Facial selectivity in the 4 + 2 reactions of a diene derived from carvone

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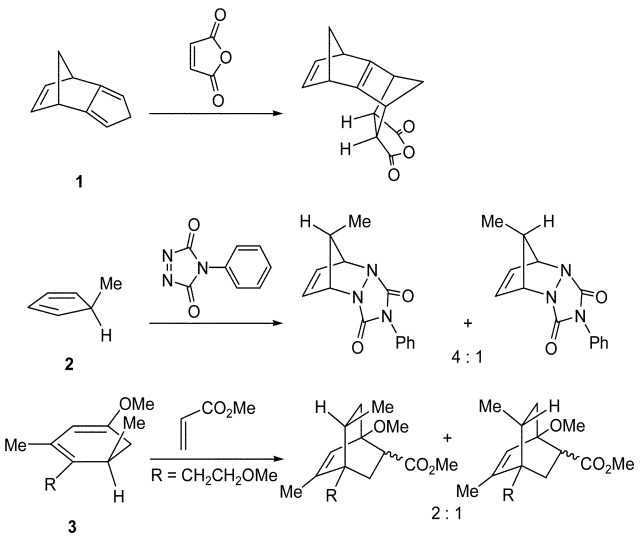
The facial selectivities of cyclohexadienes bearing isopropenyl and isopropyl groups as plane-nonsymmetric substituents were assessed in 4 + 2 reactions with *N*-phenylmaleimide, tetracyanoethylene and 4-phenyl-1,2,4-triazoline-3,5-dione. The only adducts were those arising by attack of the dienophile on the face of the diene opposite the isopropenyl or isopropyl group. In spite of some mechanistic similarities that tetracyanoethylene and 4-phenyl-1,2,4-triazoline-3,5-dione might have with the 4 + 2 addition of singlet oxygen, these dienophiles show none of the ability that singlet oxygen has shown to add *syn* to a plane-nonsymmetric isopropyl group.

Introduction

Facial selectivity in the Diels–Alder reaction has been studied in detail with many plane-nonsymmetric diene systems.[1] Generally, a dienophile will show a preference for addition to the less hindered face of the diene. This simple principle has been exploited many times in synthesis.[2,3] However, there are examples of cyclic dienes that engage in Diels–Alder reactions with facial selectivities that seem to defy a rationalization based on steric hindrance. Some plane-nonsymmetric heteroatom substituents direct the dienophile to add mainly *syn* to the heteroatom,[4] although it has been shown computationally that steric considerations play a dominant role in governing even this facial selectivity, at least with the 5-substituted cyclopentadienes.[5] Some plane-nonsymmetric hydrocarbons also display facial selectivity that seems inconsistent with straightforward steric considerations. Examples are presented in Scheme 1.

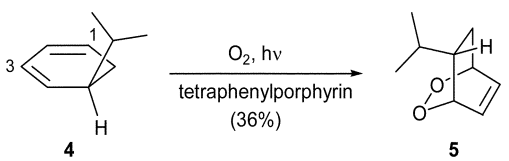
The isodicyclopentadiene system **1**, which has been studied in depth by Paquette *et al.*,[6] gives only one product with maleic anhydride.[7] 5-Methyl-1,3-cyclopentadiene (**2**) shows a preference for addition *syn* to its methyl group with 4-phenyl-1,2,4-triazoline-3,5-dione (PTAD), although a modest preference for *anti*-addition was seen with *N*-phenylmaleimide.[8] Addition mainly *syn* to the plane-nonsymmetric methyl of **3** was reported by Murai *et al.*,[3,9] but when R = H no *syn*-addition product was detected. Mehta and Uma[10] reviewed the situations in which stereoelectronic factors are believed to dominate the control of facial selectivity in Diels–Alder reactions.

The addition of singlet oxygen to a cisoid 1,3-diene to form an endoperoxide has an obvious parallel with the hetero-Diels–Alder reaction, although calculations led Dewar and Thiel[11] to hypothesise that the endoperoxide is a rearrangement product of an initially formed perepoxide. Clennan and Lewis[12] gathered experimental evidence for the perepoxide intermediate. There are a number of instances of endoperoxide formation taking place with facial selectivity that is markedly different from Diels–Alder



Scheme 1 Diels–Alder reactions of cyclic dienes **1**,[7] **2**[8] and **3**.[9]

additions. For instance, 4 + 2 addition of singlet oxygen to **1** takes place with almost no facial selectivity.[13] The addition of singlet oxygen to 5-isopropylcyclohexa-1,3-diene (**4**) in Scheme 2 is particularly intriguing. Davis and Carpenter[14] hypothesised that the perepoxide formed by *anti*-addition might rearrange to a hydroperoxide, an ene product, by abstraction of a *syn*-hydrogen from an adjacent sp^3 carbon. However, the perepoxide formed by *syn*-addition onto the 3,4-double bond of **4** would have no *syn*-hydrogen on the adjacent sp^3 carbon, so this perepoxide might rearrange to the endoperoxide **5**. This hypothesis is certainly plausible, although it is curious that the apparently least-favoured perepoxide, *i.e.*, *syn* and proximal to the sterically hindering isopropyl group, would lead to a significant amount of product **5**.



