endo/*exo* Facial selectivities in cycloaddition reactions of substituted 1,2,3-triazolium-1-methanides, unstabilised 1,3-dipoles, with some alkene dipolarophiles: models for 1,2,3-triazolium-1-aminides: new tetracyclic pyrrolo[1,2-*c*][1,2,3]benzotriazole structures: azolium 1,3-dipoles

R. N. Butler * and Leonie M. Wallace

Chemistry Department, National University of Ireland, Galway, Ireland

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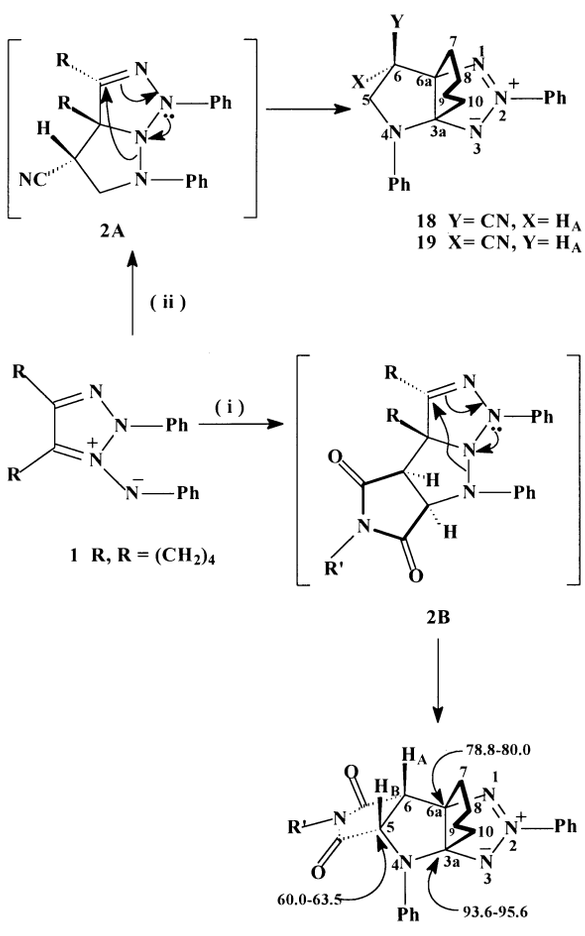
endo/*exo* Stereochemistry in the cycloaddition reactions of substituted 1,2,3-triazolium-1-aminide and 1,2,3-triazolium-1-methanide 1,3-dipoles has been explored for the dipolarophiles acrylonitrile and *N*-substituted maleimides. The cycloadditions with acrylonitrile displayed predominant *endo*-geometry but gave mixtures of *endo*- and *exo*-isomers. In contrast *N*-substituted maleimides gave almost exclusive *exo*-cycloadducts. The cycloaddition products are novel tri- and tetracyclic structures. Factors affecting *endo*/*exo* selectivities are discussed for these systems. Generalisations are not reliable and each 1,3-dipole–dipolarophile pair needs to be carefully considered.

Introduction

The cycloaddition–rearrangement reactions of substituted 1,2,3-triazolium-1-aminide 1,3-dipoles **1** have wide synthetic potential.[1] They represent a part of the wider synthetic scope of exocyclic azolium ylide 1,3-dipoles in general.[1–4] Such reactions are often characterized by rapid *in situ* rearrangements of the immediately formed cycloadduct such that the steric features of the initial cycloaddition may be lost in the subsequent steps.[5] The general reaction as outlined in Scheme 1 illustrates the difficulty where the rearrangement involves a 1,4-sigmatropic shift (the 4 π-electrons being delocalised over 3 atoms as against 4 atoms for the more common 1,5-shift) and the facial selectivity of the dipolarophile substituents in the initial cycloadduct is reversed in the final product (since *endo*-groups change to *exo*- and *vice versa* during the sigmatropic rearrangement).

While many such reactions have been studied[1] the *endo*/*exo*† selectivity of the initial cycloaddition can only be inferred and in many cases is not established. For example for the case of compound **18** (Scheme 1) an X-ray crystal structure[6,7] on the final multiple fused ring system confirmed the CN in the *exo*-position thereby indicating an initial *endo*-cycloaddition. Recently we have found[8] that the cycloadducts from the unstabilized methanide dipole **4a** (R = Ph) with reactive alkyne dipolarophiles did not rearrange *in situ*. However cycloaddition reactions could not be achieved with less reactive alkene dipolarophiles with the dipole **4** (R = Ph) because the 1,3-dipoles underwent ring-opening and ring-closure (RORC) to products such as **6** and **20** (R = Ph) too rapidly. Hence the *endo*/*exo* character of the initial cycloaddition could not be probed. We have now found that the RORC process for the dipoles **4** and **5** with alkyl substituents on the triazole is slower and it is possible to observe competitive cycloadditions but the RORC process is however still dominant. Careful work-up and separation of the small quantities of cycloadducts have allowed



Scheme 1 *Reagents*: (i) *N*-substituted maleimides; (ii) acrylonitrile. Some key ^{1}H, ^{13}C NMR shifts, ranges shown: **3**; H$_A$, 3.63–3.95 ppm; H$_B$, 4.67–5.19 ppm; 7-CH$_2$, 2.20–2.40 ppm.

† The terms *endo* and *exo* refer to the 5,5-ring skeleton structures of the fused pyrrolo[1,2-*c*][1,2,3]triazole (Scheme 2), and the pyrrolo-[2,3-*d*][1,2,3]triazole and intermediate pyrazolo[2,3-*c*][1,2,3]triazole (Scheme 1).

