Organic & Biomolecular Chemistry

ROYAL SOCIETY OF CHEMISTRY

PAPER

View Article Online
View Journal | View Issue

Cite this: *Org. Biomol. Chem.*, 2025, **23**, 4116

On the divergent reactivity of allenylstannanes generated from the O-directed free radical hydrostannation reaction of (±)-*trans*-3-(2-phenylcyclopropyl)prop-2-yn-1-ol. EPR evidence for the reversible addition of Ph_3Sn radicals to vinyl triphenyltins†‡

K. Lawrence E. Hale,[a] Alistair J. Fielding *[b] and Karl J. Hale *§[a]

Received 14th November 2024,
Accepted 11th March 2025

DOI: 10.1039/d4ob01847h

rsc.li/obc

(±)-*trans*-3-(2-Phenylcyclopropyl)prop-2-yn-1-ol (**5**) undergoes O-directed rt free radical hydrostannation with 2 equiv. of Bu_3SnH or Ph_3SnH in PhMe to produce the α-cyclopropyl-β-stannylvinyl radicals **26** and **27**, which rapidly ring-open to give the benzylic stannylhomoallenyl radicals **28** and **29**. These, in turn, react with the excess stannane that is present to provide **21** and **23** as primary reaction products. The triphenylstannylallene **23** also undergoes a competitive $Ph_3Sn^{\bullet}$ addition to its central allene carbon. This affords the allylically-stabilised radical **31c**, which itself reacts with the stannane to produce (*Z*)-6-phenyl-2,3-bis(triphenylstannyl)hex-3-en-1-ol (**24**). EPR studies of the reaction of **5** with Ph_3SnH (1 equiv.) and cat. Et_3B/O_2 in PhMe at 250 K have failed to identify the radicals **27** and **29** in the reaction mixtures. Rather, a sharp dd is always observed whose multiplicity is consistent with it being the tris-Ph_3Sn-stabilised free radical **33**. The latter is suggested to arise from a reversible O-directed $Ph_3Sn^{\bullet}$ addition to **24**. The radical **33** has $^1H^{\beta}$ values of 1.32 mT (13.2 G) and 0.57 mT (5.7 G) and a *g* of 2.0020.

Introduction

In the preceding paper,[1] we studied the kinetics of ring-opening of the intermediary α-cyclopropyl-β-stannylvinyl radicals that are formed when cyclopropylacetylenic alcohols are subjected to O-directed free radical hydrostannation with stannanes and cat. Et_3B/O_2. It was found that the high log *A* values of these ring-openings (13.27–14.95 s^{-1}) only satisfactorily align with a unimolecular E_H1 homolytic mechanism for cyclopropane ring-cleavage. As a consequence, an entirely free radical mechanism[2] was reaffirmed for the O-directed hydrostannation of dialkyl acetylenes,[3] not the ionic mechanism of the stannylvinyl cation theory.[4]

In this follow-on paper, we now describe our studies on the O-directed free radical hydrostannation[3] of the 3-(2-phenylcyclopropyl)-prop-2-yn-1-ol probe **5**, under cat. Et_3B/O_2-initiated conditions. Specifically, we will show that in both PhMe and THF/H_2O, the products that arise, originate from an entirely homolytic pathway, thus reinforcing the mechanistic conclusions of the earlier kinetic study.[1]

We will also detail here our EPR studies of the O-directed hydrostannation of **5** with Ph_3SnH/cat. Et_3B in PhMe, which have now provided good spectroscopic support for the formation of 1,2-bis-(Ph_3Sn) radical adducts from the primary vinyltriphenylstannane products of these reactions at low temperature. Observations that now require the original Hale–Manaviazar 2005 mechanism for the O-directed free radical hydrostannation of disubstituted alkyl acetylenes with Ph_3SnH/cat. Et_3B/O_2 to be restored in its entirety, but with further augmentation and refinement as outlined below.[2a]

[a]*The School of Chemistry and Chemical Engineering, Queen's University Belfast, Stranmillis Road, Belfast BT9 5AG, UK*
[b]*The School of Pharmacy and Biomolecular Sciences, Liverpool John Moores University, Byrom Street, Liverpool L3 3AF, UK. E-mail: A.J.Fielding@ljmu.ac.uk*

† Dedicated to the memory of Professor Alwyn G. Davies FRS of UCL, whose numerous profound mechanistic contributions to the field of organometallic free radical chemistry will have enduring impact. Sadly, he died on 1st September 2023, aged 97 years, but his fine work, always done correctly, with great thoroughness and thought, will forever guide and inspire future generations.

‡ Electronic supplementary information (ESI) available: EPR experimental procedures, additional discussion of the EPR results, and copies of the NMR and mass spectra for the compounds.[32–36] See DOI: https://doi.org/10.1039/d4ob01847h

§ Current address: Halazar Pharma Ltd, Edgware, Middlesex, HA8 7RB, UK. E-mail: k.hale120@btinternet.com.

Results and discussion

Although Baines[5] and Stratakis[6] have each independently demonstrated that (*trans*-2-phenylcyclopropyl)ethyne (**4**)[5] and 3-(2-phenylcyclopropyl)prop-2-yn-1-ol (**5**)[6] are both highly useful mechanistic probes for distinguishing between vinylic free radical and vinylic carbocation pathways in organic reactions,[5,6] some have found the current pathways to **5** [5–7] to be somewhat difficult to implement.[8] We have therefore devised a completely new route to **4** and **5** (Scheme 1) which now allows both probes to be conveniently prepared on multigram scale in good yield (41–56%, over 4 steps), without recourse to harsh −78 °C organolithium-based reaction conditions.

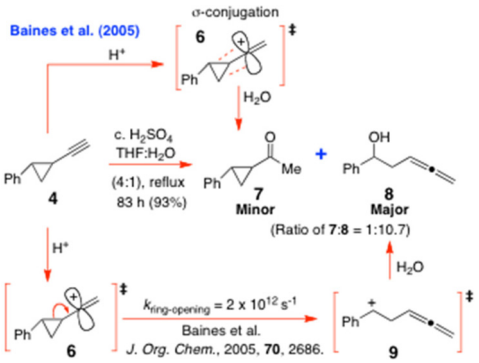
Our new pathway to **4** and **5** (see Scheme 1) sets off from commercially available (±)-*trans*-2-phenylcyclopropane-1-carboxylic acid (**1**), and requires just four steps to reach **5**: Weinreb amidation with EDCI.HCl, semi-reduction of **2** with DIBAL, Ohira–Bestmann alkynylation[9] of the aldehyde **3**, and alkyne hydroxymethylation under the mild $Zn(OTf)_2$/TMEDA conditions of Hale and Manaviazar[10] for base-sensitive acetylenes. Our new route to (±)-**5** is presented in full in Scheme 1.

According to Baines,[5] it is possible to generate the α-2-phenyl-cyclopropylvinyl cation **6** through protonation of the alkyne **4** with conc. H_2SO_4 in THF/H_2O (4 : 1) at reflux (Scheme 2) and, once it is formed, **6** undergoes rapid cyclopropane ring-cleavage ($k_{ring\text{-}opening} = 2 \times 10^{12}$ s^{-1}) to give the homoallenyl benzylic cation **9** alongside **6**.

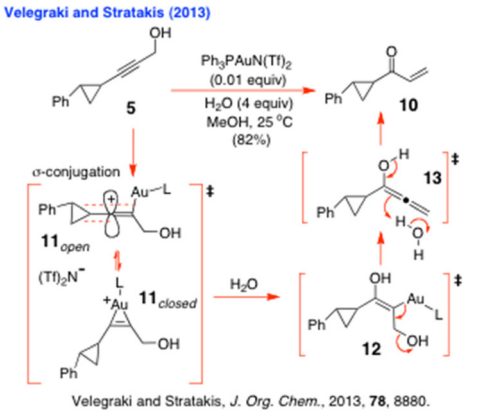
Significantly, both intermediates are capable of being successfully intercepted with the H_2O that is present in the medium, with the benzylic alcohol **8** forming alongside the methyl ketone **7** in 10.7 : 1 ratio.

Likewise, Velegraki and Stratakis[6] were able to successfully isolate the enone **10** exclusively in 82% yield from the Au-catalysed hydration of alkynol **5** (Scheme 3), which confirmed that this reaction was proceeding *via* a gold-stabilised vinyl cation that could efficiently be trapped with the H_2O that was present. Importantly, the structure of **11** very closely resembled the generalised tin-stabilised vinyl cation **18** (Scheme 4) that has been postulated to be a key intermediate in the O-directed free radical hydrostannation of dialkylacetylenes by some contributors to the field.[4]

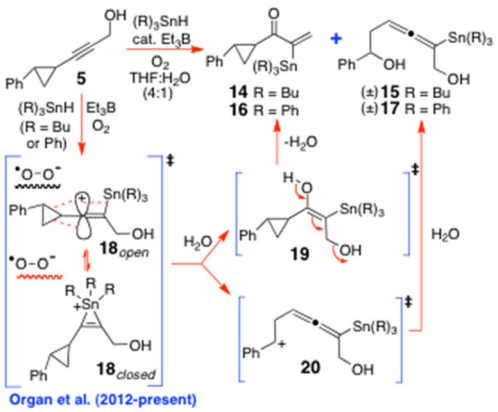
These outcomes of Baines[5] and Stratakis[6] suggested to us that it should be possible to use the aforementioned 4 : 1 THF : H_2O conditions of Baines,[5] to readily trap the tin/cyclopropyl-stabilised cation **18**, and its so-derived benzylic stannyl



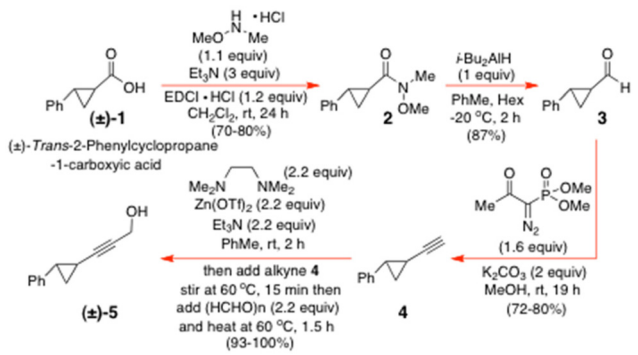
Scheme 2 Baines' successful interception of the 2-phenylcyclopropyl-vinyl cation **6** with H_2O.[5]



Scheme 3 Velegraki and Stratakis' vinyl cation trappings with H_2O.[6]



Scheme 4 Our proposed use of the probe **5** to test out the stannylvinyl cation mechanistic theory[4] of alkyne hydrostannation.

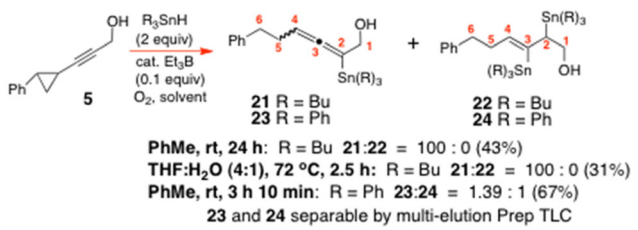


Scheme 1 A new synthesis of the alkyne probes **4** and **5**.

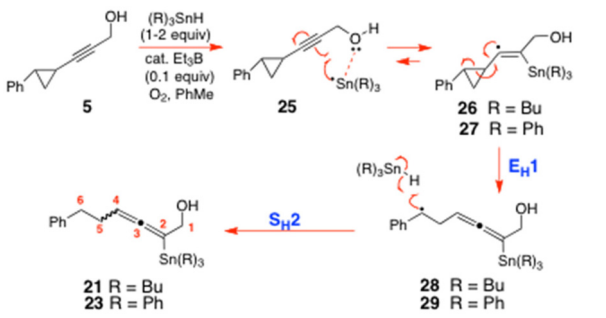
homoallenyl cation **20**, to obtain **14–17**, if the doubly-stabilised ion pair **18** (R = Bu or Ph) was indeed a genuine reaction intermediate in the O-directed free radical hydrostannation of alkynol **5** with stannanes. This would, of course, be the position taken up by proponents of the stannylvinyl cation theory of alkyne hydrostannation (see Scheme 4).[4]

Accordingly, we initially set out to investigate the O-directed free radical hydrostannation of **5** under the standard rt experimental conditions[2,4] of 2 equiv. of Bu_3SnH and 0.1 equiv. of Et_3B in PhMe, in the presence of O_2, and found that the ring-opened stannylallene **21** formed *exclusively* in 43% yield (Scheme 5). It was produced alongside unreacted starting material. Likewise, when the very same reaction was performed with **5** and Bu_3SnH in THF/H_2O (4 : 1) at 72 °C for 2.5 h, the stannylallene **21** once again formed as the sole alkyne-derived product but, on this occasion, it was isolated in 31% yield alongside unreacted starting alkynol **5**.