Scheme 2 Endoperoxide formation from diene **4**.[14]

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We wondered if such unusual facial selectivity might be observed in other apparent 4 + 2 reactions in which the transition states might be very nonsynchronous, or in which the mechanism were stepwise. Based on the hypothesis of Davis and Carpenter, it seemed appropriate initially to bias the diene, making the double bond near the plane-nonsymmetric substituent more electron-rich.

The steric difference between the faces of diene **4** would be similar to that presented by dienes **6a–c** (Fig. 1). Dienes **6a** and **6c**, in which the 3,4-double bond is electron-rich, are protected enol forms of carvone. Carvone has been used a number of times in Diels–Alder reactions, but its role has almost always been as the dienophile. In most instances, the diene has added predominantly to the face of carvone opposite the isopropenyl group,[15] although a 1-amino-3-silyloxy-1,3-butadiene was reported to add with no facial selectivity.[16] Intramolecular 4 + 2 reactions of **6c** are known,[17] but carvone has been used as a diene only a few times in intermolecular 4 + 2 reactions. At no time has the stereochemistry of the isopropenyl group in an adduct been determined rigorously. Geribaldi *et al.*[18] reacted diene **6a** with maleic anhydride. The adduct was proposed to be **7**, but their reason for choosing the particular stereochemistry of the isopropenyl was not mentioned, although this would be a reasonable assumption based on steric hindrance. Gómez Contreras and co-workers[19] reacted **6a** with diazaquinones, and the adducts were suggested to have arisen by *anti*-addition, *e.g.* **8**, but no evidence for the stereochemistry was provided. Cornforth's group[20] added acetamidobenzoquinone to diene **6b**. They obtained a 1 : 1 mixture of **9a** and **9b**, following aromatization and methylation of the adduct mixture. The stereochemistry of the isopropenyl in these compounds was inferred by NMR. There was an apparent lack of shielding by the aromatic ring, although shielding might have resulted from the annular double bond, too.

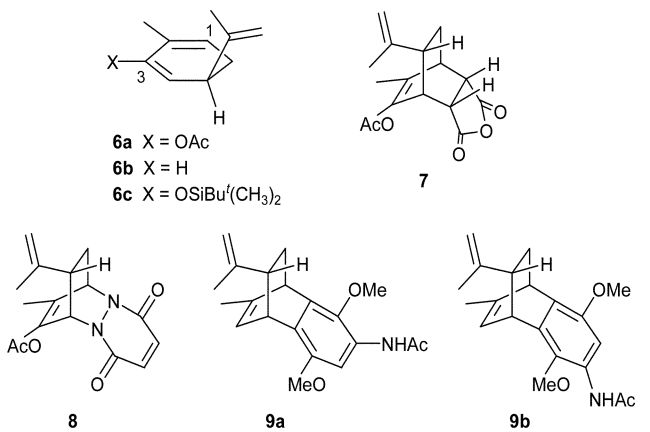

Fig. 1 Dienes **6a–c** and reported products[18–20] of their 4 + 2 cyclizations.

Results and discussion

Treatment of (−)-carvone with *tert*-butyldimethylsilyltriflate and triethyl amine in THF provided the diene **6c**. Attempted purification over silica gel resulted in the destruction of the diene, so 4 + 2 reactions were carried out by adding the dienophile directly to the reaction mixture containing the diene.

A solution of diene **6c** and *N*-phenylmaleimide in THF reacted over 4 days at room temperature to give a single adduct. The propinquity of the hydrogens on C-7*a* and C-8 was demonstrated conclusively by NOE measurements. Thus, the addition had taken place by *endo*-addition, onto the face of **6c** *anti* to the isopropenyl group, *i.e.*, the adduct was **10** (Fig. 2). Similarly, diene **11**, derived from dihydrocarvone, reacted with *N*-phenylmaleimide to give a single adduct **12** in which the addition was also *endo* and *anti* to the isopropyl group (Fig. 2). These reactions with *N*-phenylmaleimide would have proceeded *via* a concerted, and close to synchronous, Diels–Alder mechanism.[21] Other cycloadditions were carried out with compounds that react through mechanisms that are more closely related to that of singlet oxygen.

