol^{-1} (**8**). This trend in energies mirrors the trend in reactivity toward hydrogenation observed experimentally by others, *viz*. **2** > **4** > **8** (Scheme 6).

For the series of alkenes **6**, **10**, **13**, and **25**, the hydrogenation energies range from −2 kcal mol^{-1} to −13 kcal mol^{-1} (Fig. 2). These values follow the same trend as observed experimentally: the theoretically least hyperstable alkene that was studied in hydrogenation experiments, **25** ($\Delta G_{hydrog} = -9$ kcal mol^{-1}), gave trace amounts of hydrogenated product under harsher conditions, while the theoretically more hyperstable alkenes in the series, **6** and **10** ($\Delta G_{hydrog} = -4$ and −2 kcal mol^{-1}, respectively), failed to undergo hydrogenation even under forcing conditions. There are some variations between the series worth noting. Firstly, theory predicts that alkene **25** has a smaller driving force for hydrogenation than the Becker *et al.*[9] alkene **2**, consistent with the observation that experimentally **25** required harsher conditions than reported for **2**, and only afforded trace amounts of product (*i.e.,* **41**) (Scheme 6). Furthermore, the hydrogenation energies do not provide information about the barrier heights for the hydrogenation processes, nor do they take into account any differences between the mechanisms of the hydrogenations catalysed by different heterogeneous catalysts in the different solvents used experimentally. Secondly, the McMurry *et al.*[11] *in*-bicyclo[4.4.4]tetradec-1-ene (**8**) system has a 7 kcal mol^{-1} driving force for hydrogenation according to theory, but unlike alkenes **6** and **10**, it does not survive hydrogenation conditions involving platinum oxide at a pressure of 50 psi. Beyond the potential limitations of utilising thermodynamic hydrogenation energies, however, the McMurry *et al.* case is considerably different due to the *in*-bridgehead hydrogen atom (*i.e.*, all other systems are *out*-bridgehead hydrogen atoms). Such systems can stabilise any developing δ^+ charge through contact with the catalyst and the double bond (*i.e.*, lowering the energy barrier of hydrogenation).

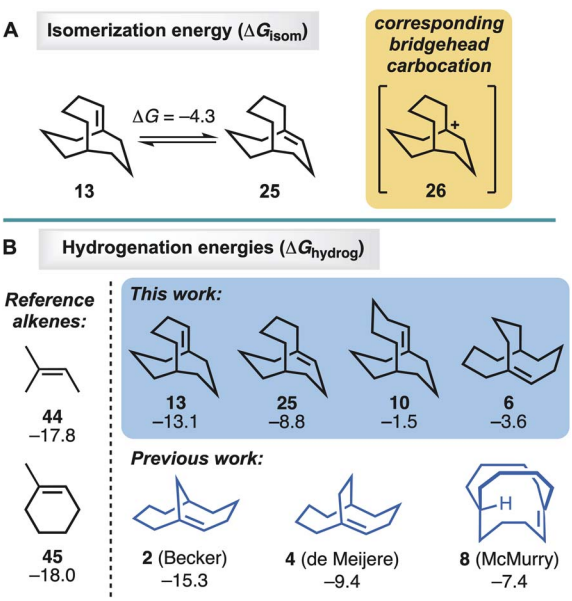

Fig. 2 Density functional theory computations of (A) alkene isomerisations and (B) alkene hydrogenations. ΔG in kcal mol^{-1} (M06-2X/def2-TZVPP).

Osmylation and X-ray crystallography

In an effort to gain an understanding of whether bridgehead alkenes **6**, **10**, and **25**, could be considered hyperstable alkenes more broadly (*i.e.*, in the context of resisting other alkene reaction conditions), they were subjected to osmylation. Donohoe *et al.*[26] have shown that the combination of osmium tetroxide (OsO_4), and *N*,*N*,*N*′,*N*′-tetramethylethylenediamine (TMEDA), is a very reactive and efficient oxidant of a wide range of alkenes. Furthermore, Rychnovsky *et al.*,[27] have demonstrated that the method can be utilised for structure determination by X-ray crystallography, as the TMEDA–osmium(VI) complex of the vicinal diol product is typically crystalline.

Therefore, alkene **25** was treated with OsO_4, and TMEDA at −78 °C, which afforded **46**. The X-ray crystal structure of **46** was

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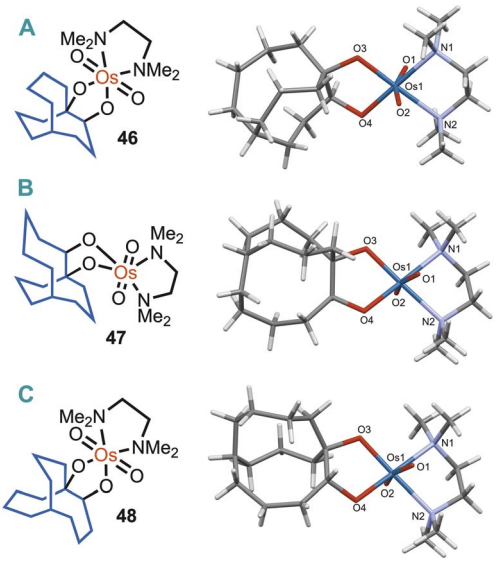
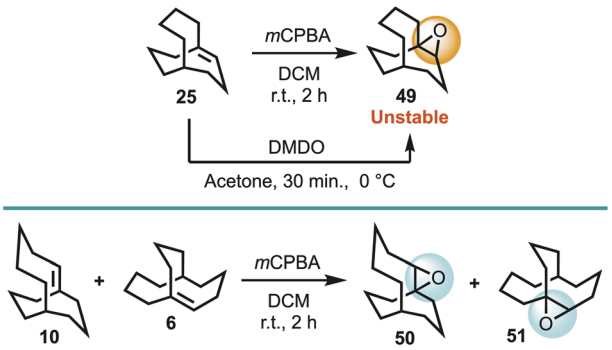