Significantly, neither the α-stannyl enone **14** (R = Bu) nor the benzylic alcohol **15** (R = Bu) (Scheme 4) were ever detected as reaction products in this aqueous mixture which, given Baines[5] and Stratakis'[6] earlier work of Schemes 2 and 3, most definitely ruled out the intermediacy of the tin-stabilized 2-phenylcyclopropyl-1-stannylvinyl cations $\mathbf{18}_{open}/\mathbf{18}_{closed}$ (R = Bu), and the benzylic stannylallenyl cation **20** (R = Bu) in such reactions. The fact that the stannylallene **21** (Scheme 5) was the only alkyne-derived product that formed in THF/H_2O, only satisfactorily aligned with a reaction mechanism where the stannylvinyl radical **26** (Scheme 6) underwent fast E_H1 eliminative ring-cleavage to give the benzylic radical **28**, which then H-atom abstracted from the Bu_3SnH. The stannylallene **21** could not possibly be forming through a Bu_3SnH-mediated



Scheme 5 Our O-directed hydrostannations[2] with the probe **5**.



Scheme 6 The mechanism by which **21** and **23** arise from **5**.

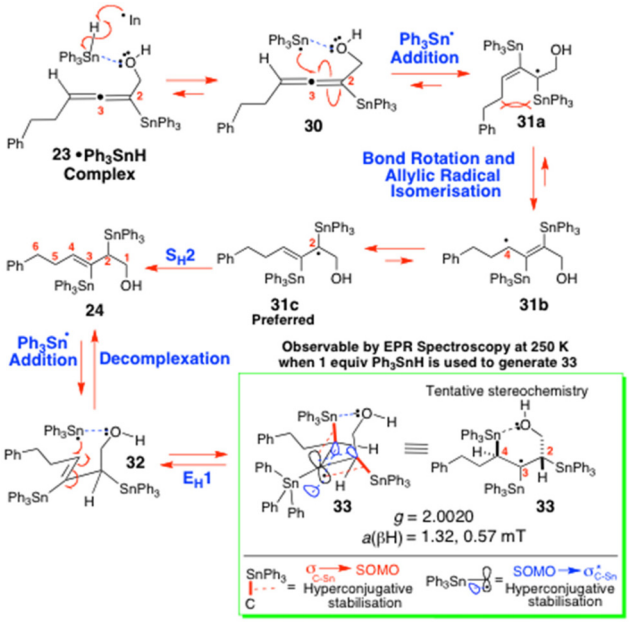
S_N1-type cationic reduction of **20** (R = Bu), nor from a concerted S_N2-type ionic reduction of the stannylvinyl cation **18** (R = Bu), otherwise **14** and **15** (R = Bu) (Scheme 4) would almost certainly have formed competitively. Their absence in THF/H_2O only realistically pointed to an entirely free radical pathway[3,11,12] being the true source of **21** (Scheme 6). Such a unimolecular E_H1 mechanism would be in accord with the high log*A* values that were recorded for the related cyclopropane ring-cleavages examined in the previous paper.[1]

Other evidence that strongly argued against the intermediacy of a stannylvinyl cation[4] in such hydrostannation reactions came from the rt reaction of **5** with Ph_3SnH (2 equiv.) and Et_3B (0.1 equiv.)/O_2 in PhMe at 0.1 M substrate concentration over 3.25 h (Scheme 5). Apart from the stannylallene **23** being formed, the (±)-bis-triphenylstannylated adduct **24** [13] was also co-created as part of a 1.39 : 1 mixture that favoured **23**. Following SiO_2 flash chromatography, the unseparated mixture was isolated in 67% yield. Separation of **23** and **24** did, however, prove possible by multi-elution SiO_2 preparative TLC using 20 : 1 petrol : EtOAc as eluent. This allowed their structures to be securely determined.

Our structural assignment of **24** is based upon detailed 2D and DEPT NMR analysis, which confirmed the presence of 35 aromatic and 9 non-aromatic protons in the 600.13 MHz ^1H spectrum of **24** in $CDCl_3$. As well as this, 48 carbons were detected in the ^{13}C NMR spectrum of **24**. The residency of two Ph_3Sn groups was deduced from there being only 8 aromatic carbon signals at δ 139.2, 138.9, 137.4, 137.1, 128.9, 128.8, 128.6 and 128.5 ppm, which revealed NMR equivalency for all the Ph groups that were present in the two Ph_3Sn residues. In the ^1H spectrum of **24**, there was a scalar ^3J coupling between the olefinic H(4) resonance at δ 6.52 ppm and the two adjacent H(5) atoms that appeared as part of 4-proton multiplet centred around δ 2.28 ppm. That multiplet also contained the protons for H(6) which were coupled to the H(5) protons. As for H(2), it resonated as much a less shielded dd at δ 3.27 ppm, and it showed ^3J couplings of 6.6 and 6.0 Hz with its neighbouring diastereotopic H(1) protons, which appeared as ddd signals at δ 4.03 and 3.87 ppm. Its attached C(2) itself resonated at δ 43.5 ppm in the ^{13}C NMR spectrum in $CDCl_3$, and importantly, it showed the expected $^2J_{^{119/117}Sn-^{13}C}$ coupling of 36.2 Hz with its neighbouring $SnPh_3$ at C(3). The latter alkenic resonance appeared at δ 141.1 ppm, and the fact that it was a quaternary carbon was proven by DEPT spectroscopy. The other olefinic carbon at C(4) appeared at δ 145.3 ppm and, as one would anticipate, it showed the requisite HSQC correlation with the H(4) signal at δ 6.52 ppm, which overlapped with the resonances for two Ph protons. Importantly, H(4) showed a large $^3J_{^1H-^{119/117}Sn}$ coupling of 166.8 Hz with the Ph_3Sn group resident at C(3) which confirmed the (*Z*)-olefin geometry for **24** and the fact that vicinal $SnPh_3$ groups must be present at C(2) and C(3). Collectively, these observations unambiguously defined the structure of **24**, and thus lent considerable weight to the EPR interpretation made herein.

The 2,3-bis(triphenylstannyl)hex-3-en-1-ol **24** that was co-formed in the hydrostannation of **5** seemingly arises from the

radical **30** by a reversible O-directed addition[3,11,12] to the central C(3)-carbon of the allene (Scheme 7). The resulting tertiary allylic radical **31a** then mesomerically isomerises and equilibrates with accompanying fast bond rotation, to give the most stable radical **31c** prior to this abstracting a H-atom to give **24**. The O-directed $Ph_3Sn^{\bullet}$ radical addition to **30** would be highly favourable due to the radical **31c** being tertiary, allylic, and doubly hyperconjugatively stabilised[14] by its α- and β-Ph_3Sn groups. Unfortunately, our extensive EPR examination[15] of the reaction of **5** with Ph_3SnH (1 equiv.) and cat. Et_3B/O_2 in PhMe at 230–250 K (Scheme 7 and Fig. 1) failed to identify either **27**, the benzylic stannyl-homoallenyl radical **29** or the 2,3-bis(triphenylstannyl)hex-3-en-2-yl radical **31c** in any of the reaction mixtures that were generated. Presumably this is because all three radicals rapidly transit into the products **23** and **24**. Invariably, the main species that was always seen accumulating over the course of 10 min to 1 h was consistent with it being the 2,3,4-tris(triphenylstannyl)hex-3-yl radical **33** (Scheme 7 and Fig. 1).



Scheme 7 The mechanism by which **24** might be arising and being converted into the 2,3,4-tris(triphenylstannyl)hexyl radical **33**.

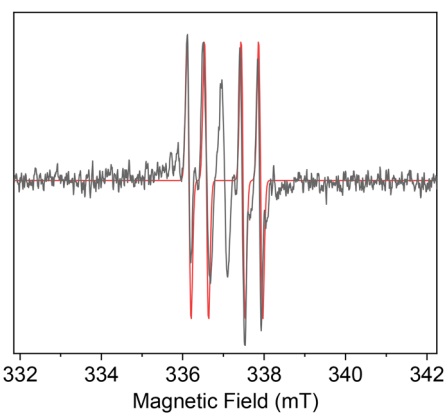


Fig. 1 The EPR spectrum of the 2,3,4-tris(triphenylstannyl)hex-3-yl radical **33** in PhMe at 250 K with EasySpin simulation[16] overlayed.

Presumably, radical **33** forms readily from **24** as a result of the new C(3)-radical centre being triply hyperconjugatively stabilised,[12,14,15] it being tertiary, and it also being extraordinarily sterically shielded by the three proximal Ph_3Sn groups, which each collectively help to prevent it from undergoing fast H-atom abstraction from the Ph_3SnH. The end-result is a radical of fairly high longevity, sufficient for **33** to be readily observed in PhMe solution at −23 °C by EPR spectroscopy.[15]

Now with regard to the dd observed for radical **33**, its multiplicity is fully consistent with the unpaired electron coupling with its two non-equivalent H-atom neighbours at C(2) and C(4) (Scheme 7). EasySpin simulations[16] have revealed $^1H^{\beta}$ *a* values of 1.32 mT (13.2 G) and 0.57 mT (5.7 G) for these splittings and, most reassuringly, our *g* of 2.0020 for **33** matches up very well with the *g* values of 2.0020 [17a] and 2.00205 [17b] reported for the $Me_3SnCH_2CH_2^{\bullet}$ radical, where substantial β-C–Sn bond hyperconjugation[14] is suggested[17] to occur.

The different magnitudes of the two $^1H^{\beta}$ hyperfine values can be attributed to variations in the dihedral angle between the β-H-atoms at C(2) and (C4) and the SOMO, as described by the Heller–McConnell equation,[18] as well as differences in spin density resulting from the varying degrees of hyperconjugation between the Ph_3Sn substituents and the C(3) radical, as it dynamically oscillates between **33** and **32**.

We strongly suspect that the O–Sn coordinated radical **32** is responsible for the broad singlet that is also present in this EPR spectrum, but clearly, such an unsupported assignment can only be considered tentative at best. For a further discussion of the EPR spectrum of **32** and **33** and the various EPR experiments that were performed, see the ESI.‡

As for the mechanism of this proposed triple hyperconjugative stabilisation of radical **33**, it is almost certainly complex. It potentially arises from the two *vicinal* β-Ph_3Sn-C bonds at C(2) and C(4) both primarily engaging in strong hyperconjugation with the partially-filled radical SOMO (*i.e.* $\sigma_{C(2)\text{ and }C(4)\text{–Sn}} \rightarrow$ SOMO electron transfer) and, concurrently, the C(3) radical itself hyperconjugatively delocalising into the empty vicinal C-$SnPh_3$ antibonding orbitals at C(2) and C(4) (*i.e.* SOMO → $\sigma^*_{C(2)\text{–Sn and }C(4)\text{–Sn}}$ electron transfer).[1,14,15]

Clearly there must be very different degrees of $\sigma_{Sn–C} \rightarrow$ SOMO and SOMO → $\sigma^*_{Sn–C(Ph)}$ hyperconjugation dynamically occurring within **33**, due to the C(4)-$SnPh_3$ bond repeatedly being broken and reforming as the radical switches between itself and **32**, most especially given that the C(2)-$SnPh_3$ bond always remains intact throughout these interconversions. While we are not in a position to accurately assess the precise extent of these differing hyperconjugative interactions at present, these primary effects are depicted in valence bond format in Scheme 7 and Fig. 2, to enable readers to readily visualise the exact electron-delocalising hyperconjugative

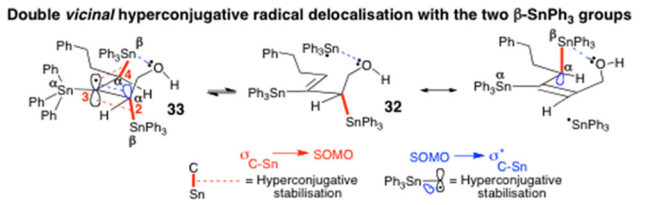


Fig. 2 How the C–Sn σ-bonds and σ*-orbitals of the β-Ph_3Sn groups might be hyperconjugatively stabilising the radical **33**. The radical SOMO can behave both as an electron-acceptor and as a donor.

movements potentially involved. One obstacle to gauging the true degree of hyperconjugation that is occurring will stem from the intermolecular nature of the O–Sn interaction that is involved. No doubt this O-atom will be stabilising[2,12a] the complexed Sn radical in **32**.