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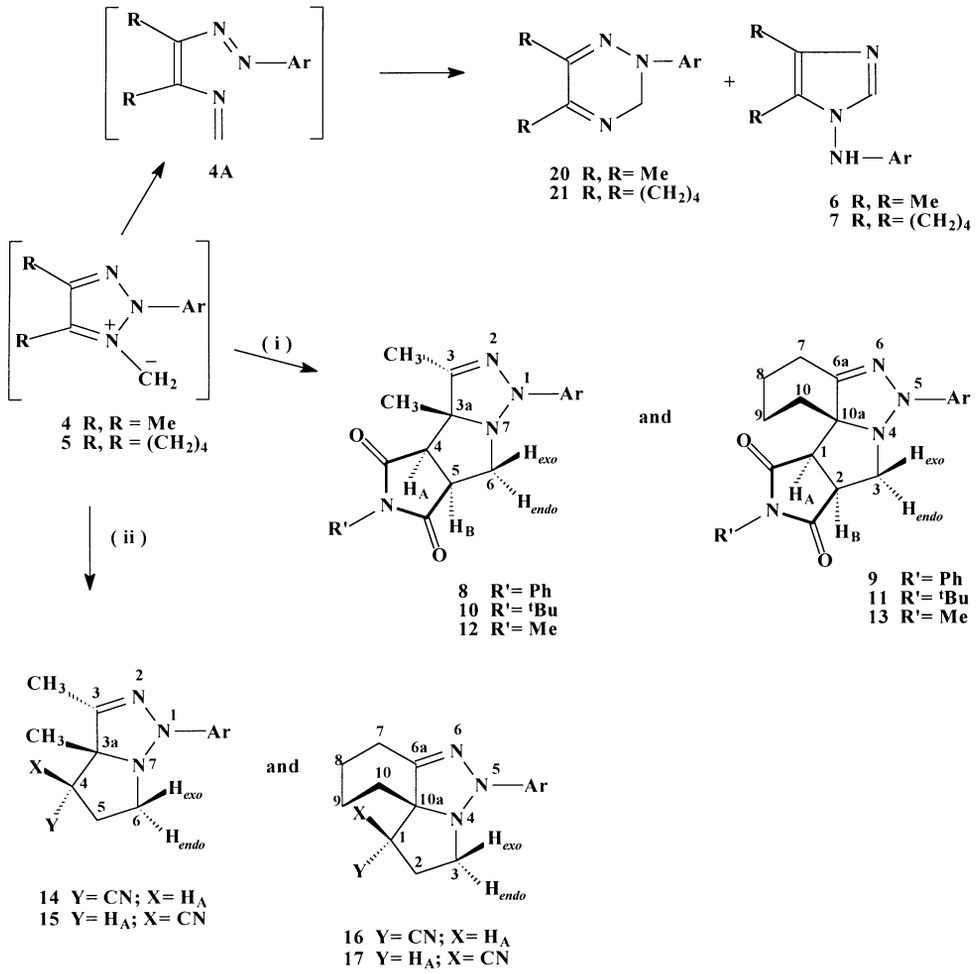


Ar: a= Ph; b= *p*-BrC_6H_4; c= *p*-MeC_6H_4

Scheme 2 *Reagents*: (i) *N*-substituted maleimides; (ii) acrylonitrile.

us, for the first time, to determine the *endo*/*exo* selectivity of the cycloadditions of the 1,2,3-triazolium-1-methanide 1,3-dipoles **4** and **5** with the alkene dipolarophiles, *N*-substituted maleimides and acrylonitrile. The results also provide a guide for the reactions of 1,2,3-triazolium-1-aminide 1,3-dipoles **1** since these parallel the methanides. The results suggest that the 1,3-dipoles **1** should react with *N*-substituted maleimides to give an initial unstable *exo*-cycloadduct **2B**. The stable cycloadducts **8**–**13** are models for this unstable cycloadduct **2B** and the *exo* geometry for the dicarboximido group in **2B** infers an *endo*-geometry for the rearranged series **3**. This has now been confirmed. The *endo*/*exo* selectivity in these systems needs to be considered individually for each dipolarophile. We have discussed the ring expansion (RORC) behaviour of azolium methanides in depth previously[9–11] and it is not considered further here.

Results and discussion

(i) *N*-Substituted maleimides

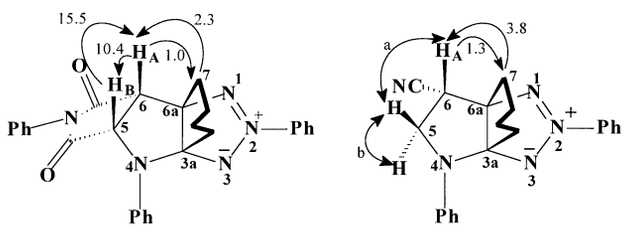
Somewhat unexpectedly the cycloadditions of maleimides with the dipoles **1** in acetone and **4** and **5** in dichloromethane gave cycloadducts with *exo*-stereochemistry. The cycloadducts **2B** (Scheme 1) were unstable and rearranged *in situ* to the products **3** where the *N*-substituted-dicarboxyimido group is now *endo* to the fused 5,5-ring system. The cycloadducts from the 1,2,3-triazolium-1-methanide dipoles **4** and **5** (Scheme 2) were the stable *exo*-products **8**–**13**. These were always accompanied by the substituted 1-aminoimidazoles **6** and **7** with traces of the triazines **20** and **21**. The compounds **8**–**13** are the first cycloadducts from dipoles of type **4** and **5** with alkene dipolarophiles and they are stable carbon analogues of the intermediates **2B** from the aminide dipoles **1** (Scheme 1). The structures and stereochemistry of the products **3** and **8**–**13** were established from microanalyses, proton and carbon-13 NMR spectra which showed all of the expected signals and multiplicities. Proton NMR assignments were confirmed by COSY and spin-decoupled spectra and carbon-13 assignments were supported by DEPT and off-resonance decoupled spectra. The *endo*-stereochemistry of the series **3** was established by clear two-way NOE enhancements from 6-H_A to the bridging cyclohexane 7-CH_2 methylene group (Scheme 1) (Fig. 1). The *endo*-geometry of the *N*-substituted dicarboximido group in the series of structures **3a**–**3e** means the initial cycloaddition to give **2B** occurred in the *exo*-manner. This cycloaddition–rearrangement reaction also occurred with the parent *N*-unsubstituted maleimide giving the product **3c** (Table 1, entry 3). Separate methylation of this gave compound **3d** identical to that obtained from the cycloaddition of **1** with *N*-methylmaleimide (Table 1, entry 4).