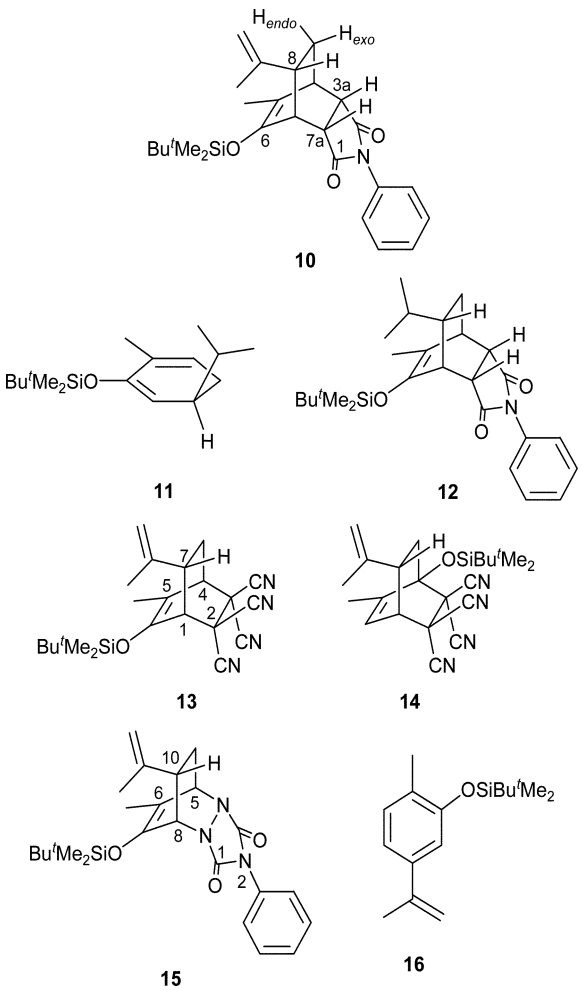

Fig. 2 Products of the 4 + 2 reactions of dienes **6c** and **11**.

Tetracyanoethene (TCNE), like singlet oxygen, is known to give 4 + 2, 2 + 2 and ene products with dienes.[22] The mechanism that leads to all of these products is likely to involve the intermediacy of radical ions.[23] Thus, the transition state geometry of 4 + 2 cycloadditions with TCNE may be considered to be lopsided compared to genuine Diels–Alder transition states. This has been probed experimentally,[24] and there are instances in which the facial preference is opposite to that with classic dienophiles, such as *N*-phenylmaleimide.[25] Diene **6c** reacted with TCNE to give two products. NMR spectra indicated that the major adduct was derived directly from **6c**, but the minor adduct was not the result of the facial alternative. It was derived from an isomerized

diene. Rearrangements and equilibration are well known in TCNE chemistry.[22,25] The relative stereochemistry of each adduct was revealed by X-ray crystallography. Both the major adduct **13** and the minor adduct **14** (Fig. 2) were the result of addition to the face of the diene *anti* to the isopropenyl group.

4-Phenyl-1,2,4-triazoline-3,5-dione (PTAD) is a more reactive and less sterically demanding cycloaddend than *N*-phenylmaleimide.[5,8,24] It can give 4 + 2, 2 + 2 and ene products with dienes, and its 4 + 2 reaction may proceed by rearrangement of an aziridinium imide intermediate.[26] This is similar to a perepoxide, although DFT calculations of additions of triazolinedione to butadiene indicate a lower barrier for a concerted pathway to a 4 + 2 product.[27] The reaction of PTAD with **6c** produced only one adduct, **15** (Fig. 2), for which the structure was determined by X-ray crystallography. Compound **15** must have arisen by addition to the face of **6c** *anti* to the isopropenyl group.

Attempts were made to form an endoperoxide from **6c** with singlet oxygen, following the procedure of Davis and Carpenter[14] in which the endoperoxide was reduced to the diol, but these were unsuccessful. Compound **16** was the inevitable result (Fig. 2).

To summarize the experiments with **6c**, the results confirmed unambiguously the very great *anti*-selectivity imparted by the isopropenyl group. TCNE and PTAD were used in attempts to elicit an addition *via* a very nonsynchronous pathway, but additions of TCNE and PTAD took place with the same facial selectivity as *N*-phenylmaleimide. It is not known what the facial selectivity of **6c** would be with singlet oxygen since the experiment failed.

The oxygen substituent of **6c** makes the double bond closer to the sterically hindering isopropenyl group more electron-rich than the other annular double bond. It was considered that if the double bond more distant from the site of plane-nonsymmetry were more electron rich then perhaps facial selectivity might be affected, particularly with a nonsynchronous 4 + 2 pathway.

Accordingly, diene **17** was produced from the corresponding enone, and reactions with *N*-phenylmaleimide, TCNE and PTAD were carried out. In these experiments, the reaction was stopped before it was complete. Nevertheless, in every instance only one adduct was detected (Fig. 3). The NOE data for the *N*-phenylmaleimide adduct **18** showed that the hydrogen on C-8 was close to the hydrogen on C-7*a*. The data for the other two adducts, **19** and **20**, included NOE enhancements that placed the isopropyl group near the olefinic hydrogen. Thus, 4 + 2 processes with **17** gave exclusively the product of addition *anti* to the isopropyl group, regardless of the dienophile. Reaction of **17** with singlet oxygen once again led to an aromatic product.