As for the C(3)-α-Ph_3Sn group, it is suggested that it will most likely stabilise the C(3) radical *via* the delocalisative mechanism shown in Fig. 3.[19a] Such a mode of stabilisation would involve the p_z electron of the radical behaving as an electron donor and delocalising into the σ*antibonding orbitals of the three Sn–C σ bonds that connect the Ph groups to the C(3)–Sn.[19,20] In other words it will be a SOMO → $\sigma^*_{Sn-C(Ph)}$ type radical stabilising interaction and, once more, a Valence Bond representation most readily allows one to easily see this.

Similar stabilising interactions have previously been proposed by Sekiguchi and coworkers,[19] to explain the high stability of $(t\text{-}Bu_2MeSi)_3M^{\bullet}$ radicals, where M is Sn, Ge or Si. In those instances, the Sn, Ge and Si radical SOMOs were suggested to beneficially interact with the σ*antibonding orbitals of the Si–C(*t*-Bu) bonds to bring about substantial radical delocalisation and stabilisation. In the case of the $(t\text{-}Bu_2MeSi)_3Sn^{\bullet}$ radical,[19a] X-ray crystallography further revealed that it had shorter Si–Sn bonds than normal, which provided very good supportive evidence for the existence of such hyperconjugation. It is thus already well established[19] how the σ*antibonding orbitals of group 14a α-metal bonds can readily engage in radical-stabilising hyperconjugative interactions with adjacent radicals. Similar hyperconjugative stabilisation has also recently been reported for α-triphenylstannyl phosphinocarbenes[21] where the carbene lone pair likewise donates into the $Sn–C_{(Ph)}$ σ* orbitals of the Ph_3Sn.

Now given that the C(4)-$SnPh_3$ group of **33** regioselectively weakens and subsequently undergoes stereospecific E_H1 elimination back into **32**, to ultimately return (*Z*)-**24**, while its C(2)-$SnPh_3$ counterpart remains totally undisturbed (Scheme 7), this observation provides very strong and convincing experimental support for the C(4)-$SnPh_3$ being regioselectively involved in strong internal O–Sn coordination with the terminal hydroxyl of **33**. Such an event would clearly lengthen and selectively weaken the C(4) C–Sn bond to guarantee that it preferentially breaks to bring about this eliminative outcome.

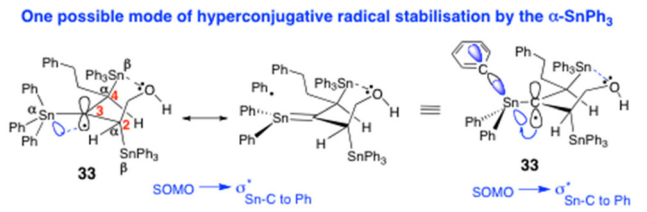


Fig. 3 The α-Ph_3Sn SOMO → $\sigma^*_{Sn-C(Ph)}$ delocalising stabilisation of **33**.

Clearly our present EPR study is significant for it has provided the first *in situ* spectroscopic evidence for O-coordinated $Ph_3Sn^{\bullet}$ radicals preferentially adding in 1,2-fashion reversibly to the least- hindered alkene carbon of the (*Z*)-trisubstituted vinyl triphenyltin products of these O-directed hydrostannations at low temperature (250 K/−23 °C).[3,22–24] It has thus powerfully shown that these events can give doubly hyperconjugatively stabilised 1,2-bis-triphenylstannylalkyl tertiary radical adducts[21] that can stereospecifically eliminate under O–Sn coordinative control,[2,12e] to return the original (*Z*)-configured vinylstannane exclusively, in the form of its O-complexed $Ph_3Sn^{\bullet}$ radical. The latter can then subsequently decomplex or re-add.

Our current work now very strongly suggests that one of the main reasons why (*Z*) → (*E*) isomerisation is NOT seriously detrimental in Et_3B-initiated hydrostannations of this type, at room temperature or below, is because these competing $Ph_3Sn^{\bullet}$ radical additions to the (*Z*)-trisubstituted vinyltriphenyltin products, and the subsequent eliminations that return those (*Z*)-vinyltriphenyltins, both proceed under O–Sn coordinative control;[3,12] which powerfully prevents full central C–C bond rotation from ever taking place within the bis-tin-1,2-radical adducts prior to the $Ph_3Sn^{\bullet}$ radical elimination occurring.

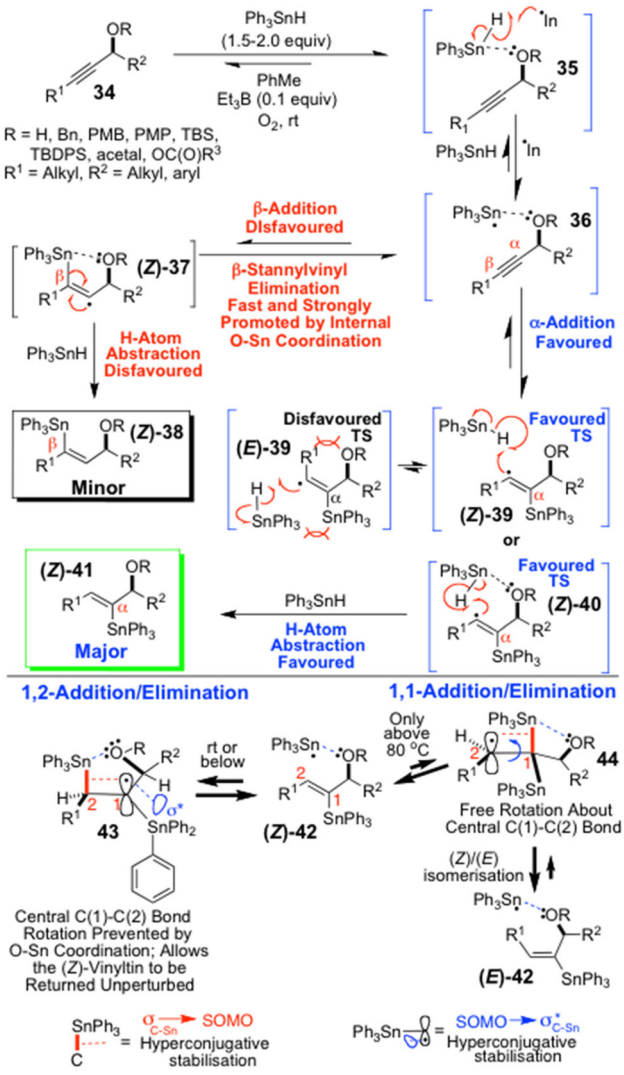
Our EPR work on **33** has thus provided remarkable new insights into the complex mechanistic course of the rt O-directed free radical hydrostannation reaction with Ph_3SnH, and it has likely helped to explain why these radical reactions typically proceed with such excellent levels of stereo- and regio-control, and without significant competing (*Z*)/(*E*) product isomerisation under the room or lower reaction temperature circumstances we always perform these reactions.

By way of contrast, when such O-directed free radical hydrostannations are conducted at high reaction temperatures, for prolonged periods, under the AIBN-mode of initiation particularly,[23,24] the normally unfavourable,[2a] geometrically-isomerising, 1,1-mode of $Ph_3Sn^{\bullet}$ radical addition/elimination[20,21] gradually starts to repeatedly occur upon the product trisubstituted (*Z*)-vinyltins of these reactions, albeit it in a minor way.

Nonetheless, such a constantly-recurrring competitive mode of isomerising tin radical addition/elimination, proceeding alongside the much more favourable, non-isomerising, 1,2-mode of addition/elimination in the (*Z*)-trisubstituted vinyltin systems, will typically lead to a stereochemically adverse outcome over time. It appears that when the ordinarily unfavourable[2a] 1,1-mode of $R_3Sn^{\bullet}$ radical addition/elimination[23,24] occurs, there is often no appropriate restraining element within the intermediary 1,1-adduct, to prevent central C–C-

bond rotation from occurring before the normally fast E_H1 elimination proceeds. Consequentially, prolonged high temperature alkyne free radical hydrostannations instigated by Bu_3SnH/AIBN (in the main)[24] will often encounter significant (*Z*)/(*E*)-isomerisation. Therefore, extended reaction times at high reaction temperature should be avoided, if excellent product stereocontrol is desired.

We trust that the present paper has now fully clarified how the O-directed free radical hydrostannation of propargylically-oxygenated dialkylacetylenes mechanistically proceeds with Ph_3SnH/cat. Et_3B at rt or below (see Scheme 8), and why competing $Ph_3Sn^{\bullet}$ radical-induced (*Z*) → (*E*) trisubstituted vinyl triphenyltin isomerisation is not usually problematical in such reactions.



Scheme 8 The mechanism[2] of the rt O-directed hydrostannation of propargylically-oxygenated dialkylacetylenes Ph_3SnH/cat. Et_3B, and why the favourable rt 1,2-addition/elimination of $Ph_3Sn^{\bullet}$ radicals does not cause (*E*)/(*Z*) isomerisation, while the high temperature, disfavoured, minor 1,1-addition/elimination pathway frequently does over extended timeframes.

While the 1,2-mode of $Ph_3Sn^{\bullet}$ radical addition and elimination does continuously occur upon the (*Z*)-vinyltriphenyltin products of these reactions, while active Ph_3SnH is still present, such processes are generally inconsequential due to O–Sn coordinative control seemingly operating throughout, and this preventing full central C–C-bond rotation from taking place in the intermediary 1,2-di-tin adducts before stannyl radical elimination occurs. It is thus typically non-isomerising and benign, when it does occur, under our standard rt or below reaction conditions.

This contrasts very sharply with its sterically unfavourable, high temperature, 1,1-additive/eliminative counterpart (Scheme 8) which is gradually isomerising over time.[23,24]

Conclusions

Alkyne hydrometallation reactions[25] are continuing to play a prominent role in the fields of complex natural product total synthesis and medicinal chemistry, and the highly α- and (*Z*)-selective O-directed free radical hydrostannation of propargylically-oxygenated dialkylacetylenes with Ph_3SnH and cat. Et_3B/O_2 in PhMe[3] remains one of the most expedient and reliable methods for positioning (*Z*)-trisubstituted alkenes within highly complex target structures,[26] particularly alkene motifs that are flanked by allylic stereocentres. In this aspect, this protocol has proven particularly powerful when it has been allied with the Marshall chiral allenylzinc addition to aldehydes,[26d,27,28] the Carreira asymmetric alkynylation,[29] and the Hale–Manaviazar alkyne hydroxymethylation[10] reactions.

In full agreement with the work previously published by our two teams over the period 2005–2021,[2,3,15] the results reported here, and the paper that precedes it,[1] once more define an entirely free radical mechanism[2,3,15,23] for the O-directed hydrostannation of dialkylacetylenes with stannanes under cat. Et_3B/O_2 initiation (Scheme 8), and they further argue against the recently hypothesised roles for stannylvinyl cation intermediates[4] in these processes.

As a result of the new EPR work performed here on the probe **5** with Ph_3SnH/cat. Et_3B, a new triply hyperconjugatively stabilised O-coordinated radical **33** has had its structure securely determined at low temperature, and its O-coordinated $Ph_3Sn^{\bullet}$ radical precursor **32** has additionally been potentially characterised. The detection of these two key radical intermediates has now given unique mechanistic insights into why many room temperature $Ph_3Sn^{\bullet}$ radical additions to the (*Z*)-vinyl triphenyltin products of these reactions [*i.e.* (*Z*)-**41**] *do not* cause significant erosive (*Z*) → (*E*)-isomerisation.

This is likely because the room temperature or below Et_3B/O_2-mediated $Ph_3Sn^{\bullet}$ radical addition reactions follow a predominantly sterically-controlled 1,2-addition/elimination pathway that operates under strong internal O–Sn coordinative control. The existence of prolonged internal O–Sn coordination within these adducts would clearly prevent central C(1)–C(2) bond rotation from freely proceeding which, in turn, would powerfully halt the (*Z*) → (*E*)-isomerisation event.

While this benign 1,2-addition/elimination pathway will continue to dominate the high temperature alkyne hydrostannation process, the much less favourable 1,1-addition/elimination pathway will also gradually start to compete and have a presence at higher temperatures, even if in a very minor way, in comparative terms.