The *exo*-stereo orientation of the products **8**–**13** was also established from NOE difference spectra. The four atoms labeled H_A, H_B, H_{exo} and H_{endo} stood out in the spectra and were readily assigned. For the series the H_{exo} atom appeared at 3.8–4.1 δ but its geminal partner H_{endo} was not deshielded by the dicarboxyimido group and appeared at 2.85–3.4 δ. This geminal pair showed the expected *J* value of 11–13 Hz and intense NOE enhancements. The shift ranges for H_A, 3.0–3.6 δ, and H_B 3.1–

Table 1 Products

Entry	Compound	Mp/°C	Yield(%)	Compound[e]	Yield(%)
(i) From aminide 1,3-dipole **1**					
1	**3a**	224–225[a]	86[d]	—	—
2	**3b**	255–257[a]	90	—	—
3	**3c**	173–174[b]	78	—	—
4	**3d**	193–194[a]	90	—	—
5	**3e**	191–192[c]	66[d]	—	—
6	**18**	173–174[a]	79	—	—
7	**19**	Gum	10	—	—
(ii) From methanide 1,3-dipoles **4**, **5**					
8	**8a**	153–154[c]	19	**6a**	75
9	**9a**	172–174[c]	20	**7a**	57
10	**9b**	177–179[c]	17	**7b**	76
11	**9c**	171–173[c]	29	**7c**	55
12	**10a**	Gum	17[d]	**6a**	58
13	**11a**	133–136[c]	20	**7a**	69
14	**12a**	133–135[c]	21[d]	**6a**	65
15	**13a**	132–133[c]	22	**7a**	73
16	**13b**	133–134[c]	11	**7b**	65
17	**13c**	Gum	30	**7c**	65
18	**16a**	127–129[c]	8	**7a**	70
	17a	100–102[c]	5	—	—
19	**14a**	Gum	10	**6a**	80
	15a	Gum	5	—	—

[a] From ethanol. [b] From methanol.[c] From hexane : CH_2Cl_2. [d] Small quantities of intractable resins were encountered. [e] Ref. 9–11 and 22.



3a: H_A, 3.86ppm; H_B, 4.90ppm; **19:** Overlap of 6-H_A and 5-H_{endo} (3.52ppm,m); (a+b<31%).

12a: No NOE from H_A to Me-C-3a; (H_A, H_B signals too close); **14a**

Fig. 1 Examples of key NOE effects (%) and some proton chemical shifts.

3.65 δ were close and sometimes overlapped but they could be readily assigned from COSY and single proton decoupled spectra. The vicinal pair H_A and H_B showed expected J values of 8–9 Hz and strong NOE enhancements. (Fig. 1). The compounds **8**, **10** and **12** were prepared as more simple analogues of the tetracyclic structures **9**, **11** and **13** and the strong signals of the methyl groups at C-3 (2.15–2.20 δ) and C-3a (1.14–1.25 δ) were particularly useful for NOE analyses. The results obtained for the methyl derivatives **8**, **10** and **12** were fully paralleled with the more complicated spectra of the tetracyclic structures **9**, **11**, **13**. For all of these compounds strong NOE effects were observed, as expected between the geminal *exo*/*endo* proton pairs at C-3 and C-6, between H_B and 3- and 6-H_{endo} and between the vicinal pair H_A and H_B (Fig. 1). There was no NOE between H_A and the *trans* CH_3 or CH_2 groups at the C-3a and C-10a bridgeheads.

Computed structures using the NEMESIS programme and Dreiding molecular models gave distances from H_A to the *trans* C-atom bonded to C-3a of greater than 3.3 Å while the distance from H_A underneath the 5,5-ring to the C-atom bonded to the planar C-3 was *ca*. 2.7 Å. For compounds **8**, **10** and **12** NOE effects from H_A to the 3-C-Me group were readily observed in both directions (Fig. 1). Similarly for compounds **9**, **11** and **13** NOE effects in both directions were observed from H_A to the 7-CH_2 group in the cyclohexyl envelope.

These results show unequivocally that the cycloaddition has a predominantly *exo*-orientation. Where both isomers were encountered they were stable under the reaction conditions and no interconversions occurred. The NOE effects from H_A to the substituents at C-3 and C-6a beneath the buckled fused 5,5-ring also point to the reason for the *exo*-cycloaddition.

(ii) Acrylonitrile

We have previously reported[6,7] the synthesis and X-ray crystal structure of compound **18** (Scheme 1) from the reaction of the dipole **1** with acrylonitrile. In this compound the CN group is in the *exo*-position and there was no NOE from H_A to the fused benzo 7-CH_2 group bonded at the C-6a bridgehead. In this present work we have also isolated for the first time a small quantity of the *endo*-isomer **19** in crude form and proton NMR spectra of this compound showed an NOE from H_A to the bridgehead 7-CH_2 as expected (Fig. 1). The agreement between the NOE effects and the X-ray crystal structure of compound **18** is important. The fact that the isomer **18** is the major product means that in the initial cycloaddition to the adduct **2A** (Scheme 1) the *endo* transition state is favoured in contrast to the maleimide dipolarophiles. Hence it was expected, and observed, that the *endo*-isomers **14** and **16** (Scheme 2) would be the major products from the reactions of the dipoles **4** and **5** with acrylonitrile (Table 1, entries 18 and 19). Because of competition from the RORC process *via* the intermediate **4A**, which we have discussed previously,[9–11] only small quantities of the compounds **14**–**17** were available. Nevertheless pure samples of the major isomers were obtained by a work-up which sacrificed the minor isomer and the NMR spectral signals of the minor isomers were then obtained from spectra of the mixtures. The more simple methyl derivatives **14** and **15** were again used as guides for the analysis of the NMR spectra of the tricyclic substituted 2,3,7,8,9,10-hexahydro-

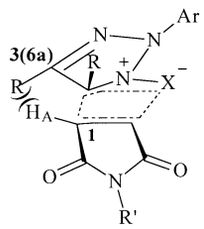


Fig. 2 Proximity of substituents at C-1 and C-3a (**6a**) as planar carbons change to tetrahedral in the transition state.

1*H*,5*H*-pyrrolo[1,2-*c*][1,2,3]benzotriazole derivatives **16** and **17**. The exclusive regiochemistry of these products is that expected[12] from a dipole$_{HOMO}$–dipolarophile$_{LUMO}$ interaction[13] where the unsubstituted methanide terminus of the dipole bonds to the unsubstituted terminus of the acrylonitrile. The C-13 and proton NMR spectra confirmed this with the expected multiplicities of the off-resonance decoupled carbon signals for carbons 3, 3a and 4 (compounds **14**, **15**) and carbons 6a, 10a and 1 (compounds **16** and **17**). In the proton spectra H_A was a doublet of doublets at 2.95 δ and gave NOE effects with the adjacent *cis* Me group at C-3a for compound **14** and with the 10-CH_2 group for compound **16**.