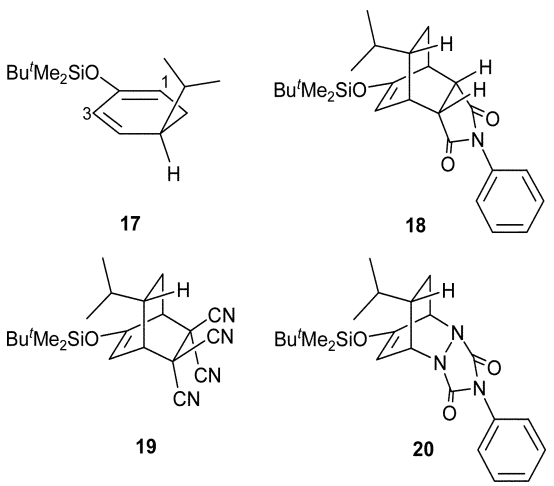

Fig. 3 Diene **17** and its adducts.

Conclusions

The 4 + 2 reactions of dienes **6c** and **17** with *N*-phenylmaleimide and with two dienophiles, TCNE and PTAD, for which the mechanisms for their 4 + 2 reactions are purported to be nonsynchronous gave adducts arising from the approach of the dienophile onto the face of the diene *anti* to the plane-nonsymmetric substituent. Deviations from the classical Diels–Alder transition state geometry, which would have been expected by the nature of TCNE and PTAD and by the presence of an electron-donating group on the diene, are not sufficient to attenuate significantly the influence of the hindrance that an isopropenyl group must exert. This study confirms the stereochemical assumptions made by previous workers, but, more importantly, it serves to stress the extraordinary nature of singlet oxygen chemistry observed by Davis and Carpenter.[14]

Experimental

General

Melting points are uncorrected. NMR chemical shifts are relative to internal tetramethylsilane. Nuclear Overhauser effect (NOE) measurements were made using difference spectra. *N*-Phenylmaleimide was recrystallized from cyclohexene. 4-Phenyl-1,2,4-triazoline-3,5-dione (PTAD)[28] was sublimed at 100 °C at approximately 1 mmHg. Reactions were carried out under an atmosphere of dry nitrogen. "Chromatography" refers to flash column chromatography using 230–400 mesh silica gel with elution by hexanes containing an increasing proportion of ethyl acetate.

Representative procedure for the 4 + 2 reactions of 6c: (3*a*S,4*S*,7*R*,7*a*R,8*R*)-6-[(1,1-dimethylethyl)dimethylsilyloxy]-2,3,3*a*,4,7,7*a*-hexahydro-5-methyl-8-(methylethenyl)-2-phenyl-4,7-ethano-1*H*-isoindole-1,3(2*H*)-dione 10. *tert*-Butyldimethylsilyl-trifluoromethylsulfonate (0.57 ml, 2.5 mmol) was added dropwise to a solution of (−)-carvone (312 mg, 2.07 mmol) in THF (15 ml) at 0 °C. This was followed immediately by addition of triethylamine (0.43 ml, 3.1 mmol). This mixture was stirred at 0 °C for 30 min to generate diene **6c**. To this was added a solution of *N*-phenylmaleimide (0.71 g, 4.1 mmol) in THF (4.0 ml). The mixture was stirred at RT for 96 h. The solvent was removed under vacuum, and chromatography provided **10** (776 mg, 85%) as a colourless solid: mp 132–136 °C; $[\alpha]_D$ +19 (c = 0.0039, benzene); $\nu_{max}(CCl_4)/cm^{-1}$ 1718; δ_H (C_6D_6, 300 MHz) 7.43 (2 H, br d, J 8.1, 2′-H and 6′-H), 7.16 (2 H, m, 3′-H and 5′-H), 7.00 (1 H, br t, J 7.5, 4′-H), 4.74 (2 H, narrow m, =CH_2), 3.01 (1 H, m, 7-H), 2.88 (1 H, m, 4-H), 2.38 (1 H, dd, J 8.1 and 3.3, 7*a*-H), 2.29 (1 H, dd, J 8.1 and 3.1, 3*a*-H), 1.90 (1 H, m, 8-H), 1.67 (3 H, s, 5-CH_3), 1.60 (3 H, s, $CH_3C{=}CH_2$), 1.34 (1 H, ddd, J 12.8, 10.2 and 2.8, 9-H_{exo}), 1.15 (1 H, ddd, J 12.8, 7.3 and 3.2, 9-H_{endo}), 0.89 (9 H, s, $SiC(CH_3)_3$), 0.18 (3 H, s, $SiCH_3$) and −0.05

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(3 H, s, $SiCH_3$); some short distances identified by NOE: 3*a*-H to 4-H, 3*a*-H to 9-H_{exo}, 7-*H* to 7*a*-H, 7-H to 8-H, 7-H to $=CH_2$, 7-H to $CH_3C{=}CH_2$ and 7*a*-H to 8-H; δ_C ($CDCl_3$, 74.5 MHz) 177.8, 177.1, 147.3, 144.0, 132.0, 129.0 (2 C), 128.4, 126.5 (2 C), 111.8, 111.0, 46.5, 44.5, 44.3, 42.4, 39.0, 31.2, 25.5 (3 C), 22.3, 18.1, 13.9, −3.8 and −4.1; *m/z* no M^+, 380.1666 (M^+-Bu^t, 100%, $C_{22}H_{26}NO_3Si$ requires 380.1682), 207 (19), 165 (19), 91 (25), 77 (10), 75 (25), 73 (36), 59 (10) and 41 (12); analysis: found C, 71.4; H, 8.3; N, 3.1%; $C_{26}H_{35}NO_3Si$ requires C, 71.3; H, 8.1; N, 3.1%.