Nonetheless, the continued repeated occurrence of this process, over time, will eventually allow significant (*Z*) → (*E*)-product isomerisation to proceed, in vinyltin systems where central C(1)–C(2) bond rotation is rotationally possible, and the process cannot be easily restrained before stannyl radical elimination occurs (see Scheme 8 for a mechanistic depiction of this process with Ph_3SnH, but similar arguments hold with other R_3SnH reagents).

With the new experimental data that has been gathered here and in the previous paper,[1] it is hoped that the longstanding debate about how the rt O-directed free radical hydrostannation of propargylically-oxygenated dialkyl acetylenes with Ph_3SnH/cat. Et_3B/O_2 mechanistically proceeds will now finally be settled. What is demonstrably clear from all of the mechanistic work conducted to date[1–3,11*a*,12,15,23] is that an entirely free radical, O-directed, mechanism operates both for this and the high temperature Bu_3SnH variant of this reaction under both the cat. Et_3B/O_2 and AIBN initiated conditions.

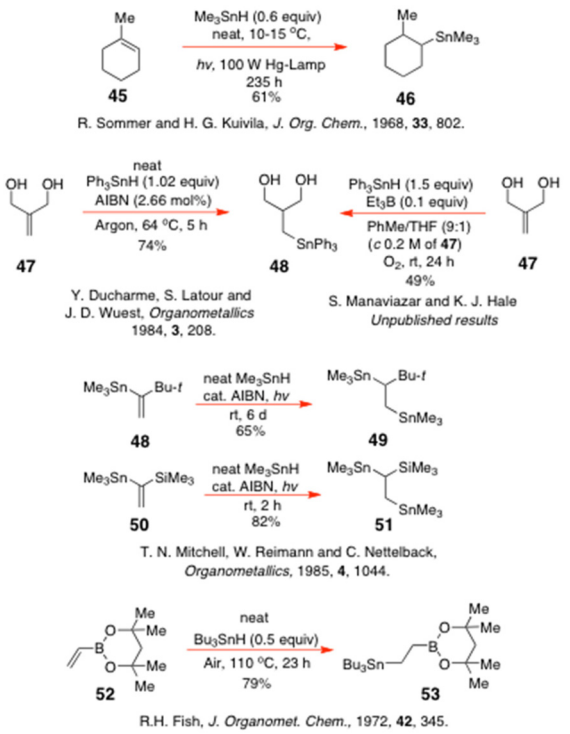
The present paper has also spectroscopically demonstrated that stannyl radical 1,2-addition/elimination processes are occurring constantly and dynamically at low temperatures throughout the course of the alkyne hydrostannation process, until all of the tin hydride has been consumed, and it has shown that such competitive side-reactions are not stereochemically erosive in their nature, at least not in the room temperature variant of the Ph_3SnH/cat. Et_3B dialkylacetylene hydrostannation reaction.[2,3,26,28]

However, for analogous high temperature hydrostannation protocols, conducted over extended periods,[16] such addition/elimination processes can have a very dramatic and quite profound effect on the final (*Z*)/(*E*)-selectivity attained,[16] but in a time- and temperature-dependent manner, by allowing the normally unfavourable, stereochemically erosive, 1,1-addition/elimination process to gradually contribute to outcome in the manner shown in Scheme 8.[16]

Of course, because EPR spectroscopy is a highly sensitive technique for detecting the presence of reasonably long-lived free radicals, and even very tiny quantities of a particular radical can give rise to a quite reasonable signal, it is difficult to quantitatively assess to what degree **33** is being formed relative to **24** in terms of a providing a relative ratio between the two entities at any point in time, since **24** is EPR inactive. While it would indeed be very interesting to ascertain this, using paramagnetic reference standards, such work is far from trivial to conduct, and it can be fraught with errors.

Nonetheless, we might try to look into this in the very near future to give a much greater idea of the true extent of competitive $Ph_3Sn^{\bullet}$ radical addition that is typically going on.

Finally, we would point out that our low temperature EPR data from the Ph_3SnH/cat. Et_3B mediated hydrostannation of **5**



Scheme 9 Past free radical hydrostannations of alkenes.[30]

and **24** mechanistically aligns with the sterically-controlled outcomes of past alkene free radical hydrostannation reactions (Scheme 9),[30] which generally have the tin radical adding reversibly, predominantly at the least hindered alkenic carbon. In particular, our results are strongly consonant with the work of Sommer and Kuivila[30*a*] on the photochemical addition of $Me_3Sn^{\bullet}$ radicals to methylcyclohexene (**45**). They are also in agreement with the studies of Mitchell[22*a*] and Fish.[30*d*]

They are likewise concordant with the more recent hydrostannation observations of Hale and Manaviazar on 2-methylene propane-1,3-diol (**47**) in solution (Scheme 9),[30*b*] and Wuest beforehand.[30*c*]

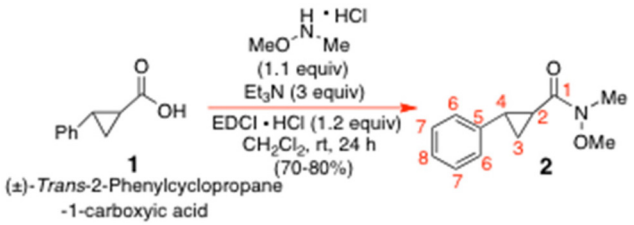
Experimental details

New experimental procedures for the preparation of the (±)-*trans*-3(2-phenylcyclopropyl)-prop-2-yn-1-ol, mechanistic probe 5

General information. Unless stated otherwise, all reactions were run in dry solvents under an N_2 atmosphere. In this study, dry THF and dry CH_2Cl_2 were used that had been freshly distilled from CaH_2 under a N_2 atmosphere, and dry PhMe was used as it had been supplied by Sigma-Aldrich. All dry solvents were withdrawn by dry syringe under an N_2 atmosphere. Ph_3SnH was purchased from Sigma-Aldrich and used as supplied; it was always handled inside a glove-bag under N_2. Bu_3SnH was purchased from Alfa and was used as supplied under N_2. SiO_2 flash chromatography was carried out using

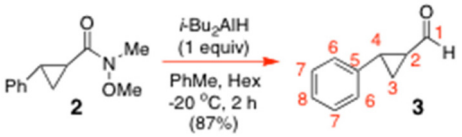
Fluorochem silica gel 60 Å. Petrol refers to the 40–60 °C b.p. fraction; it was distilled prior to use in chromatography. HPLC grade EtOAc was used for all chromatographic purifications. TLC analysis and preparative TLC were performed on Merck glass-backed TLC plates coated with silica gel 60 F_{254}. NMR analyses were carried out using the QUB School of Chemistry Bruker Avance III HD Ascend 600 instrument operating at a frequency of 600.1337 MHz. All the 600.13 MHz ^{1}H NMR spectra in $CDCl_3$ were referenced upon tetramethylsilane (TMS) at δ 0.00 ppm or the δ 77.00 ppm triplet for the corresponding 150.9 MHz ^{13}C spectra. EPR experiments were carried out using a Bruker MicroEMX spectrometer with a super high Q cavity at 9.4 GHz, microwave power of 2–20 mW, field modulation of 100 kHz and modulation amplitude of 1–2 G. Field calibration was carried out using 2,2-diphenyl-1-picrylhydrazyl (DPPH). All samples were analyzed in 4 mm quartz EPR tubes.

(1*S,2*R**)-*N*-Methoxy-*N*-methyl-2-phenylcyclopropane-carboxamide (2)**



To a well-stirred solution of (±)-*trans*-2-phenylcyclopropane carboxylic acid **1** (5.0 g, 30.83 mmol) and *N*,*O*-dimethylhydroxylamine hydrochloride (3.31 g, 33.91 mmol, 1.1 equiv.) in dry CH_2Cl_2 (49.7 mL) at rt under N_2 was added Et_3N (12.9 mL, 92.48 mmol, 3 equiv.) in a slow stream. The initial slightly cloudy solution gradually formed a thick white precipitate by the time the Et_3N addition was complete. The reaction mixture was stirred for 5 min before EDCI (7.09 g, 36.99 mmol, 1.2 equiv.) was added in one portion. The thick slurry was stirred at rt for 24 h, maintaining the N_2 atmosphere throughout. TLC analysis (4 : 1 petrol : EtOAc as eluent, PMA stain) showed the amide **2** as a dark black/blue spot; it was faster-moving than the starting acid **1**, and was formed cleanly. The reaction mixture was diluted with CH_2Cl_2 (30 mL) and washed with H_2O (20 mL). The aqueous layer was further extracted with CH_2Cl_2 (3 × 20 mL). The combined organic layers were then washed with H_2O (50 mL), dried over $MgSO_4$, filtered and concentrated *in vacuo*. The crude residue was purified by gradient-elution SiO_2 flash chromatography with petrol–EtOAc (10 : 1 → 8 : 1 → 5 : 1) to give the title Weinreb amide **2** (5.03 g, 79%) as a runny oil. ^{1}H NMR of **2** (600.13 MHz, $CDCl_3$) δ: 7.30–7.26 (m, 2H, H7), 7.19 (tt, J = 7.8, 1.2 Hz, 1H, H8), 7.15–7.11 (m, 2H, H6), 3.69 (s, 3H, –OMe), 3.23 (s, 3H, –NMe), 2.50 (ddd, J = 9.0, 6.0, 4.2 Hz, 1H, H4), 2.41 (very br s, 1H, H2), 1.63 (ddd, J = 9.0, 5.4, 4.2 Hz, 1H, H3a), 1.30 (ddd, J = 8.4, 6.0, 4.2 Hz, 1H, H3b) ppm. ^{13}C NMR of **2** (150.9 MHz, $CDCl_3$) δ: 173.1 (C1), 140.8 (C5), 128.4 (C7), 126.23 (C8), 126.19 (C6), 61.6 (–OMe), 32.6 (–NMe), 25.9 (C4), 21.5 (C2), 16.4 (C3) ppm. Electrospray HRMS of **2**: Calcd for $C_{12}H_{15}NO_2Na$ $[M + Na]^+$: 228.1001. Found: 228.1004.

(1*S,2*R**)-2-Phenylcyclopropanecarbaldehyde (3)**



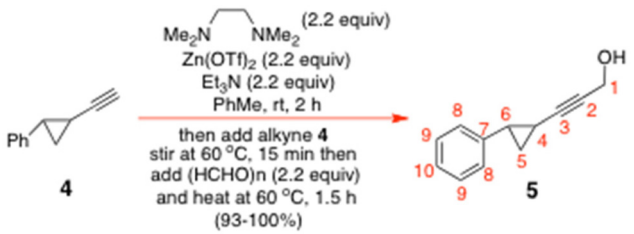
To a well-stirred −20 °C solution of the Weinreb amide **2** (5.03 g, 24.51 mmol) in dry PhMe (223 mL) under N_2 was added i-Bu_2AlH (1.0 M solution in hexanes, Aldrich, 24.51 mL, 24.51 mmol, 1 equiv.) dropwise over 18 min. Stirring was continued at −20 °C under N_2 and the reaction was continuously monitored by TLC. After 3.5 h, the reaction was deemed to be essentially over by TLC analysis (4 : 1 petrol : EtOAc, eluent, PMA stain), with only a very tiny quantity of the starting amide **2** still seen to be remaining, and the faster-moving aldehyde **3** dominating the plate; it stained black in PMA stain. The mixture was quenched by the careful dropwise addition of MeOH. The reaction mixture was then diluted with Et_2O (20 mL). Saturated aqueous Rochelle salt solution (10 mL) was then added cautiously *via* a pipette. More Et_2O (80 mL) was added, followed by more saturated aqueous Rochelle salt solution (40 mL). The mixture was transferred to a separatory funnel, vigorously shaken, and when the layers had separated, the organic layer was removed. The aqueous layer was then extracted further with Et_2O (2 × 20 mL) and the combined organic extracts were dried over $MgSO_4$, filtered and concentrated *in vacuo*. The crude residue was purified by SiO_2 flash chromatography with petrol–EtOAc (15 : 1) to give the title aldehyde **3** (3.12 g, 87%) as a colourless oil. ^{1}H NMR of **3** (600 MHz, $CDCl_3$) δ: 9.32 (d, J = 4.8 Hz, 1H, –CHO), 7.29 (m, 2H, H7), 7.22 (tt, J = 7.2, 1.2 Hz, 1H, H8), 7.13–7.09 (complex m, 2H, H6), 2.62 (ddd, J = 9.6, 6.6, 4.2 Hz, 1H, H4), 2.165 (dddd, J = 8.4, 5.4, 4.8, 4.2 Hz, 1H, H2), 1.72 (dt, J = 9.6, 4.8 Hz, 1H, H3a), 1.52 (ddd, J = 8.4, 6.6, 4.8 Hz, 1H, H3b). ^{13}C NMR of **3** (150.9 MHz, $CDCl_3$) δ: 199.7 (C1), 138.9 (C5), 128.6 (C7), 126.8 (C8), 126.2 (C6), 33.7 (C2), 26.5 (C4), 16.4 (C3).