Conclusion

The results illustrate that minor kinetic effects have large influences on the stereochemical outcome of these cycloadditions. The products once formed are stable and do not interconvert or revert to starting materials. For acrylonitrile, which favours the *endo*-isomer, the mixtures of both isomers encountered indicates a difference in the energy between both transition states[14] of less than 1 kcal^{-1}. It has been traditional to ascribe preferred *endo*-cycloadditions to secondary orbital interactions in the transition state.[15,16] In the present cases, which involve primary orbital interactions between the dipole$_{HOMO}$ and dipolarophile$_{LUMO}$, favourable secondary orbital interactions are indeed available for maleimides and acrylonitrile.[13] Azomethine ylides derived from prototropy in α-amino acids, with stabilised methanide termini, gave *endo* cycloadditions with maleimides[17] while those from *N*-(pyridin-2-yl)imines gave almost equal mixtures of *endo*- and *exo*-isomers[18] in reactions where secondary orbital interactions favoured the *endo*-transition state. The importance of normal polar effects in the *endo*-phenomenon has recently been emphasized.[14] In the present reactions a polar interaction could arise through a dipole moment alignment so that electron-withdrawing substituents ($\delta-$) on the alkene would lie under the positive terminus (the triazolium ring) of the 1,3-dipole and hence favour an *endo*-transition state. Grigg[19,20] highlighted the importance of the subtle interplay of steric and electronic effects in the *endo*-selectivity of cycloadditions with the additional factor that 1,3-dipolar cycloadditions will involve significant dipole moments of the substrates entering the transition state[20] and hence dipole alignments may occur to reduce the dipole moment of the transition state. The *exo*-cycloadditions observed here must be considered in the light of all of these factors. A key structural feature of the 1,3-dipoles herein is the substituent-bearing carbon (C-3 and C-6a, Scheme 2) bonded to the α-carbon of the dipole. Models show that this substituent at C-3 and C-6a provides a significant steric effect with substituents on the incoming dipolarophile. This is experimentally confirmed by the NOE effect from this substituent to H_A in the final *exo*-product (Fig. 1, structure **12a**). If the *endo* isomer were to form from the *N*-substituted maleimides the steric interaction from this C-3 and C-6a substituent to the larger –CO-N(R)-CO-unit should be significantly greater (Fig. 2). Hence we believe that the almost the exclusive *exo*-cycloadditions observed herein with the maleimides are due to a steric effect from the substituents at C-3 and C-6a in the developing fused 5,5-ring system. Preliminary results[21] on a 1,3,4-thiadiazolium analogue of the dipole **4**, where the atom corresponding to C-3 in structures **8**, **10** and **12** is a sulfur and the substituent is now moved one bond further away from the bridgehead thereby removing the steric effect, have shown *endo*-cycloadditions with *N*-substituted maleimides. With acrylonitrile as dipolarophile the steric effect is reduced and both stereoisomers are formed with a preference for the *endo*-form possibly arising from the dipolar interaction mentioned. The results show that generalizations of expected *endo*- or *exo*-preferences with these systems would be unreliable and each dipole–dipolarophile pair needs careful consideration.

Experimental

Mps were measured on an Electrothermal apparatus. IR spectra were measured with a Perkin-Elmer Spectrum 1000 FT-IR spectrometer. NMR spectra were measured on a JEOL LAMBDA 400 MHz instrument with tetramethylsilane as an internal reference and deuteriochloroform or hexadeuteriodimethyl sulfoxide or tetradeuteriomethanol as solvents. *J* Values are given in Hz. The terms J_{gem} and J_{vic} refer to geminal and vicinal proton pairs respectively. All carbon-13 NMR assignments were supported by DEPT. Microanalyses were measured on a Perkin-Elmer model 240 CHN analyser. The substrate **1** was prepared as previously described[1,6] and the dipoles **4** and **5** were generated *in situ* from the corresponding 1-trimethylsilylmethyl-2,4,5-trisubstituted-1,2,3-triazolium trifluoromethanesulfonate salts by methods previously described[8,22,23] using a literature[24,25] process with CsF. The required trisubstituted-1,2,3-triazoles were obtained by deamination of the corresponding triazolium aminide compounds **1**, and/or the corresponding *N*-oxides, with PCl_3 as previously described.[9,26] The following are a selection of typical examples.

N,2,4-Triphenyl-3a,6a-tetramethylene-3,3a,4,5,6,6a-hexahydropyrrolo[2,3-*d*][1,2,3]triazole-*endo*-5,6-dicarboximide (or *endo*-*N*,8,10-triphenyl-7,8,9,10-tetraazatricyclo[4.3.3.0^{1,6}]dodec-7-ene-11,12-dicarboximide) (3a) (Table 1, entry 1)

A solution of compound **1** (0.29 g, 1 mmol) in dry acetone (10 cm^3) was treated with *N*-phenylmaleimide (0.18 g, 1.04 mmol), and stirred under reflux for 4 h and the solvent evaporated under reduced pressure. The residue in CH_2Cl_2 (3 cm^3) was placed on a silica gel-60 column (230–400 mesh ASTM) and eluted with a gradient mixture (1 : 0–0 : 1 v/v) of petroleum spirit (bp 40–60 °C)–CH_2Cl_2 to give **3a** (0.4 g, 86%), mp 224–225 °C (from EtOH or hexane–CH_2Cl_2) (Found: C, 72.5; H, 5.5; N, 14.7. $C_{28}H_{25}N_5O_2$ requires C, 72.5; H, 5.4; N, 15.1%); ν_{max}(mull)/cm^{-1} 1718, 1780 (C=O); δ_H ($CDCl_3$) 1.26–1.54, 1.81–1.92, 2.29–2.33, 2.54–2.59 (8H, m's, $(CH_2)_4$), 3.86 (1H, d, *J* 8.8, 6-H_A), 4.90 (1H, d, 5-H_B), 6.9–6.93 (1H, m, aromatic), 7.24–7.63 (12H, m, aromatic), 8.08 (2H, d, *J* 7.7, 2-Ph, 2′-H); δ_C ($CDCl_3$) 19.6, 21.0, 27.9, 30.0 $(CH_2)_4$, 52.2 (C-6), 61.0 (C-5), 79.3 (C-6a), 94.5 (C-3a), 118.6, 120.4, 122.8, 126.1, 128.7, 128.9, 131.7 (C, aromatic), 140.6, 143.5 (2-Ph, 4-Ph, both C-1′), 172.7, 174.4 (C=O). Intractable resins were also eluted.