(3*aS*,4*S*,7*R*,7*aR*,8*S*)-6-[(1,1-Dimethylethyl)dimethylsilyloxy]-2,3,3*a*,4,7,7*a*-hexahydro-5-methyl-8-(methylethyl)-2-phenyl-4,7-ethano-1*H*-isoindole-1,3(2*H*)-dione 12. By a procedure similar to that for **10**, **12** was produced from *N*-phenylmaleimide and **11** in 93% yield after 96 h at RT. For **12**: colourless solid, mp 132–135 °C; $[\alpha]_D$ +10 (c = 0.0053, benzene); $\nu_{max}(CCl_4)/cm^{-1}$ 1778, 1712 and 1673; δ_H (C_6D_6, 300 MHz) 7.50 (2 H, br d, *J* 8.1, 2′-H and 6′-H), 7.18 (2 H, br t, *J* 7.8, 3′-H and 5′-H), 7.02 (1 H, br t, *J* 7.2, 4′-H), 3.11 (1 H, m, 7-H), 2.88 (1 H, m, 4-H), 2.36 (1 H, dd, *J* 8.6 and 3.0, 7*a*-H), 2.30 (1 H, dd, *J* 8.6 and 3.0, 3*a*-H), 1.71 (3 H, s, 5-CH_3), 1.29 (1 H, ddd, *J* 11.0, 8.3 and 3.0, 9-H_{exo}), 1.14 (1 H, m, CH_3CHCH_3), 0.94 (3 H, d, *J* 6.6, CH_3CHCH_3), 0.93 (1 H, overlapped m, 8-H), 0.92 (9 H, s, $SiC(CH_3)_3$), 0.82 (1 H, m, 9-H_{endo}), 0.72 (3 H, d, *J* 6.6, CH_3CHCH_3), 0.26 (3 H, s, $SiCH_3$) and −0.06 (3 H, s, $SiCH_3$); some short distances identified by NOE: 3*a*-H to 4-H, 3*a*-H to 9-H_{exo}, 4-H to 5-CH_3, 4-H to 9-H_{exo}, 4-H to 9-H_{endo}, 7-H to 7*a*-H, 7-H to CH_3CHCH_3, 7-H to CH_3CHCH_3 (δ 0.94), 7-H to $SiCH_3$ (δ 0.26) and 7*a*-H to 8-H; δ_C (C_6D_6, 74.5 MHz) 177.5 (C=O), 177.2 (C=O), 145.2 (C-6), 133.5 (C-1′), 129.1 (2 C, C-3′ and C-5′), 128.5 (C-4′), 127.0 (2 C, C-2′ and C-6′), 112.5 (C-5), 46.7 (C-7*a*), 46.6 (C-8), 44.6 (C-3*a*), 41.0 (C-7), 39.8 (C-4), 33.7 (CH_3CHCH_3), 32.3 (C-9), 26.1 (3 C, $SiC(CH_3)_3$), 21.5 (CH_3CHCH_3), 20.8 (CH_3CHCH_3), 18.4 ($SiC(CH_3)_3$), 14.4 (5-CH_3), −3.3 ($SiCH_3$) and −3.7 ($SiCH_3$); *m/z* no M^+, 382.1834 (M^+-Bu^t, 100%, $C_{22}H_{28}NO_3Si$ requires 382.1839), 209 (40), 165 (15), 91 (25), 79 (14), 75 (53), 73 (56), 59 (12), 43 (15) and 41 (20); analysis: found C, 71.3; H, 8.7; N, 3.1%; $C_{26}H_{37}NO_3Si$ requires C, 71.0; H, 8.5; N, 3.2%.