((1*R,2*S**)-*trans*-2-Ethynylcyclopropyl)benzene (4)**

To a stirred rt solution of the aldehyde **3** (2.68 g, 18.33 mmol) in dry MeOH (160 mL) at rt under N_2 was added K_2CO_3 (5.07 g, 36.67 mmol, 2 equiv.) in one portion. A solution of freshly prepared dimethyl-1-diazo-2-oxopropylphosphonate (5.63 g, 1.6 equiv.) (Ohira–Bestmann reagent)[9] in dry MeOH (23.3 mL) was then added dropwise to the reaction mixture *via* cannula over

15 min, whilst maintaining the N_2 atmosphere. The reactants were thereafter stirred at rt for 21 h, whereupon TLC analysis (neat petrol as eluent) showed a single faster-moving product **4** had formed cleanly; it stained black on a glass-backed TLC plate in PMA stain. The reaction mixture was diluted with CH_2Cl_2 (80 mL) and H_2O (50 mL) and separated. The aqueous layer was then further extracted with CH_2Cl_2 (30 mL × 3) and the combined organic extracts were dried over $MgSO_4$, filtered and concentrated *in vacuo*. The crude residue was purified by SiO_2 flash chromatography with neat petrol to give the title alkyne **4** (1.88 g, 72%), as a colourless oil. ^{1}H NMR of **4** (600.13 MHz, $CDCl_3$) δ: 7.27–7.23 (m, 2H, H8), 7.19–7.17 (m, 1H, H9), 7.07–7.05 (m, 2H, H7), 2.27 (ddd, J = 8.4, 6.0, 4.2 Hz, 1H, H5), 1.89 (d, J = 1.8 Hz, 1H, H1), 1.49 (m, 1H, H3), 1.31 (ddd, J = 9.0, 6.0, 4.8 Hz, 1H, H4a), 1.22 (ddd, J = 8.4, 6.0, 4.8 Hz, 1H, H4b) ppm. ^{13}C NMR of **4** (150.9 MHz, $CDCl_3$) δ: 140.4 (C6), 128.4 (C8), 126.3 (C9), 125.9 (C7), 86.2 (C2), 64.8 (C1), 26.0 (C5), 17.4 (C4), 10.8 (C3) ppm. A satisfactory mass spectral confirmation of identity could not be obtained for the alkyne **4** at the QUB mass spectrometry facility. Nonetheless, there was excellent ^{13}C NMR spectral agreement between our version of **4** and the spectrum that had previously been reported in the literature; that data was as follows: 100 MHz ^{13}C NMR data for **4** in $CDCl_3$: δ: 140.4 (C6), 128.3 (–Ph), 126.2 (–Ph), 125.9 (–Ph), 86.1 (C2), 64.7 (C1), 26.0 (C5), 17.3 (C4), 10.8 (C3) ppm (see: ref. 7). Significantly, these workers did report a satisfactory HRMS for $[M + H]^+$ = 143.0857. Calcd for $C_{11}H_{11}$ $[M + H]^+$ = 143.086.

3-((1*S**,2*R**)-2-Phenylcyclopropyl)prop-2-yn-1-ol (5)



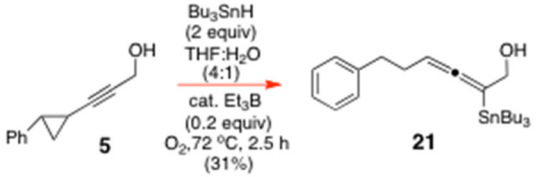
To a very vigorously stirred rt suspension of $Zn(OTf)_2$ (9.45 g, 25.99 mmol, 2.2 equiv.) and TMEDA (3.9 mL, 25.99 mmol, 2.2 equiv.) in dry PhMe (40 mL) under N_2 was added Et_3N (3.62 mL, 25.99 mmol, 2.2 equiv.) in one portion. The reactants were stirred vigorously at rt for 2 h before a solution of the alkyne **4** (1.68 g, 11.81 mmol) in PhMe (9.2 mL) was introduced *via* cannula maintaining the N_2 atmosphere throughout the addition. The reaction mixture was then heated at 60 °C under N_2 for 15 min, whereupon solid paraformaldehyde (0.78 g, 25.99 mmol, 2.2 equiv.) was added in one portion, whilst maintaining the N_2 atmosphere throughout the addition. The reactants were stirred under N_2 at 60 °C for 25 h, whereafter, the reaction was judged complete by TLC analysis (7 : 1 petrol : EtOAc eluent, PMA stain). The reaction was then quenched by adding saturated aqueous $NaHCO_3$ solution (20 mL) and Et_2O (40 mL). The aqueous layer was extracted with Et_2O (40 mL × 2) and the combined organic layers were dried over $MgSO_4$, filtered, and concentrated *in vacuo*. The crude oily residue so obtained was purified by gradient-elution SiO_2 flash chromatography with petrol–EtOAc (20 : 1 → 10 : 1 → 5 : 1) to give the title alkynol **5** (1.88 g (93%)) as a thick colourless oil that crystallised as a white solid upon storage. Our ^{1}H NMR data for **5** (600.13 MHz, $CDCl_3$) δ: 7.27–7.24 (m, 2H, 2 × H9), 7.19–7.16 (m, 1H, H10), 7.07–7.05 (m, 2H, 2 × H8), 4.25 (dd, J = 6.0, 1.8 Hz, 2H, H1ab), 2.25 (ddd, J = 8.4, 6.0, 4.8 Hz, 1H, H6), 1.85 (t, J = 6.0 Hz, 1H, –OH), 1.51 (m, 1H, H4), 1.30 (ddd, J = 9.0, 5.4, 4.8 Hz, 1H, H5a), 1.24 (ddd, J = 8.4, 6.0, 4.8 Hz, 1H, H5b). Our ^{13}C NMR for **5** (150.9 MHz, $CDCl_3$) δ: 140.5 (C7), 128.4 (C9), 126.2 (C10), 125.9 (C8), 88.1 (C3), 74.9 (C2), 51.3 (C1), 26.1 (C6), 17.5 (C5), 11.2 (C4). LR electrospray MS: Calcd for $C_{24}H_{26}LiO_2$ $[2M + 2H + Li]^+$: 353.20928. Found: 353.2003. Literature[6] 75 MHz ^{13}C NMR data for 5 in $CDCl_3$: δ: 140.4 (C7), 128.3 (–Ph), 126.1 (–Ph), 125.8 (–Ph), 87.8 (C3), 75.0 (C2), 51.0 (C1), 26.0 (C6), 17.4 (C5), 11.1 (C4) ppm. Lit. HRMS:[6] Calcd for $C_{12}H_{13}O$ $[M + H]^+$: 173.0966. Found: 173.0960 (see: ref. 6).

O-Directed free radical hydrostannation studies with the alkynol 5 and spectral data for 21, 23 and 24

O-Directed free radical hydrostannation of alkynol 5 with Bu_3SnH/cat. Et_3B/O_2 in PhMe at rt

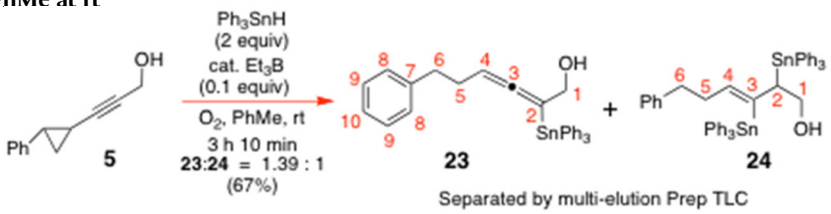
To a round-bottomed flask containing a well-stirred solution of **5** (0.1 g, 0.58 mmol) in PhMe (5.81 mL) under N_2 was added Bu_3SnH (0.31 mL, 1.1613 mmol, 2 eq.) dropwise, followed by Et_3B (0.06 mL, 1 M soln in hexanes, 0.05807 mmol, 0.1 equiv.). Air (5 mL) was then added *via* a syringe, and the reactants were left to stir under N_2 for 24 h at rt, before being concentrated *in vacuo*. The crude residue was purified by gradient-elution SiO_2 flash chromatography with petrol–EtOAc (50 : 1 → 25 : 1) to give the pure allenyltin **21** (130 mg, 43%) as an oil. ^{1}H NMR of **21** (600.13 MHz, $CDCl_3$) δ: 7.33–7.26 (m, 2H, Ph), 7.22–7.16 (m, 3H, Ph), 4.91 (m, 1H, H4), 4.05 (m, 2H, H1), 2.79–2.63 (m, 2H, H6), 2.32 (m, 2H, H5), 1.51 (m, 6H, –C$\underline{H}_2$– of $SnBu_3$), 1.36 (t, J = 6.0 Hz, C1-OH), 1.31 (q, 6H, J = 7.2 Hz, 3 × –C$\underline{H}_2$Me of –$SnBu_3$), 0.95 (m, 6H, –C$\underline{H}_2$Sn– of $SnBu_3$), 0.90 (t, 9H, J = 7.2 Hz, 3 × Me of $SnBu_3$). ^{13}C NMR of **21** (150.9 MHz, $CDCl_3$) δ: 199.6 (C3), 141.8 (C7), 128.5 (C9), 128.3 (C8), 125.9 (C10), 96.4 (C2, $^1J_{^{119}Sn-^{13}C}$ = 304.8 Hz, $^1J_{^{117}Sn-^{13}C}$ = 291.2 Hz), 85.5 (C4, $^3J_{^{119/117}Sn-^{13}C}$ = 39.2 Hz), 63.0 (C1, $^2J_{^{119/117}Sn-^{13}C}$ = 31.7 Hz), 35.9 (C6, $^5J_{^{119/117}Sn-^{13}C}$ = 9.1 Hz), 30.43 (C5, $^4J_{^{119/117}Sn-^{13}C}$ = 16.6 Hz), 29.0 (3 × –$\underline{C}$H$_2$Me of $SnBu_3$, $^3J_{^{119/117}Sn-^{13}C}$ = 21.1 Hz), 27.3 (3 × –$\underline{C}$H$_2$CH$_2$Me of $SnBu_3$, $^2J_{^{119}Sn-^{13}C}$ = 57.3 Hz, $^2J_{^{117}Sn-^{13}C}$ = 54.3 Hz), 13.7 (3 × $\underline{Me}$ of $SnBu_3$), 10.2 (3 × –$\underline{C}$H$_2$Sn of $SnBu_3$, $^1J_{^{119}Sn-^{13}C}$ = 339.5 Hz, $^1J_{^{117}Sn-^{13}C}$ = 324.4 Hz). LRMS Electrospray: Calcd for $C_{24}H_{42}LiOSn$ $[M + 2H + Li]^+$: 473.2418. Found: 473.2976.

O-Directed free radical hydrostannation of alkynol 5 with Bu_3SnH/cat. Et_3B/O_2 in THF/H_2O at rt



To a round-bottomed flask containing a well-stirred solution of **5** (0.1 g, 0.5807 mmol) in THF : H_2O (4 : 1, 5.81 mL) under N_2 was added Bu_3SnH (0.31 mL, 1.1613 mmol, 2 equiv.) dropwise. The reactants were heated to between 72 °C, whereupon Et_3B (0.06 mL, 1 M soln in hexanes, 0.05807 mmol, 0.1 equiv.) was added, followed by air (5 mL) added *via* a syringe. The reaction mixture was allowed to stir at 72 °C for 1 h, whereafter more Et_3B (0.06 mL, 0.05807 mmol, 0.1 eq.) was again added. The reactants were then allowed to stir for 1.5 h at 72 °C. The reaction mixture was quenched by dilution with EtOAc (30 mL) and aqueous NaCl solution (30 mL). The organic layer was washed with H_2O (50 mL), dried with $MgSO_4$, filtered and concentrated *in vacuo*. The residue was purified by SiO_2 flash chromatography with petrol–EtOAc (50 : 1) to give the pure allenyltin **21** (93 mg, 31%) as an oil.