N-(4′-Bromophenyl)-2,4-diphenyl-3a,6a-tetramethylene-3,3a,4,5,6,6a-hexahydropyrrolo[2,3-*d*][1,2,3]triazole-*endo*-5,6-dicarboximide (3b) (Table 1, entry 2)

A solution of compound **1** (0.29 g, 1 mmol) in dry acetone (10 cm^3) was treated with *N*-(4-bromophenyl)maleimide (0.25 g, 1 mmol), stirred under reflux for 3 h and cooled to give **3b** (0.49 g, 90%), mp 255–257 °C (from EtOH) (Found: C, 62.2; H, 4.4; N, 12.7. $C_{28}H_{24}N_5O_2Br$ requires C, 62.0; H, 4.5; N, 12.9%); ν_{max} (mull)/cm^{-1} 1725, 1785 (C=O); δ_H ([$^2H_6$]DMSO at 90 °C) 1.16–1.60, 2.24–2.28, 2.68–2.72 (8H, m's, $(CH_2)_4$), 3.95 (1H, d, *J* 8.6, 6-H_A), 5.19 (1H, d, 5-H_B), 6.75–6.79 (1H, m, aromatic),

7.18–7.74 (11H, m, aromatic), 8.00 (2H, d, *J* 7.7, 2-Ph, 2′-H); δ_C ([$^2H_6$]DMSO at 90 °C) 19.2, 19.3, 27.7, 29.0 $(CH_2)_4$, 51.7 (C-6), 60.1 (C-5), 79.0 (C-6a), 93.6 (C-3a), 116.9, 118.8, 122.3, 128.4, 128.6, 128.9, 129.3, 131.0, 132.2 (C, aromatic), 139.9, 143.3 (2-Ph, 4-Ph, both C-1′), 172.7, 174.8 (C=O).

2,4-Diphenyl-3a,6a-tetramethylene-3,3a,4,5,6,6a-hexahydropyrrolo[2,3-*d*][1,2,3]triazole-*endo*-5,6-dicarboximide (3c) (Table 1, entry 3)

A solution of compound **1** (0.29 g, 1 mmol) in dry acetone (10 cm^3) was treated with maleimide (0.1 g, 1.03 mmol), stirred under reflux for 24 h and the solvent evaporated under reduced pressure. The residue in CH_2Cl_2 (3 cm^3) was placed on a silica gel-60 column (230–400 mesh ASTM) and eluted with a gradient mixture (1 : 0–0 : 1 v/v) of petroleum spirit (bp 40–60 °C)–CH_2Cl_2 to give **3c** (0.31 g, 78%), mp 173–174 °C (from MeOH) (Found: C, 68.3; H, 5.4; N, 18.0. $C_{22}H_{21}N_5O_2$ requires C, 68.2; H, 5.5; N, 18.1%); ν_{max}(mull)/cm^{-1} 1718, 1774 (C=O), 3235 (N–H); δ_H (CD_3OD) 1.24–1.74, 2.29–2.34, 2.53–2.57 (8H, m's, $(CH_2)_4$), 3.74 (1H, d, *J* 8.4, 6-H_A), 4.88 (1H, d, 5-H_B), 6.82–6.85 (1H, m, aromatic), 7.18–7.55 (7H, m, aromatic), 7.96 (2H, d, *J* 8.0, 2-Ph, 2′-H); δ_C (CD_3OD) 20.9, 21.1, 29.3, 30.9 $(CH_2)_4$, 54.4 (C-6), 63.2 (C-5), 80.0 (C-6a), 95.6 (C-3a), 119.9, 121.1, 123.8, 129.5, 130.2, 133.0 (C, aromatic), 142.0, 145.0 (2-Ph, 4-Ph, both C-1′), 176.9, 178.9 (C=O).

N-Methyl-2,4-diphenyl-3a,6a-tetramethylene-3,3a,4,5,6,6a-hexahydropyrrolo[2,3-*d*][1,2,3]triazole-*endo*-5,6-dicarboximide (3d) (Table 1, entry 4)

A solution of compound **1** (0.29 g, 1 mmol) in dry acetone (10 cm^3) was treated with *N*-methylmaleimide (0.12 g, 1.08 mmol), stirred under reflux for 1 h and the solvent evaporated under reduced pressure. The residue was crystallised from ethanol to give **3d** (0.36 g, 90%), mp 193–194 °C (from EtOH) (Found: C, 68.4; H, 6.0; N, 17.5. $C_{23}H_{23}N_5O_2$ requires C, 68.8; H, 5.8; N, 17.4%); ν_{max}(mull)/cm^{-1} 1701, 1771 (C=O); δ_H ($CDCl_3$) 1.10–1.72, 2.07–2.10, 2.46–2.49 (8H, m's, $(CH_2)_4$), 2.94 (3H, s, CH_3), 3.67 (1H, d, *J* 8.8, 6-H_A), 4.69 (1H, d, 5-H_B), 6.80–6.84 (1H, m, aromatic), 7.18–7.51 (7H, m, aromatic), 7.96 (2H, d, *J* 7.3, 2-Ph, H-2′); δ_C ($CDCl_3$) 19.7, 20.0, 28.1, 29.9 $(CH_2)_4$, 24.7 (N–Me), 52.1 (C-6), 60.8 (C-5), 78.8 (C-6a), 94.4 (C-3a), 118.3, 120.2, 122.7, 128.7, 128.9, 131.6 (C, aromatic), 140.7, 143.5 (2-Ph, 4-Ph, both C-1′), 173.9, 175.5 (C=O). (Compound **3d** (58%) was also obtained on methylation of **3c** with MeI and NaOH in 95% EtOH.)