(1*R*,4*S*,7*R*)-6-[(1,1-Dimethylethyl)dimethylsilyloxy]-5-methyl-7-(methylethenyl)bicyclo[2.2.2]oct-5-ene-2,2,3,3-tetranitrile 13. By a procedure similar to that for **10**, two adducts, **13** (73%) and **14** (19%), were obtained from TCNE and **6c** after 48 h at RT. For **13**: colourless solid, mp 88–90 °C; $[\alpha]_D$ +8 (c = 0.0026, benzene); $\nu_{max}(CCl_4)/cm^{-1}$ 2244 (very weak) and 1677; δ_H ($CDCl_3$, 300 MHz) 4.96 (1 H, s, $=CH_2$), 4.80 (1 H, s, $=CH_2$), 3.36 (1 H, m, 4-H), 3.18 (1 H, narrow m, 1-H), 2.87 (1 H, apparent br t, 7-H), 2.37 (1 H, ddd, *J* 14.5, 9.6 and 2.9, 8-H), 1.89 (3 H, s, 5-CH_3), 1.79 (3 H, s, $CH_3C{=}CH_2$), 1.63 (1 H, ddd, *J* 14.5, 5.6 and 3.0, 8-H), 0.96 (9 H, s, $SiC(CH_3)_3$), 0.27 (3 H, s, $SiCH_3$) and 0.25 (3 H, s, $SiCH_3$); δ_C ($CDCl_3$, 74.5 MHz) 144.4, 143.5, 113.5, 112.7, 111.7, 111.6, 111.4, 111.3, 49.2, 47.5, 44.5, 43.1, 38.2, 26.6, 25.4 (3 C), 21.7, 18.2, 14.7, −3.5 and −3.7; *m/z* no M^+, 335.1317 (M^+-Bu^t, 39%, $C_{18}H_{19}N_4OSi$ requires 335.1328), 208 (20), 207 (100), 165 (44), 133 (12), 91 (25), 75 (57), 73 (98), 68 (10), 59 (28), 57 (24), 45 (11), 43 (13) and 41 (32); analysis: found C, 67.2; H, 7.1; N, 14.2%; $C_{22}H_{28}N_4OSi$ requires C, 67.3; H, 7.2; N, 14.3%.

X-Ray crystal structure determination for 13†. Measurements were made on a Bruker P4/CCD system with graphite monochromated Mo–Kα radiation and a rotating anode generator. A colourless fragment crystal of dimensions 0.50 × 0.40 × 0.30 mm was mounted on a glass fibre: $C_{22}H_{28}N_4OSi$, M = 392.57, orthorhombic, a = 7.4112(4), b = 15.3453(8), c = 19.811(1) Å, V = 2253.1(2) Å^3, T = −193 K, space group $P2_12_12_1$ (no. 19), Z = 4, μ(Mo–Kα) 1.23 cm^{-1}, 12262 reflections collected, 2192 observed ($I > 2.00\sigma(I)$); R = 0.039, R_w = 0.037, goodness of fit = 1.43.

(1*S*,4*R*,7*S*)-4-[(1,1-Dimethylethyl)dimethylsilyloxy]-5-methyl-7-(methylethenyl)bicyclo[2.2.2]oct-5-ene-2,2,3,3-tetranitrile 14. For **14**: colourless solid, mp 135–136 °C; $[\alpha]_D$ +6 (c = 0.0020, benzene); $\nu_{max}(CCl_4)/cm^{-1}$ 2256 (weak) and 1649; δ_H ($CDCl_3$, 300 MHz) 6.09 (1 H, br d, *J* 6.2, 6-H), 4.93 (1 H, s, $=CH_2$), 4.67 (1 H, s, $=CH_2$), 3.36 (1 H, d, *J* 6.6, 1-H), 2.99 (1 H, apparent br t, 7-H), 2.58 (1 H, dd, *J* 13.4 and 9.8, 8-H), 2.02 (3 H, s, 5-CH_3), 1.74 (3 H, s, $CH_3C{=}CH_2$), 1.64 (1 H, dd, *J* 13.4 and 6.9, 8-H), 1.03 (9 H, s, $SiC(CH_3)_3$), 0.38 (3 H, s, $SiCH_3$) and 0.27 (3 H, s, $SiCH_3$); δ_C ($CDCl_3$, 74.5 MHz) 146.2, 143.3, 122.3, 113.3, 111.6, 111.5 (2 C), 110.9, 82.0, 49.9, 44.7, 42.4, 39.0, 33.5, 25.5 (3 C), 21.6, 18.5, 17.8, −1.5 and −2.2; *m/z* no M^+, 335.1330 (M^+-Bu^t, 4%, $C_{18}H_{19}N_4OSi$ requires 335.1328), 264 (34), 249 (12), 223 (15), 207 (26), 205 (12), 165 (22), 133 (14), 128 (29), 91 (17), 76 (31), 75 (84), 73 (100), 69 (12), 59 (21), 57 (14) and 41 (17); analysis: found C, 67.2; H, 7.4; N, 13.9%; $C_{22}H_{28}N_4OSi$ requires C, 67.3; H, 7.2; N, 14.3%.

X-Ray crystal structure determination for 14†. Measurements were made on a Rigaku AFC6S diffractometer with graphite monochromated Cu–Kα radiation. A colourless, irregular crystal of dimensions 0.35 × 0.35 × 0.25 mm was mounted on a glass fibre: $C_{22}H_{28}N_4OSi$, M = 392.57, orthorhombic, a = 17.488(1), b = 17.514(1), c = 7.601(2) Å, V = 2328.0(5) Å^3, T = 299 K, space group $P2_12_12_1$ (no. 19), Z = 4, μ(Cu–Kα) 10.25 cm^{-1}, 2026 reflections collected, 1841 observed ($I > 2.00\sigma(I)$); R = 0.039, R_w = 0.042, goodness of fit = 2.63.