O-Directed free radical hydrostannation of alkynol 5 with Ph_3SnH/cat. Et_3B/O_2 in PhMe at rt



To a 50 mL pear-shaped flask inside a glove-bag filled with dry N_2 gas was added Ph_3SnH (0.57 g, 1.624 mmol). The flask was capped by a rubber septum, removed from the glove bag, and an N_2-filled balloon connected to the septum *via* a wide-gauge needle. A small magnetic stirring bar was introduced into the flask against a counter-flow of N_2, followed by the crystalline alkynol **5** (0.14 g, 0.812 mmol). Dry PhMe (8.12 mL) was added to the reaction vessel *via* syringe, and the contents were manually swirled to assist in dissolution. With vigorous stirring, Et_3B (0.081 mL, 1 M soln in hexanes, 0.1 equiv.) was then added to the reaction flask dropwise at rt over 10 seconds. Air (5 mL) was then added to the reaction vessel *via* syringe, and the reactants were thereafter stirred at rt for 3 h 10 min. TLC analysis (10 : 1 petrol : EtOAc as eluent; anisaldehyde as TLC stain) thereupon indicated that a seemingly single faster-moving major product had formed, but it transpired that this single spot was actually a mixture of two main components **23** and **24** (formed in 1.39 : 1 ratio), when the reaction was examined by multi-elution TLC analysis. At this point, the reaction was judged to be complete, whereafter the crude reaction mixture was concentrated *in vacuo* on a rotary evaporator. The oil so obtained was purified by gradient-elution SiO_2 flash chromatography initially using petrol : CH_2Cl_2 (3 : 1 → 2 : 1 → 1 : 1) to remove non-alkyne-derived tin-by-products, and then with petrol : EtOAc (25 : 1 → 20 : 1 → 10 : 1) to obtain the seemingly homogenous mixture of **23** and **24** (0.43 g, 67%). For structural analysis purposes only, however, a small portion of that crude unseparated mixture was dissolved in EtOAc and applied to two glass-backed TLC plates. These were then eluted and briefly air-dried on multiple occasions until the two main components were deemed to be separated. The respective compounds **23** and **24** were then scraped from the plate, and eluted from the TLC silica by suspension in EtOAc and filtration. The now separated individual components **23** and **24** were thereafter further purified individually by SiO_2 flash chromatography with 10 : 1 petrol : EtOAc to give **23** and **24** which were both obtained as oils.

6-Phenyl-2-(triphenylstannyl)hexa-2,3-dien-1-ol (23). The triphenylstannylallene **23** had the following spectral characteristics.

^{1}H NMR of **23** (600.13 MHz, $CDCl_3$) δ: 7.64–7.53 (complex m, 6H, $^3J_{^{119}Sn-^1H}$ = *ca.* 49.8 Hz, *o*-C<u>H</u>, –$SnPh_3$), 7.41–7.33 (complex m, 9H, *m*- and *p*-C<u>H</u>, –$SnPh_3$), 7.24 (d, 1H, J = 7.8 Hz, *p*-C<u>H</u>, Ph), 7.16 (t, 2H, J = 7.8 Hz, *m*-C<u>H</u>, Ph), 7.07 (d, 2H, J = 6.6 Hz, *o*-C<u>H</u>, Ph), 4.99 (complex m, 1H, H4), 4.24 (m, 2H, 2 × H1), 2.57 (complex m, 1H, H6a), 2.49 (complex m, 1H, H6b), 2.33–2.15 (complex m, 2H, H5a,b), 1.46 (t, 1H, J = 6.0 Hz, –O<u>H</u>) ppm.

^{13}C NMR of **23** (150.9 MHz, $CDCl_3$) δ: 202.7 (C3), 141.6 (quaternary C of Ph), 138.0 (3 × quaternary C of Ph_3Sn), 137.1 ($^2J_{^{119}/^{117}Sn-^{13}C}$ = 37.7 Hz, 6 × *o*-<u>C</u>H of Ph_3Sn), 129.1 ($^4J_{^{119}/^{117}Sn-^{13}C}$ = 10.6 Hz, 3 × *p*-<u>C</u>H of Ph_3Sn), 128.6 ($^3J_{^{119}/^{117}Sn-^{13}C}$ = 51.3 Hz, 6 × *m*-CH of Ph_3Sn), 128.5 (2 × *o*-<u>C</u>H of Ph), 128.3 (2 × *m*-<u>C</u>H of Ph), 125.9 (*p*-<u>C</u>H of Ph), 96.1 (C2), 86.7 (C4), 63.4 (C1), 35.5 (C6, $^5J_{^{117}/^{119}Sn-^{13}C}$ = 15.1 Hz), 30.2 (C5, $^4J_{^{117}/^{119}Sn-^{13}C}$ = 21.1 Hz) ppm.

(*Z*)-6-Phenyl-2,3-bis(triphenylstannyl)hex-3-en-1-ol (24). The (*Z*)-6-phenyl-2,3-bis(triphenylstannyl)hex-3-en-1-ol **24** that was prepared had the following spectral characteristics.

^{1}H NMR of **24** (600.13 MHz, $CDCl_3$) δ: 7.52–7.39 (2× complex m, each 6H [*i.e.* 12H in total] *o*-C<u>H</u>, –$SnPh_3$), 7.38–7.27 (complex m, 18H, *m*- and *p*-C<u>H</u>, –$SnPh_3$), 7.08–7.03 (complex m, 3 H, 2 × *m*-CH, and 1 *p*-CH, of Ph ring at C6), 6.52 (complex m, 3H, comprised of 2 multiplets for 2 × *o*-C<u>H</u> of Ph ring at C6 superimposed upon H4 (t), $^3J_{^{119}Sn-H4}$ = 166.8 Hz), 4.03 (ddd, 1H, J = 10.2 Hz, 7.2 Hz, 6.0 Hz, H1a), 3.87 (ddd, 1H, J = 11.4 Hz, 6.0 Hz, 6.0 Hz, $^3J_{^{119}Sn-^1H1}$ = 66 Hz, $^3J_{^{117}Sn-^1H1}$ = *ca.* 62 Hz, H1b), 3.27 (dd, 1H, J = 6.6, Hz, 6.0 Hz, $^1J_{^{119}/^{117}Sn-^1H2}$ = *ca.* 64 Hz, H2), 2.33–2.23 (complex m, 4H, H5 and H6), 1.58 (t 1H, J = 5.4 Hz, –CH_2O<u>H</u> of C1) ppm.

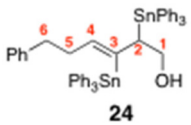
^{13}C NMR of **24** (150.9 MHz, $CDCl_3$) δ: 145.3 (C4, $^2J_{^{119/117}Sn-^{13}C(4)}$ = 54.3 Hz), 141.14 (C3), 141.11 (quaternary C of Ph), 139.2 (3× quaternary C of Ph_3Sn, $^1J_{^{119}Sn-^{13}C}$ = 479.9 Hz, $^1J_{^{117}Sn-^{13}C}$ = 458.7 Hz), 138.9 (3× quaternary C of Ph_3Sn, $^1J_{^{119}Sn-^{13}C}$ = 504.0 Hz, $^1J_{^{117}Sn-^{13}C}$ = 482.9 Hz), 137.4 ($^2J_{^{119/117}Sn-^{13}C}$ = 36.2 Hz, 6 × *o*-CH of Ph_3Sn), 137.1 (6 × *o*-CH of Ph_3Sn, $^2J_{^{119/117}Sn-^{13}C}$ = 36.2 Hz), 128.9 (3 × *p*-CH of Ph_3Sn, $^4J_{^{119/117}Sn-^{13}C}$ = 10.6 Hz), 128.8 (3 × *p*-CH of Ph_3Sn, $^4J_{^{119/117}Sn-^{13}C}$ = 10.6 Hz), 128.6 (6 × *m*-CH of Ph_3Sn, $^3J_{^{119/117}Sn-^{13}C}$ = 48.3 Hz), 128.5 (6 × *m*-CH of Ph_3Sn, $^2J_{^{119/117}Sn-^{13}C}$ = 48.3 Hz), 128.3 (2 × *o*-CH of Ph), 128.1 (2 × *m*-CH of Ph), 125.7 (*p*-CH of Ph), 65.7 (C1, $^2J_{^{119/117}Sn-^{13}C1}$ = 15.1 Hz), 43.5 (C2, $^2J_{^{117/119}Sn-^{13}C2}$ = 36.2 Hz), 38.0 (C5, $^3J_{^{117/119}Sn-^{13}C5}$ = 42.3 Hz, $^4J_{^{119/117}Sn-^{13}C5}$ = 9.1 Hz), 35.7 (C6, $^4J_{^{117/119}Sn-^{13}C6}$ = 9.0 Hz) ppm.

NMR assignment of the structure of the triphenylstannylallene 23

The triphenylstannylallene **23** had its structural identity supported by high field NMR analysis. Specifically, the triphenylstannylallene **23** gave rise to the highly characteristic signal[2c] for the central C(3)-quaternary carbon of an allene at δ 202.7 ppm in its 150.9 MHz ^{13}C NMR spectrum in $CDCl_3$. As was the case with **21**, where the C(2) carbon resonated at δ 96.4 ppm ($^1J_{^{119}Sn-^{13}C}$ = 304.8 Hz, $^1J_{^{117}Sn-^{13}C}$ = 291.2 Hz), in **23**, the other C(2)-quaternary carbon bearing the Ph_3Sn substituent appeared at δ 96.1 ppm, it again being considerably more deshielded than the C(4)-allenyl carbon bearing the H-atom, which resonated some 10 ppm further upfield at δ 86.7 ppm. In the HSQC spectrum of **23**, C(4) gave rise to the anticipated cross peak with the H(4)-allenyl proton multiplet at δ 4.99 ppm.

As regards the 600 MHz ^{1}H NMR spectrum of **23**, numerical integration of the aromatic region confirmed that there were 20 aromatic H-atoms in the structure, which clearly pointed to only four phenyl rings being present. Noticeably, the $-CH_2OH$ hydroxyl resonance appeared as a triplet (J = 6.0 Hz) at the highly shielded position of δ 1.46 ppm. According to Willem and Gielen[11] such a shift is highly indicative of such an OH being involved in a Sn–O coordinative interaction. However, hand-held molecular models of **23** suggested that such an O–Sn coordinative interaction could not be internal between the allylic $-CH_2OH$ and the allenyl $SnPh_3$ due this OH being far too removed from the Sn atom. It is much more likely therefore that **23** is self-associating, forming a symmetrical dimer, in which the OH of one molecule of **23** coordinates intermolecularly to the Sn atom of another **23** molecule. Possibly this better explains the highly shielded resonance position of this hydroxyl.

NMR assignment of the structure of (*Z*)-6-phenyl-2,3-bis(triphenyl-stannyl)hex-3-en-1-ol (24)



24

The (*Z*)-6-phenyl-2,3-bis(triphenylstannyl)hex-3-en-1-ol (**24**) had its structure determined by extensive 600 MHz multi-dimensional ^{1}H NMR spectroscopy in $CDCl_3$, and DEPT NMR analysis. The latter revealed the presence of a deshielded hydroxymethyl carbon [C(1)] at δ 65.7 ppm. Importantly, this signal showed a $^2J_{^{119/117}Sn-^{13}C(2)}$ coupling of 15.1 Hz with the adjacent $SnPh_3$ group at C(2). The fact that this ^2J was much lower in magnitude than most typical $^2J_{^{119/117}Sn-^{13}C}$ couplings (which are generally *ca.* 17–38 Hz)[31] was consistent with an electronegative OH group being stationed at C(1), and the C(1)–O bond being capable of taking up a near antiperiplanar orientation with the C(2)–Sn bond to maximise the O-atom's *J*-lowering effect.

As one might expect for a pair of allylic and benzylic carbons, the C(5) and C(6) $-CH_2-$ groups of **24** resonated at δ 38.0 (C5) and 35.7 (C6) ppm respectively, as verified by DEPT-135 spectroscopy. The latter showed the requisite negative peaks for these two carbons, which confirmed their methylenic ($-CH_2-$) identity. An expansion of this region further revealed that the less shielded C(6) benzylic-carbon at δ 35.7 ppm exhibited an averaged long-range $^4J_{^{119/117}Sn-^{13}C(6)}$ coupling of *ca.* 9.0 Hz with the Sn atom at C(3). Although this averaged $^4J_{^{119/117}Sn-^{13}C(6)}$ coupling was fairly small, its existence did nevertheless allow this carbon to be confidently assigned to C(6), and it confirmed that a Ph_3Sn group was resident at C(3). That same Sn-atom also showed a much larger averaged $^3J_{^{119/117}Sn-C(5)}$ coupling of 42.3 Hz with the allylic C(5)–carbon which resonated at δ 38.0 ppm, which further reinforced this assignment. The allylic C(5) itself appeared to be involved in a long-range ^4J coupling (9.1 Hz) with the $SnPh_3$ resident at C(2).