Fig. 3 X-ray crystal structures of the Os(VI) complexes **46** (A), **47** (B) and **48** (C).

determined (Fig. 3A), and although disordered, the C-atom positions and connectivity were all clearly resolved (see ESI†). This analysis also confirmed the structure of the parent [4.3.3] alkene **25** and revealed that the bridgehead alkene was susceptible to attack by OsO_4 in the usual manner. In light of these results the isomeric mixture of **10** and **6** was similarly reacted with OsO_4/TMEDA, which afforded osmium(VI) complexes **47** and **48.** Recrystallisation gave a co-crystal comprising both isomers **47** and **48** (in a ratio of 62 : 38 respectively) where the Os, TMEDA and all O-donor atoms occupy identical positions within the structure, but the C-atoms of the bicyclic cages are disordered between positions corresponding to their [5.3.3] or [4.4.3] parent (see ESI† for a more detailed discussion). The Os(VI)-coordinated [5.3.3] bicycle **47** is shown in Fig. 3B (derived from **10**) and the [4.4.3] isomer **48** (derived from **6**) is shown in Fig. 3C.

Epoxidation

Given that the OsO_4/TMEDA oxidant system is reported to be 10 000 times more reactive than OsO_4,[24a] it was deemed instructive to explore whether a less reactive oxidant would oxidise the bridgehead alkenes **6**, **10**, and **25**. Although, a number of oxidants could be envisaged, *meta*-chloroperbenzoic acid (*m*CPBA) was first chosen, and was found to afford the corresponding epoxides **49**, **50** and **51**. However, **49** was found to be quite unstable to moisture, and could not be sufficiently purified, although it could be obtained in high purity using the oxidant dimethyldioxirane (DMDO) (Scheme 7).



Scheme 7 Reaction of bridgehead alkenes **6**, **10**, and **25** with the common oxidants *m*CPBA and DMDO.

Interestingly, the structure of cerorubenic acid-I, which contains a bicyclo[4.4.1] hyperstable alkene skeleton (see **2** in Fig. 1), slowly oxidises in air to give the corresponding epoxide[28] (*i.e.,* a result of the oxidant triplet oxygen[29]). Therefore, as a class, hyperstable alkenes are seemingly not resistant to oxidation. These observations are not too surprising given that oxidants (oxidation reagents) are highly reactive species, that operate *via* a redox mechanism, which transfers an electronegative oxygen atom(s).[30] This process is in stark contrast to hydrogenation.

Conclusions

In summary, while developing predictive theoretical methods to classify the stability of cage bicyclic bridgehead alkenes, Schleyer, Maier and McEwen introduced the term "hyperstable alkene",[1a,6] followed by Kim some years later.[7] Together, they predicted over 60 bicyclo[*m.n.o*] alkenes to be hyperstable, using as their criteria olefin strain energy calculations, in addition to predicting resistance of these alkenes to hydrogenation under normal conditions. Of these 60 theoretical examples the syntheses of only three alkenes (*i.e.,* **2**, **4** and **8**) that resided in this theoretical optimal hyperstability zone had been reported, albeit independently; **2** being reported before the term hyperstable alkene was even developed. A major limitation to testing this theory more extensively was the inability to access bridgehead double bond containing systems which matched the Schleyer–Maier–McEwen–Kim predicted hyperstable alkenes.

Herein described are further examples of hyperstable systems (*i.e.,* **6**, **10**, **13**, and **25**) obtained *via* an optimised Brown–Matteson homologation sequence. Three of these were found to be isolable (*i.e.,* **6**, **10**, and **25**) and resistant to hydrogenation under a variety of conditions, consistent with the previously reported Schleyer and Maier definition of an "unreactive" hyperstable alkene *i.e.,* **6** and **10** represent the most stable hyperstable systems reported to-date. However, the bridgehead alkenes **6**, **10**, and **25** were observed to undergo reaction with both strong and mild oxidants to afford osmate esters and epoxides, respectively. As a result of these studies, it is apparent that the computationally derived term "hyperstable alkene" only applies to resistance of hydrogenation, whether it be normal transition metal catalysed hydrogenation or non-metal based conditions. Lastly, it is important to recognise that alkene hyperstability is not a blanket term for all reaction conditions, and that bridgehead alkenes continue to be reported in the natural product literature that can likely attribute their stability to unique cage bicyclic structure *i.e.,* "Such olefins should be very unreactive-not due to steric hindrance or to enhanced π-bond strength but due to

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special stability afforded by the cage structure of the olefin and to the greater strain of the parent polycycloalkane".[1a]

Data availability

All experimental data are provided in the ESI.†

Author contributions

M. D. S. and S. C. performed chemical synthesis. L. R. G. and E. H. K. carried out *in silico* calculations. G. K. P. performed high field NMR measurements of target alkenes and associated osmium complexes. P. V. B. acquired the X-ray crystallographic data and performed the analysis. C. M. W. conceived the project, coordinated the study, assisted in analysing and interpreting the data, and wrote the manuscript. All authors read and agreed on the content of the paper.

Conflicts of interest

There are no conflicts to declare.

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