N-*tert*-Butyl-2,4-diphenyl-3a,6a-tetramethylene-3,3a,4,5,6,6a-hexahydropyrrolo[2,3-*d*][1,2,3]triazole-*endo*-5,6-dicarboximide (3e) (Table 1, entry 5)

A solution of compound **1** (0.29 g, 1 mmol) in dry acetone (10 cm^3) was treated with *N*-*tert*-butylmaleimide (0.145 cm^3, 1.00 mmol), stirred under reflux for 18 h and the solvent evaporated under reduced pressure. The residue in CH_2Cl_2 (3 cm^3) was placed on a silica gel-60 column (230–400 mesh ASTM) and eluted with a gradient mixture (1 : 0–0 : 1 v/v) of petroleum spirit (bp 40–60 °C)–CH_2Cl_2 to give **3e** (0.29 g, 66%), mp 191–192 °C (from hexane–CH_2Cl_2) (Found: C, 70.3; H, 6.6; N, 15.8. $C_{26}H_{29}N_5O_2$ requires C, 70.4; H, 6.6; N, 15.8%); ν_{max} (mull)/cm^{-1} 1711, 1774 (C=O); δ_H ($CDCl_3$) 1.25–1.76, 2.30–2.33, 2.71–2.74 (8H, m's, $(CH_2)_4$), 1.58 (9H, s, $C(Me)_3$), 3.62 (1H, d, *J* 8.8, 6-H_A), 4.67 (1H, d, 5-H_B), 6.81–6.85 (1H, m, aromatic), 7.22–7.52 (7H, m, aromatic), 8.00 (2H, d, *J* 7.7, 2-Ph, 2-H); δ_C ($CDCl_3$) 19.8, 19.9, 29.8, 29.9 $(CH_2)_4$, 28.2 (Me of $C(Me)_3$), 51.4 (C-6), 58.9 (C of $C(Me)_3$), 60.0 (C-5), 79.5 (C-6a), 93.6 (C-3a), 117.2, 119.3, 122.7, 128.6, 128.8, 131.6 (C, aromatic), 140.6, 143.5 (2-Ph, 4-Ph, both C-1′), 174.4, 176.6 (C=O). Intractable resins were also eluted.

exo-6-Cyano-2,4-diphenyl-3a,6a-tetramethylene-3,3a,4,5,6,6a-hexahydropyrrolo[2,3-*d*][1,2,3]triazole (18) and its stereoisomer (19) (Table 1, entry 6 and 7)

A solution of compound **1** (0.29 g, 1 mmol) in dry acetone (10 cm^3) was treated with acrylonitrile (0.7 cm^3, 10 mmol), stirred under reflux for 5 h and the solvent evaporated under reduced pressure. The residue in CH_2Cl_2 (3 cm^3) was placed on a silica gel-60 column (230–400 mesh ASTM) and eluted with a gradient mixture (1 : 0 to 0 : 1 v/v) of petroleum spirit (bp 40–60 °C)–CH_2Cl_2. First eluted off the column was **18** (0.27 g, 79%) followed by **19** (0.034 g, 10%), a gum, which was recolumned.

18: mp 173–174 °C (from EtOH), lit.,[6] mp 175 °C, spectra previously reported;[6] δ_H ($CDCl_3$) 3.38–3.40 (1H, dd, *J* 8.0, <1, 6-H_A, no NOE to 7-CH_2).

19: (crude sample), gum: ν_{max} (mull)/cm^{-1} 2238 (C≡N); δ_H ($CDCl_3$) 1.26–2.88 (8H, m, $(CH_2)_4$), 3.48–3.55 (2H, m, 5-H_{endo} and 6-H_A, NOE to 7-CH_2, 1.3%), 3.74–3.79 (1H, dd, J_{gem} 11.7, J_{vic} 8.0, 5-H_{exo}), 6.82–6.86 (1H, m, aromatic), 7.10–7.51 (7H, m, aromatic), 8.10 (2H, d, *J* 7.7, 2-Ph, 2′-H); δ_C ($CDCl_3$) 18.5, 19.8, 28.6, 29.9 $(CH_2)_4$, 36.6 (C-6), 49.5 (C-5), 79.3 (C-6a), 91.7 (C-3a), 117.9 (C≡N), 119.0, 122.5, 122.9, 128.8, 131.6 (C, aromatic), 141.0, 143.7 (2-Ph, 4-Ph, both C-1′).

N,1-Diphenyl-3,3a-dimethyl-3a,4,5,6-tetrahydro-1*H*-pyrrolo-[1,2-*c*][1,2,3]triazole-*exo*-4,5-dicarboximide (8a) (Table 1, entry 8)

A solution of 4,5-dimethyl-2-phenyl-2*H*-1,2,3-triazole (0.43 g, 2.5 mmol) in trimethylsilylmethyl trifluoromethanesulfonate (0.75 cm^3, 3.75 mmol) and dry CH_2Cl_2(1 cm^3) was stirred at 100 °C under a reflux condenser for 5 h, cooled to ambient temperature and the solid was dissolved in dry CH_2Cl_2 (20 cm^3). *N*-Phenylmaleimide (2.15 g, 12.4 mmol) followed by CsF (0.57 g, 3.75 mmol) were added to the mixture, which was stirred for 18 h at ambient temperature, followed by 7 h at 60 °C after which it was filtered to remove insoluble salts. The solvent was removed under reduced pressure and the residue in CH_2Cl_2 (3 cm^3) was placed on a silica gel-60 column (230–400 mesh ASTM) and eluted with a gradient mixture (1 : 0–0 : 1 v/v) of petroleum spirit (bp 40–60 °C)–CH_2Cl_2, followed by elution with increasing portions of Et_2O in the eluent. The first product eluted off the column was **8a** (0.18 g, 19%), mp 153–154 °C (from hexane–CH_2Cl_2) (Found: C, 69.5; H, 5.65; N, 15.4. $C_{21}H_{20}N_4O_2$ requires C, 70.0; H, 5.6; N, 15.5%); ν_{max} (mull)/cm^{-1} 1716, 1774 (C=O); δ_H ($CDCl_3$) 1.25 (3H, s, CH_3-C-3a), 2.20 (3H, s, CH_3-C-3), 2.98–3.02 (1H, dd, J_{gem} 11.2, J_{vic} 8.0, 6-H_{endo}), 3.46–3.50 (1H, m, 5-H_B), 3.53–3.56 (1H, m, 4-H_A, slight overlap with 5-H_B), 3.90 (1H, dd, J_{gem} 11.2, J_{vic} <1, 6-H_{exo}), 6.94–6.97 (1H, m, aromatic), 7.26–7.52 (9H, m, aromatic); δ_C ($CDCl_3$) 11.4 (CH_3-C-3a), 20.0 (CH_3-C-3), 44.1 (C-4), 49.0 (C-5), 54.8 (C-6), 80.8 (C-3a), 115.7, 121.8, 126.3, 128.8, 129.0, 129.3, 131.5 (C, aromatic), 146.5 (1-Ph, C-1′), 152.7 (C-3), 174.3, 176.5 (C=O). Intractable resins were also eluted and when the column was washed with acetone, **20a** (trace) and **6a** (0.35 g, 75%) were eluted.