(5*R*,8*S*,10*R*)-7-[(1,1-Dimethylethyl)dimethylsilyloxy]-5,8-dihydro-6-methyl-10-(methylethenyl)-2-phenyl-5,8-ethano-1*H*-[1,2,4]-triazolo[1,2*a*]pyridazine-1,3(2*H*)-dione 15. By a procedure similar to that for **10**, **15** was produced from PTAD and **6c** in 76% after 48 h at RT. For **15**: colourless solid, mp 128–130 °C; $[\alpha]_D$ +38 (c = 0.0027, benzene); $\nu_{max}(CCl_4)/cm^{-1}$ 1772 and 1719; δ_H (C_6D_6, 300 MHz) 7.71 (2 H, br d, *J* 8.1, 2′-H and 6′-H), 7.10 (2 H, apparent br t, *J* 8.0, 3′-H and 5′-H), 6.94 (1 H, br t, *J* 7.5, 4′-H), 4.82 (1 H, d, *J* 3.0, 8-H), 4.72 (1 H, br s, $=CH_2$), 4.68 (1 H, br s, $=CH_2$), 4.60 (1 H, t, *J* 3.0, 5-H), 2.69 (1 H, br m, 10-H), 1.95 (1 H, ddd, *J* 12.8, 4.9 and 2.6, 11-H), 1.60 (3 H, s, 6-CH_3), 1.47 (3 H, s, $CH_3C{=}CH_2$), 1.07 (1 H, ddd, *J* 12.8, 4.9 and 2.6, 11-H), 0.90 (9 H, s, $SiC(CH_3)_3$), 0.28 (3 H, s, $SiCH_3$) and 0.04 (3 H, s, $SiCH_3$); δ_C ($CDCl_3$, 74.5 MHz) 155.7, 155.0, 144.2, 144.0, 131.5, 129.0 (2 C), 128.0, 125.3 (2 C), 113.5, 112.0, 58.0, 56.1, 42.6, 29.8, 25.4 (3 C), 21.4, 18.0, 12.7, −4.3 and −4.6; *m/z* 439.2278 (M^+, 14%, $C_{24}H_{33}N_3O_3Si$ requires 439.2291), 372 (16), 371 (16), 263 (28), 224 (23), 205 (28), 168 (10), 167 (17), 119 (13), 99 (10), 91 (22), 75 (29), 73 (100), 59 (19), 57 (12) and 41 (21); analysis: found

† CCDC reference numbers 290629 (**13**), 290630 (**14**) and 290631 (**15**). For crystallographic data in CIF or other electronic format see DOI: 10.1039/b516675f

C, 65.6; H, 7.6; N, 9.4%; $C_{24}H_{33}N_3O_3Si$ requires C, 65.6; H, 7.6; N, 9.6%.

X-Ray crystal structure determination for 15†. Measurements were made on a Rigaku AFC6S diffractometer with graphite monochromated Cu–Kα radiation. A colourless, irregular crystal of dimensions 0.38 × 0.25 × 0.38 mm was mounted on a glass fibre: $C_{24}H_{33}N_3O_3Si$, $M = 439.63$, monoclinic, $a = 8.087(1)$, $b = 11.369(1)$, $c = 14.0678(9)$ Å, $\beta = 104.498(7)°$, $V = 1252.1(2)$ Å^3, $T = 299$ K, space group $P2_1$ (no. 4), $Z = 2$, μ(Cu–Kα) 10.5 cm^{-1}, 2128 reflections collected, 1900 observed ($I > 2.00\sigma(I)$); $R = 0.036$, $R_w = 0.038$, goodness of fit = 3.77.

Representative procedure for the 4 + 2 reactions of 17: (3*aR,4*R**,7*S**,7*aS**,8*R**)-5-[(1,1-dimethylethyl)dimethylsilyloxy]-2,3,3*a*,4,7,7*a*-hexahydro-8-(methylethyl)-2-phenyl-4,7-ethano-1*H*-isoindole-1,3(2*H*)-dione 18.** The diene **17** was prepared by a procedure similar to that for **6c**. Diene **17**, initially a pale yellow oil, became dark quickly at RT. *N*-Phenylmaleimide (1.5 equiv.) with **17** in CH_2Cl_2 solution was maintained at RT for 72 h. Chromatography provided **18** (39%), and a significant amount of **17** and the enone from which it was derived were recovered. For **18**: colourless solid, mp 162–163 °C; δ_H ($CDCl_3$, 500 MHz) 7.43 (2 H, m, 3′-H and 5′-H), 7.35 (1 H, m, 4′-H), 7.21 (2 H, m, 2′-H and 6′-H), 4.84 (1 H, dd, *J* 6.8 and 1.9, 6-H), 3.27 (1 H, m, 7-H), 2.99 (1 H, m, 4-H), 2.95 (1 H, dd, *J* 7.9 and 3.0, 3*a*-H), 2.90 (1 H, dd, *J* 7.6 and 3.3, 7*a*-H), 1.84 (1 H, m, 8-H), 1.26 (3 H, m, 9-H_2 and CH_3CHCH_3), 0.94 (3 H, d, *J* 6.3, CH_3CHCH_3), 0.89 (9 H, s, $SiC(CH_3)_3$), 0.87 (3 H, d, *J* 6.6, CH_3CHCH_3), 0.12 (3 H, s, $SiCH_3$) and 0.09 (3 H, s, $SiCH_3$); some short distances identified by NOE: 3*a*-H to 8-H, 6-H to 7-H, 7-H to 7*a*-H, 7-H to CH_3CHCH_3 and 7*a*-H to 8-H; δ_C ($CDCl_3$, 125 MHz) 178.3, 177.6, 154.9, 132.3, 129.1, 128.5, 126.6, 98.3, 46.5, 45.4, 44.2, 39.2, 35.6, 33.4, 31.8, 25.7, 21.3, 20.6, 18.0, −4.3 and −4.6.