As for the allylic carbon at C(2), it was assigned on the basis of its downfield chemical shift at δ 43.5 ppm, and its $^2J_{^{119/117}Sn-C(3)}$ coupling of 36.2 Hz with the C(3)-$SnPh_3$ substituent. Taken together, these three Sn–C J couplings provided very strong evidence for two $SnPh_3$ groups being present on successive carbons at C(2) and C(3) within **24**. Unfortunately, the $^1J_{^{119/117}Sn-^{13}C}$ couplings associated with C(2) and C(3) were essentially invisible. Undoubtedly this is due to the wide spectral width of these couplings and the low signal intensities that so arise from the low natural abundance of the $^{119/117}$Sn isotopes.

With respect to the olefinic C(3) quaternary carbon of **24**, it resonated as a low intensity signal at δ 141.14 ppm in $CDCl_3$. Its strongly downfield position unambiguously confirmed it was an alkenic-type carbon, and the fact that it was a quaternary carbon was verified by the absence of this signal from the DEPT-135 spectrum of **24**. Importantly, C(3) also showed a long-range HMBC correlation with the H(2)-signal at δ 3.27 ppm. H(2) also showed strong HMBC correlations with C(4) at δ 145.3 ppm and C(1) at δ 65.7 ppm, which further confirmed their mutual proximity and skeletal connectivity.

Further proof that a vinyl triphenyltin was present within **24** came from the 600 MHz ^{1}H NMR spectrum of **24** in $CDCl_3$. Specifically, the olefinic signal for H(4) resonated as part of a highly complex multiplet centred at around δ 6.52 ppm, which quantitative NMR signal integration revealed contained 3H atoms in total, two of which were ultimately assignable to Ph protons. The chemical shift region around δ 6.5–6.6 ppm is

typically where (*Z*)-trisubstituted vinyl triphenyltin olefinic protons resonate, and so our knowledge of this fact enabled us to make this assignment with confidence.[3a] Saying this, however, the presence of the stannylvinylic H(4) within this highly complicated 3H multiplet could only be unambiguously confirmed from its associated vicinal $^{3}J_{^{1}H-^{119/117}Sn}$ coupling of *ca*. 166.8 Hz between H(4) and the Sn atom at C(3). Its magnitude very clearly indicated that these two atoms were antiperiplanar to one another and, on this basis, we have assigned (*Z*)-geometry to the C(3)–C(4)-alkene present within **24**.

The COSY spectrum of **24** subsequently pinpointed a strong vicinal coupling between H(4) and its two neighbouring allylic protons at H(5), which themselves resonated as part of a much more extensive and highly complex 4H-multiplet cluster positioned at around δ 2.28 ppm, which also contained the resonances for the two H(6) protons.

The quantitative signal integration to which we have just referred did ultimately reveal that 9 non-aromatic H-atoms were present alongside 35 aromatic H-atoms in **24**, and so this careful quantification of the proton count did ultimately lead to great confidence in the structure that was ultimately assigned to **24**.

Other findings that supported the assigned structure of **24** included the strong vicinal couplings of 6.6 and 6.0 Hz observed between H(2) and its diastereotopic H(1) neighbours which appeared as ddd signals at δ 4.03 and 3.87 ppm. Their multiplicities were attributable to couplings with the OH triplet (J = 5.4 Hz) at δ 1.58 ppm, the H(2) multiplet at δ 3.27 ppm, and each other. Those same ^{2}J and $^{3}J_{^{1}H-^{1}H}$ couplings were subsequently ratified by appropriate cross peaks in the COSY spectrum of **24** in $CDCl_3$. The very shielded resonance position for the OH triplet at δ 1.58 ppm was strongly suggestive of this C(1)-OH being involved in transient, but repeated, internal complexation events with the β-C(3)-Sn atom,[11] but this is the main evidence for such a proposal.

Extra evidence for the presence of two Ph_3Sn groups within the skeleton of **24** was provided by the 150.9 MHz ^{13}C NMR spectrum of **24** in $CDCl_3$, which contained 6 aryl carbon C–H signals at δ 137.4, 137.1, 128.9, 128.8, 128.6 and 128.5 ppm. There were also signals at δ 139.2 and 138.9 ppm for the quaternary carbons of those two Ph_3Sn groups. The fact that only eight signals were observed for these two substituents confirmed that the three Ph groups present within each Ph_3Sn subunit were magnetically equivalent and were each only producing four separate carbon signals.

To lend further support to our final structural assignment of **24**, only four other aromatic carbon signals could be detected in the ^{13}C NMR spectrum of **24**. These appeared at δ 141.11 (quaternary C of Ph), 128.3 (2 × *o*-CH of Ph), 128.1 (2 × *m*-CH of Ph), and 125.7 (*p*-CH of Ph) ppm, and their magnetic equivalency and visibility clearly corroborated an additional Ph group being present at C(6).

Accordingly, the (*Z*)-6-phenyl-2,3-bis(triphenylstannyl)hex-3-en-1-ol structure (**24**) was eventually assigned to this co-product that was being formed alongside **23** in the hydrostannation reaction of **5** with Ph_3SnH/cat. Et_3B.

Data availability

All data supporting this article are included in the Experimental details section of this paper and the ESI.‡

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We thank QUB, LJMU and Dr Joseph S. Vyle of QUB for generous gifts of chemicals. We also thank Mr Adam Brookfield for access to the EPSRC UK National EPR Facility and for technical support and chemical purchases under EPSRC grant EP/W014521/1.

References

1 H. A. Watson, K. L. E. Hale, J. M. Marron, S. Manaviazar, A. J. Fielding and K. J. Hale, *Org. Biomol. Chem.*, 2024, **23**, DOI: **10.1039/d4ob01846j**.
2 (*a*) P. Dimopoulos, J. George, D. A. Tocher, S. Manaviazar and K. J. Hale, *Org. Lett.*, 2005, **7**, 5377; (*b*) H. A. Watson, S. Manaviazar, H. G. Steeds and K. J. Hale, *Tetrahedron*, 2020, **76**, 131061; (*c*) H. A. Watson, S. Manaviazar, H. G. Steeds and K. J. Hale, *Chem. Commun.*, 2019, **55**, 14454.
3 (*a*) P. Dimopoulos, A. Athlan, S. Manaviazar, J. George, M. Walters, L. Lazarides, A. E. Aliev and K. J. Hale, *Org. Lett.*, 2005, **7**, 5369; (*b*) Review: K. J. Hale, S. Manaviazar and H. A. Watson, *Chem. Rec.*, 2019, **19**, 238.
4 (*a*) M. S. Oderinde, R. D. J. Froese and M. G. Organ, *Angew. Chem., Int. Ed.*, 2013, **52**, 11334; (*b*) M. S. Oderinde, R. D. J. Froese and M. G. Organ, *Chem. – Eur. J.*, 2014, **20**, 8579; (*c*) M. S. Oderinde and M. G. Organ, *Chem. – Eur. J.*, 2013, **19**, 2615; (*d*) M. S. Oderinde, H. N. Hunter, R. D. J. Froese and M. G. Organ, *Chem. – Eur. J.*, 2012, **18**, 10821.
5 S. E. Gottschling, T. N. Grant, K. K. Milnes, M. C. Jennings and K. M. Baines, *J. Org. Chem.*, 2005, **70**, 2686.
6 G. Velegraki and M. Stratakis, *J. Org. Chem.*, 2013, **78**, 8880.
7 A. B. Charette and A. Giroux, *J. Org. Chem.*, 1996, **61**, 8718.
8 M. Schmittel, A. A. Mahajan, G. Bucher and J. W. Bats, *J. Org. Chem.*, 2007, **72**, 2166.
9 (*a*) S. Ohira, *Synth. Commun.*, 1989, **19**, 561; (*b*) S. Muller, B. Liepold, G. J. Roth and H. J. Bestmann, *Synlett*, 1996, 521; (*c*) Review: M. Dhameja and J. Pandey, *Asian J. Org. Chem.*, 2018, **7**, 1502; (*d*) For a highly convenient method of synthesising Ohira–Bestmann reagent, see: J. Pietruszka and A. Witt, *Synthesis*, 2006, 4266. This is the protocol that was used to prepare the reagent we used here. It is an excel-

lent protocol that gives high quality Ohira–Bestmann reagent that can be stored successfully for 2 years, if kept in a −20 °C freezer under N_2.

10 K. J. Hale, Z. Xiong, L. Wang, S. Manaviazar and R. Mackle, *Org. Lett.*, 2015, **17**, 198.

11 For other O-directed Ph_3SnH hydrostannations: (*a*) R. Willem, A. Delmotte, I. De Borger, M. Biesemans, M. Gielen and F. Kayser, *J. Organomet. Chem.*, 1994, **480**, 255; (*b*) F. Kayser, M. Biesemans, A. Delmotte, I. Verbruggen, I. De Borger, M. Gielen and R. Willem, *Organometallics*, 1994, **13**, 4026; (*c*) K. Micoine, P. Persich, J. Llaveria, M.-H. Lam, A. Merderna, F. Loganzo and A. Furstner, *Chem. – Eur. J.*, 2013, **19**, 7370.

12 (*a*) K. Pati, G. dos Passos Gomes, T. Harris, A. Hughes, H. Phan, T. Banerjee, K. Hanson and I. V. Alabugin, *J. Am. Chem. Soc.*, 2015, **137**, 1165; (*b*) N. P. Tsvetkov, E. Gonzales-Rodriguez, A. Hughes, G. dos Passos Gomes, F. D. White, F. Kuriakose and I. V. Alabugin, *Angew. Chem., Int. Ed.*, 2018, **57**, 3651; (*c*) E. Gonzalez-Rodriguez, M. A. Abdo, G. dos Passos Gomes, S. Ayad, F. D. White, N. P. Tsvetkov, K. Hanson and I. V. Alabugin, *J. Am. Chem. Soc.*, 2020, **142**, 8352; (*d*) C. Hu, L. Kuhn, F. D. Makurvet, E. S. Knorr, X. Lin, R. K. Kawade, F. Mentink-Vigier, K. Hamson and I. V. Alabugin, *J. Am. Chem. Soc.*, 2024, **146**, 4187; (*e*) For a related RO→ Sn interaction facilitating an unusual alkoxy radical elimination, as opposed to a stannyl radical addition to an alkyne or a β-stannyl radical elimination, see: T. Harris, G. dos Passos Gomes, R. J. Clark and I. V. Alabugin, *J. Org. Chem.*, 2016, **81**, 6007.

13 For an extensive review on molecules that contain two Sn atoms, see: W. J. Kerr and P. L. Pauson, Chapter 4.15 Functions Containing Two Atoms of the Same Metallic Element, in *Comprehensive Organic Functional Group Transformations*, 1995, vol. 4, p. 667.

14 (*a*) I. V. Alabugin, *Stereoelectronic Effects*, John Wiley & Sons Ltd, 2016, ch. 3, 5 and 9; (*b*) I. V. Alabugin, G. dos Passos Gomes and M. A. Abdo, *Wiley Interdiscip. Rev.: Comput. Mol. Sci.*, 2019, **9**, e1389; (*c*) I. V. Alabugin, K. M. Gilmore and P. W. Peterson, *Wiley Interdiscip. Rev.: Comput. Mol. Sci.*, 2011, **1**, 109; (*d*) C. Hu, J. Mena and I. V. Alabugin, *Nat. Rev. Chem.*, 2023, **7**, 405.

15 For our own groundbreaking EPR spectroscopy work on the observation of β-triphenylstannylvinyl radicals that were generated in PhMe and THF *via* the O-directed free radical hydrostannation of dialkyl acetylenic alcohols with Ph_3SnH/cat. Et_3B and O_2, see: H. A. Watson, A. J. Fielding and K. J. Hale, *Chem. Commun.*, 2021, **57**, 7449.