N,5-Diphenyl-2,3,7,8,9,10-hexahydro-1*H*,5*H*-pyrrolo[1,2-*c*]-[1,2,3]benzotriazole-*exo*-1,2-dicarboximide (9a) (Table 1, entry 9)

A solution of 2-phenyl-4,5,6,7-tetrahydro-2*H*-1,2,3-benzotriazole (0.5 g, 2.5 mmol) in trimethylsilylmethyl trifluoromethanesulfonate (0.75 cm^3, 3.75 mmol) and dry CH_2Cl_2 (1 cm^3) was stirred at 80 °C under a reflux condenser for 5 h, cooled to ambient temperature, and the solid was dissolved in dry CH_2Cl_2 (20 cm^3) and treated with *N*-phenylmaleimide (2.08 g, 12 mmol) followed by CsF (0.57 g, 3.75 mmol). The mixture was stirred at ambient temperature for 18 h, filtered to remove insoluble salts and the solvent was evaporated under reduced pressure. The

residue in CH_2Cl_2 (3 cm^3) was placed on a silica gel-60 column (230–400 mesh ASTM) and eluted with a gradient mixture (1 : 0–0 : 1 v/v) of petroleum spirit (bp 40–60 °C)–Et_2O. The first product eluted off the column was the starting material, 2-phenyl-4,5,6,7-tetrahydro-2*H*-1,2,3-benzotriazole (0.03 g, 6%), followed by **9a** (0.19 g, 20%), mp 172–174 °C (from hexane–CH_2Cl_2) (Found: C, 71.9; H, 5.7; N, 14.6. $C_{23}H_{22}N_4O_2$ requires C, 71.5; H, 5.7; N, 14.5%); ν_{max} (mull)/cm^{-1} 1706, 1774 (C=O); δ_H ($CDCl_3$) 1.53–2.06, 2.60–2.74 (8H, m's, $(CH_2)_4$), 3.34–3.39 (2H, m, 1-H_A, 3-H_{endo}, overlap), 3.59–3.63 (1H, m, 2-H_B), 4.08 (1H, dd, J_{gem} 14.1, J_{vic} <1, 3-H_{exo}), 7.12–7.48 (10H, m, aromatic); δ_C ($CDCl_3$) 21.3, 24.5, 26.5, 37.8 $(CH_2)_4$, 48.4 (C-2), 54.8 (C-3), 56.4 (C-1), 81.3 (C-10a), 121.0, 125.5, 126.6, 128.6, 128.8, 129.3, 132.2 (C-aromatic), 147.1 (5-Ph, C-1′), 155.5 (C-6a), 175.4, 177.2 (C=O). Also eluted off the column with acetone were **21a** (trace) and **7a** (0.29 g, 57%).

N-tert-Butyl-5-phenyl-2,3,7,8,9,10-hexahydro-1*H*,5*H*-pyrrolo-[1,2-*c*][1,2,3]benzotriazole-*exo*-1,2-dicarboximide (11a) (Table 1, entry 13)

A solution of 2-phenyl-4,5,6,7-tetrahydro-2*H*-1,2,3-benzotriazole (0.5 g, 2.5 mmol) in trimethylsilylmethyl trifluoromethanesulfonate (0.75 cm^3, 3.75 mmol) and dry CH_2Cl_2 (1 cm^3) was stirred at 80 °C under a reflux condenser for 5 h, cooled to ambient temperature, and the solid was dissolved in dry CH_2Cl_2 (20 cm^3) and treated with *N-tert*-butylmaleimide (1.73 cm^3, 12 mmol) followed by CsF (0.57 g, 3.75 mmol). The mixture was stirred at ambient temperature for 18 h, filtered to remove insoluble salts and the solvent was evaporated under reduced pressure. The residue in CH_2Cl_2 (3 cm^3) was placed on a silica gel-60 column (230–400 mesh ASTM) and eluted with a gradient mixture (1 : 0–0 : 1 v/v) of petroleum spirit (bp 40–60 °C)–Et_2O. The first product eluted off the column was **11a** (0.18 g, 20%), mp 133–136 °C (from hexane–CH_2Cl_2) (Found: C, 68.5; H, 7.2; N, 15.5. $C_{21}H_{26}N_4O_2$ requires C, 68.8; H, 7.2; N, 15.3%); ν_{max} (mull)/cm^{-1} 1686, 1774 (C=O); δ_H ($CDCl_3$) 1.44–1.99, 2.55–2.62 (8H, m's, $(CH_2)_4$), 1.49 (9H, s, $C(Me)_3$), 2.99 (1H, d, *J* 7.0, 1-H_A), 3.21–3.24 (2H, m, 2-H_B, 3-H_{endo}, overlap), 3.89 (1H, dd, J_{gem} 13.2, J_{vic} <1, 3-H_{exo}), 7.03–7.07 (1H, m, 5-Ph, 4′-H), 7.22–7.28 (4H, m, 5-Ph, 2′-H, 3′-H); δ_C ($CDCl_3$) 21.2, 24.7, 26.4, 38.4 $(CH_2)_4$, 27.9 $(Me)_3$, 48.1 (C-2), 55.2 (C-3), 56.4 (C-1), 58.3 (C of $C(Me)_3$), 81.5 (C-10a), 147.4, 119.8, 128.7, 124.6 (5-Ph, C-1′, C-2′, C-3′, C-4′), 154.6 (C-6a), 177.3, 178.9 (C=O). Also eluted off the column with acetone were **21a** (trace) and **7a** (0.37 g, 69%).