(1*R,4*S**,7*R**)-5-[(1,1-Dimethylethyl)dimethylsilyloxy]-7-(methylethyl)bicyclo[2.2.2]oct-5-ene-2,2,3,3-tetranitrile 19.** By a procedure similar to that for **18**, **19** was obtained from TCNE and **17** in 23% yield after 48 h at RT An equal amount of **17** was recovered. For **19**: colourless solid, δ_H (C_5D_5N, 500 MHz) 5.52 (1 H, d, *J* 6.8, 6-H), 4.12 (1 H, d, *J* 7.4, 1-H), 3.84 (1 H, br s, 4-H), 2.49 (1 H, m, 8-H), 2.12 (1 H, m, 7-H), 1.51 (1 H, m, 8-H), 1.33 (1 H, m, CH_3CHCH_3), 1.02 (9 H, s, $SiC(CH_3)_3$), 0.94 (3 H, d, *J* 7.1, CH_3CHCH_3), 0.81 (3 H, d, *J* 6.7, CH_3CHCH_3), 0.44 (3 H, s, $SiCH_3$) and 0.34 (3 H, s, $SiCH_3$); some short distances identified by NOE: 1-H to 6-H, 1-H to 7-H, 1-H to CH_3CHCH_3, 6-H to CH_3CHCH_3, 7-H to 8-H_{exo}, 8-H_{endo} to CH_3CHCH_3 and CH_3CHCH_3 to $SiOC(CH_3)_3$; δ_C (C_5D_5N, 125 MHz) 155.7, 114.6, 114.1 (2 C), 113.6, 100.0, 47.5, 47.3, 45.5, 45.0, 39.9, 33.6, 27.3, 25.9, 20.9, 20.1, 18.5, −4.4 and −4.7.

(5*R,8*S**,10*S**)-6-[(1,1-Dimethylethyl)dimethylsilyloxy]-5,8-dihydro-9-(methylethyl)-2-phenyl-5,8-ethano-1*H*-[1,2,4]-triazolo[1,2-*a*]pyridazine-1,3(2*H*)-dione 20.** Crude **20** was obtained almost immediately upon addition of PTAD to a CH_2Cl_2 solution of **17** at RT. The crude product was contaminated with unidentified material. Repeated crystallization from CH_2Cl_2–hexanes gave a small amount (11%) of **20** as colourless crystals: mp 121–122 °C; δ_H ($CDCl_3$, 500 MHz) 7.44 (4 H, narrow m, phenyl), 7.26 (1 H, m, 4′-H), 5.15 (1 H, dd, *J* 3.0 and 6.5, 7-H), 4.96 (1 H, dd, *J* 2.5 and 6.5, 8-H), 4.67 (1 H, narrow m, 5-H), 2.32 (1 H, m, 10-H), 1.88 (1 H, m, 9-H), 1.42 (1 H, m, 10-H), 1.26 (1 H, m, CH_3CHCH_3), 1.00 (3 H, d, *J* 6.8, CH_3CHCH_3), 0.92 (3 H, overlapped but presumed d, CH_3CHCH_3), 0.92 (9 H, s, $SiC(CH_3)_3$), 0.17 (3 H, s, $SiCH_3$) and 0.15 (3 H, s, $SiCH_3$); some short distances identified by NOE: 5-H to 10-H_{endo}, 5-H to 10-H_{exo}, 7-H to 8-H, 7-H to 10-H_{endo}, 7-H to CH_3CHCH_3, 8-H to 9-H, 9-H to 10-H_{exo} and 10-H_{endo} to CH_3CHCH_3; δ_C ($CDCl_3$, 125 MHz) 156.3, 156.1, 154.4, 131.8, 129.3, 128.3, 125.7, 98.1, 56.0, 54.5, 43.7, 32.6, 29.9, 25.8, 21.0, 20.2, 18.2, −4.3 and −4.7.

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