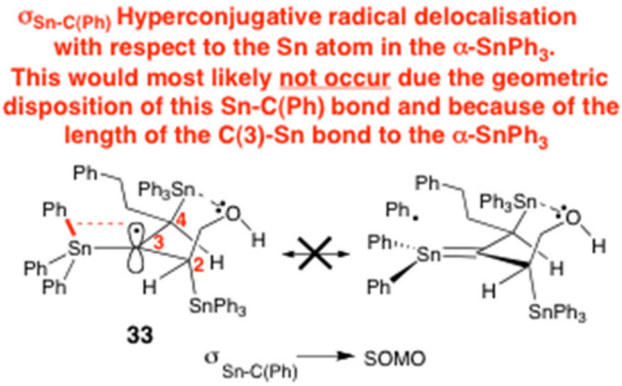
16 EasySpin: (*a*) S. Stoll and A. Schweiger, *J. Magn. Reson.*, 2006, **178**, 42; (*b*) S. Stoll and R. D. Britt, *Phys. Chem. Chem. Phys.*, 2009, **11**, 6614.

17 (*a*) A. G. Davies, B. P. Roberts and M.-W. Tse, *J. Chem. Soc., Perkin Trans. 2*, 1978, 145; (*b*) T. Kawamura and J. K. Kochi, *J. Am. Chem. Soc.*, 1972, **94**, 648; (*c*) P. J. Krusic and J. K. Kochi, *J. Am. Chem. Soc.*, 1971, **93**, 846.

18 C. Heller and H. M. McConnell, *J. Chem. Phys.*, 1960, **32**, 1535.

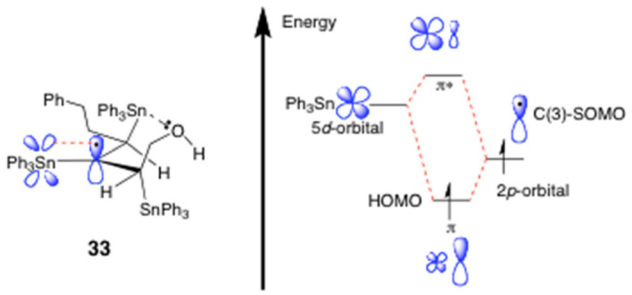
19 For a related α-*stabilising* delocalisative hyperconjugative interaction between the radical SOMO of a $(t\text{-}Bu_2MeSi)_3Sn^{\bullet}$ radical and its proximal antibonding σ*(Si-$C_{t\text{-}Bu}$) orbitals, see: (*a*) A. Sekiguchi, T. Fukawa, V. Ya Lee and M. Nakamoto, *J. Am. Chem. Soc.*, 2003, **125**, 9250 For similar stabilising interactions in other $(t\text{-}Bu_2MeSi)_2M^{\bullet}$ radicals, see also: (*b*) S. Inoue, M. Ichinohe and A. Sekiguchi, *Organometallics*, 2008, **27**, 1358; (for M = Si) (*c*) A. Sekiguchi, T. Fukawa, M. Nakamoto, V. Ya Lee and M. Ichinohe, *J. Am. Chem. Soc.*, 2002, **124**, 9865 (for M = Si and Ge) (*d*) For a very informative review on such group 14 "heavy" atom stabilised radicals and their bonding interactions, see: V. Ya Lee and A. Sekiguchi, *Acc. Chem. Res.*, 2007, **40**, 410.

20 (*a*) A most helpful reviewer of our current paper has very kindly informed us that the long C(3)-$SnPh_3$ bond length of **33** (*ca.* 2.14 Å) would almost certainly geometrically preclude the Sn–$C_{(Ph)}$ σ bond of **33** from ever being able to delocalisatively stabilise the C(3) radical in **33** *via* a hyperconjugative mechanism:



Rather, this reviewer suggests that the main stabilising influence of the α-Ph_3Sn group would emanate from its ability to engage in significant geminal hyperconjugative delocalisation of the radical into the σ* Sn–$C_{(Ph)}$ antibonding orbitals of the Ph_3Sn group (*i.e. via* SOMO → σ*$_{Sn-C(Ph)}$ interactions) (see: Fig. 3 of our main manuscript). We are most grateful to this learned reviewer for their highly valuable intellectual input and insights here in rationalising the high stability of radical **33** (*b*) Whilst on the topic of the radical stabilisation of **33**, it is perhaps pertinent to point out that the teams of Kochi (ref. 17*b*) and Mackey (see ref. 19*b*: J. H. Mackey and D. E. Wood, *Mol. Phys.*, 1970, **18**, 783) have both suggested that 2p→ 5d radical delocalisation is a significant factor in helping to electronically-stabilise α-stannyl methyl radicals, on the basis of EPR g-factor and metal d-orbital odd-electron spin density measurements, as well as CNDO calculations. However, we would point out that the existence of p_{π}→ d_{π^*} stabilisation in organotin compounds is still a subject of great controversy, and has been so for quite some time. See: (*c*) R. C. Poller, in *The Chemistry of Organotin Compounds*, Logos Press Limited, 1970, ch. 1, p. 5. Readers should

therefore bear this in mind when assessing the likely possible contribution of pπ → dπ bonding to the stability of **33**. In this aspect, this same reviewer of our article, who commented on the long C(3)-SnPh$_3$ bond length of **33** (*ca.* 2.14 Å) precluding Sn–C$_{(Ph)}$ σ bond hyperconjugative stabilisation of the radical in **33** is very much of the opinion that the Kochi and Mackey 2p → 5d radical stabilisation hypothesis would be equally unfeasible for similar reasons, due to the poor degree of orbital overlap that would result. We concur fully with the opinion of this learned reviewer. Nevertheless, we show below how such a $p_\pi \rightarrow d_\pi$ homoconjugative α-effect could potentially stabilise the radical in **33**, if such stabilisation was operational:



.

21 R. Wei, X.-F. Wang, C. Hu and L. L. Liu, *Chem. Commun.*, 2024, **60**, 9793.

22 Our observation of the radical adduct **33** takes on even greater significance if one considers that Mitchell and Lehnig and their two teams had never previously been able to observe such 1,2-bis-trimethyltin tertiary radical adducts of general structure Me$_3$SnCH$_2$C$^\bullet$(R)SnMe$_3$ by EPR spectroscopy, when this type of radical was generated by UV mediated Me$_3$Sn$^\bullet$ radical addition to the corresponding vinyltins. Presumably this is due to the normally very fast rate of β-scission of such radical adducts, once they are formed. See: (*a*) T. N. Mitchell, W. Reimann and C. Nettelbeck, *Organometallics*, 1985, **4**, 1044; (*b*) Until now, we too have been unable to observe a 1,2-bis-triphenyltin adduct forming from a trisubstituted vinyl triphenyltin by EPR spectroscopy until the vinyl triphenyltin **24** was exposed to proximally O-coordinated Ph$_3$Sn radicals (see ref. 15 for our past EPR studies) (*c*) For similar negative EPR results with regard to the observation of β-trialkylstannylvinyl radicals and their adducts, see the important paper of: K. Suzuki, N. Sugihara, Y. Nishimoto and M. Yasuda, *Angew. Chem., Int. Ed.*, 2022, **61**, e202201883.

23 (*a*) C. Nativi and M. Taddei, *J. Org. Chem.*, 1988, **58**, 820; (*b*) D. P. Curran and T. McFadden, *J. Am. Chem. Soc.*, 2016, **138**, 7741.

24 M. Taniguchi, K. Nozaki, K. Miura, K. Oshima and K. Utimoto, *Bull. Chem. Soc. Jpn.*, 1992, **65**, 349.

25 (*a*) For a recent excellent review on alkyne hydrometallation reactions with group IV metal hydrides, see the following book chapter by: T. Wiesner and M. Haas, *Reference Module in Chemistry, Molecular Sciences and Chemical Engineering*, Elsevier, 2024, DOI: 10.1016/B978-0-323-96025-0.00125-3(*b*) For McLaughlan and Roberts' recent highly regiocontrolled PtCl$_2$/XPhos-catalysed hydrostannation of terminal aryl acetylenes and propargylic alcohols, see: D. D. Roberts and M. G. McLaughlin, *Adv. Synth. Catal.*, 2023, **365**, 1602; (*c*) For McLaughlin's recent deployment of the PtCl$_2$/XPhos/Et$_3$SiH-catalyst system in the regioselective hydroboration of terminal alkyl, aryl and heteroaryl acetylenes with HBPin, see: K. L. E. Hale, D. D. Roberts and M. G. McLaughlin, *Eur. J. Org. Chem.*, 2025, e202401355.

26 (*a*) (+)-Pumiliotoxin B formal total synthesis: S. Manaviazar, K. J. Hale and A. LeFranc, *Tetrahedron Lett.*, 2011, **52**, 2080; (*b*) (−)-(3*R*)-Inthomycin C total synthesis: K. J. Hale, M. Grabski, S. Manaviazar and M. Maczka, *Org. Lett.*, 2014, **16**, 1164; (*c*) (−)-(3*R*)-Inthomycin revision of absolute stereochemistry: K. J. Hale, S. Hatakeyama, F. Urabe, J. Ishihara, S. Manaviazar, M. Grabski and M. Maczka, *Org. Lett.*, 2014, **16**, 3536; (*d*) Synthesis of the C(7)–C(22)-sector of (+)-acutiphycin by two-directional double O-directed free radical hydrostannation of a diyne, see: K. J. Hale, M. Maczka, A. Kaur, S. Manaviazar, M. Ostovar and M. Grabski, *Org. Lett.*, 2014, **16**, 1168; (*e*) For Furstner's elegant asymmetric total synthesis of (+)-isomigrastatin via an O-directed dialkylacetylene free radical hydrostannation with Ph$_3$SnH/cat. AIBN, see ref. 11*c*.

27 J. A. Marshall and S. Xie, *J. Org. Chem.*, 1995, **60**, 723.

28 For our recent asymmetric total synthesis of the HDAC-inhibitory (+)-trichostatins A and C *via* the O-directed free radical hydrostannation of an alkyne derived from Marshall chiral allenylzinc addition to an aldehyde, see the paper that follows this, in this issue of OBC. See: K. Pan, S. Manaviazar and K. J. Hale, *Org. Biomol. Chem.*, 2025, **23**, DOI: 10.1039/d4ob01848f.

29 N. K. Anand and E. M. Carreira, *J. Am. Chem. Soc.*, 2001, **123**, 9687.

30 (*a*) R. Sommer and H. Kuivila, *J. Org. Chem.*, 1968, **33**, 802. It was in this paper that Sommer and Kuivila first postulated that fast reversible addition of tin radicals to acyclic alkenes could cause (*Z*)/(*E*) isomerisation (*b*) Dr Soraya Manaviazar of this laboratory has likewise successfully hydrostannated 2-methylene-propane-1,3-diol analogously to Wuest *et al.*,[30c] except in solution at room temperature, using our Ph$_3$SnH/cat. Et$_3$B/O$_2$ method in PhMe : THF (9 : 1) over 24 h; she obtained the product **48** in 49% yield after SiO$_2$ flash chromatography. This result was first published in Scheme 87, of ref. 3*c*, on page 310. Naturally, the latter outcome further confirms that such Ph$_3$Sn$^\bullet$ radical additions can readily take place upon alkenes in solution at rt and, under our O-directed hydrostannation conditions. In this specific instance, the application of our method even allowed a successful trapping of the tertiary radical adduct. For the earlier Wuest work, see: (*c*) Y. Ducharme, S. Latour and J. D. Wuest, *Organometallics*, 1984, **3**, 208. Note how his procedure used neat Ph$_3$SnH and cat. AIBN to thermally hydrostannylate 2-methylene-propane-1,3-diol at 64 °C, over 5 h, in 74% yield (*d*) R. H. Fish, *J. Organomet. Chem.*, 1972, **42**, 345.

31 (*a*) A. G. Davies, *Organotin Chemistry*, Wiley-VCH, 2nd edn, 2004, ch. 2 ; (*b*) T. N. Mitchell and B. Kowall, *Mag. Reson. Chem.*, 1995, **33**, 325.
32 M. Lehnig, H.-U. Buschhaus, W. P. Neumann and T. H. Apoussidis, *Bull. Soc. Chim. Belg.*, 1980, **89**, 90 (refer to material that can be found in the ESI‡).
33 T. Berclaz and M. Geoffroy, *Chem. Phys. Lett.*, 1977, **52**, 606 (refer to material that can be found in the ESI‡).
34 M. Lehnig and K. Dören, *J. Organomet. Chem.*, 1981, **210**, 331 (refer to material that can be found in the ESI‡).
35 P. J. Krusic and J. K. Kochi, *J. Am. Chem. Soc.*, 1968, **90**, 7155 (refer to material that can be found in the ESI‡).
36 M. Castaing, M. Pereyre, M. Ratier, P. M. Blum and A. G. Davies, *J. Chem. Soc., Perkin Trans. 2*, 1979, 589 (refer to material that can be found in the ESI‡).