N-Methyl-5-(4′-bromophenyl)-2,3,7,8,9,10-hexahydro-1*H*,5*H*-pyrrolo[1,2-*c*][1,2,3]benzotriazole-*exo*-1,2-dicarboximide (13b) (Table 1, entry 16)

A solution of 2-(4′-bromophenyl)-4,5,6,7-tetrahydro-2*H*-1,2,3-benzotriazole (0.5 g, 1.8 mmol) in trimethylsilylmethyl trifluoromethanesulfonate (0.54 cm^3, 2.7 mmol) and dry CH_2Cl_2 (1 cm^3) was stirred at 80 °C under a reflux condenser for 5 h, cooled to ambient temperature, and the solid was dissolved in dry CH_2Cl_2 (20 cm^3) and treated with *N*-methylmaleimide (1.0 g, 9 mmol) followed by CsF (0.41 g, 2.7 mmol). The mixture was stirred at ambient temperature for 18 h, filtered to remove insoluble salts and the solvent was evaporated under reduced pressure. The residue in CH_2Cl_2 (3 cm^3) was placed on a silica gel-60 column (230–400 mesh ASTM) and eluted with a gradient mixture (1 : 0–0 : 1 v/v) of petroleum spirit (bp 40–60 °C)–Et_2O. The first product eluted off the column was **13b** (0.08 g, 11%), mp 133–134 °C (from hexane–CH_2Cl_2) (Found: C, 53.3; H, 4.8; N, 13.5. $C_{18}H_{19}N_4O_2Br$ requires C, 53.6; H, 4.8; N, 13.9%); ν_{max} (mull)/cm^{-1} 1701, 1773 (C=O); δ_H ($CDCl_3$) 1.53–2.06, 2.56–2.71 (8H, m's, $(CH_2)_4$), 2.91 (3H, s, N–Me), 3.24–3.32 (2H, m, 1-H_A, 3-H_{endo}, overlap), 3.42–3.44 (2H, m, 2-H_B), 3.91 (1H, dd, J_{gem} 13.9, J_{vic} <1, 3-H_{exo}), 7.13 (2H, d, *J* 8.8, 5-Ar, 3′-H), 7.41 (2H, d, 5-Ar, 2′-H); δ_C ($CDCl_3$) 21.3, 24.6, 26.5, 37.9 $(CH_2)_4$, 25.2 (N–Me), 48.1 (C-2), 54.1 (C-3), 56.5 (C-1), 81.0 (C-10a), 146.2, 122.1, 131.8, 117.9 (5-Ar, C-1′, C-2′, C-3′, C-4′), 155.8 (C-6a), 176.1, 178.0 (C=O). Also eluted off the column with acetone were **21b** (trace) and **7b** (0.34 g, 65%).

endo-1-Cyano-5-phenyl-2,3,7,8,9,10-hexahydro-1*H*,5*H*-pyrrolo-[1,2-*c*][1,2,3]benzotriazole (16a) and its stereoisomer (17a) (Table 1, entry 18)

A solution of 2-phenyl-4,5,6,7-tetrahydro-2*H*-1,2,3-benzotriazole (0.5 g, 2.5 mmol) in trimethylsilylmethyl trifluoromethanesulfonate (0.75 cm^3, 3.75 mmol) and dry CH_2Cl_2 (1 cm^3) was stirred at 80 °C under a reflux condenser for 5 h, cooled to ambient temperature, and the solid was dissolved in dry CH_2Cl_2 (20 cm^3) and treated with acrylonitrile (3.3 cm^3, 49.5 mmol) followed by CsF (0.57 g, 3.75 mmol). The mixture was stirred at ambient temperature for 18 h, filtered to remove insoluble salts and the solvent was evaporated under reduced pressure. The residue in CH_2Cl_2 (3 cm^3) was placed on a silica gel-60 column (230–400 mesh ASTM) and eluted with a gradient mixture (1 : 0–0 : 1 v/v) of petroleum spirit (bp 40–60 °C)–Et_2O. The first product eluted off the column was **17a** (0.03 g, 5%) followed by **16a** (0.05 g, 8%).

17a: mp 100–102 °C (from hexane–CH_2Cl_2) (Found: C, 72.3; H, 6.9; N, 21.0. $C_{16}H_{18}N_4$ requires C, 72.1; H, 6.8; N, 21.0%); ν_{max} (mull)/cm^{-1} 2238 (C≡N); δ_H ($CDCl_3$) 1.58–2.26, 2.78–2.81 (8H, m's, $(CH_2)_4$), 2.02–2.10 (1H, m, 2-H_{endo}), 2.17–2.26 (1H, m, 2-H_{exo}), 3.29–3.43 (3H, m, 1-H_A, 3-CH_2), 6.98–7.01 (1H, m, 5-Ph, 4′-H), 7.26–7.31 (4H, m, 5-Ph, 2-H′, 3-H′); δ_C ($CDCl_3$) 23.2, 25.8, 27.1, 38.0 $(CH_2)_4$, 30.2 (C-2), 37.3 (C-1), 57.0 (C-3), 80.9 (C-10a), 118.8 (C≡N), 149.1, 116.1, 128.7, 122.2 (5-Ph, C-1′, C-2′, C-3′, C-4′), 152.0 (C-6a).

16a: mp 127–129 °C (from hexane–CH_2Cl_2) (Found: C, 72.2; H, 6.7; N, 21.1. $C_{16}H_{18}N_4$ requires C, 72.1; H, 6.8; N, 21.0%); ν_{max} (mull)/cm^{-1} 2235 (C≡N); δ_H ($CDCl_3$) 1.67–2.06, 2.80–2.85 (8H, m's, $(CH_2)_4$), 2.28–2.35 (2H, m, 2-CH_2), 3.01–3.05 (1H, dd, *J* 7.4, 7.4, 1-H_A), 3.32–3.35 (2H, m, 3-CH_2), 6.99–7.01 (1H, m, 5-Ph, 4′-H), 7.26–7.31 (4H, m, 5-Ph, 2′-H, 3′-H); δ_C ($CDCl_3$) 23.2, 26.1, 26.7, 41.8 $(CH_2)_4$, 30.8 (C-2), 38.8 (C-1), 56.4 (C-3), 81.5 (C-10a), 119.7 (C≡N), 148.9, 116.4, 128.7, 122.3 (5-Ph, C-1′, C-2′, C-3′, C-4′), 151.9 (C-6a). Also eluted off the column with acetone were **21a** (trace) and **7a** (0.37 g, 70%).

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