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Chromene-Annulated Bacteriochlorins

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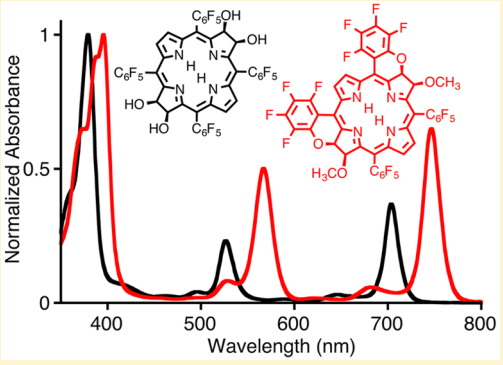
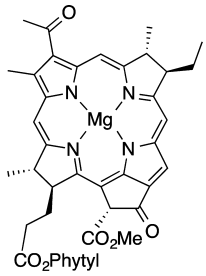
Supporting Information

ABSTRACT: Syntheses and optical properties of mono- and bis-chromene-annulated bacteriochlorins are described. Known monochromene-annulated *meso*-(pentafluorophenyl)chlorin is susceptible to a regioselective OsO_4-mediated dihydroxylation, generating two monochromene-annulated trihydroxybacteriochlorin stereoisomers: either the newly introduced *vic-cis*-diol functionality is on the same side as the *vic-cis*-diol moiety the chromene-annulation was based on or on the opposite side. Treatment of the two isomers with heat or base generates different sets of bis-chromene-annulated bacteriochlorin stereo- and regioisomers. Detailed 1D and 2D ^{1}H and ^{19}F NMR spectroscopic investigations allowed the characterization of the isomers that formed. The regioselectivity of the second annulation reaction was rationalized computationally on steric grounds. The bacteriochlorin-type optical spectra of the mono- and bis-chromene-annulated bacteriochlorins are modulated as a result of the annulation, with each isomer possessing a unique spectrum, attributed to the effects the regiochemically distinct annulations have on the conformation of the chromophore. The formation of a bis-chromene-annulated chlorin from the bacteriochlorins is also described, including its X-ray crystal structure, revealing some details of the metrics of the chromene-annulated moiety. The *vic*-diol functionality of monochromene-annulated trihydroxybacteriochlorins is also susceptible to oxidation and ring-expansion reactions, generating chromene-annulated pyrrole-modified chlorins incorporating oxazolone and morpholine moieties. The work expands the body of work on the synthesis and optical fine-tuning of *meso*-aryl-substituted bacteriochlorins.



INTRODUCTION

Hydroporphyrins are the key light-harvesting pigments in nature.[1] Algae and higher plants utilize the green Mg(II) complexes of 2,3-dihydroporphyrins (chlorins), the chlorophylls (with a longest wavelength absorbance band, λ_{max}, below 700 nm). The photosynthetic pigments of the anoxygenic photosynthetic bacteria are Mg(II) complexes of 2,3,12,13-tetrahydroporphyrins (bacteriochlorins), such as BChl *a*, **1**, lending these bacteria their characteristic purple color.[2] Bacteriochlorins possess characteristic three-band UV−vis absorption spectra with a high-intensity λ_{max} band well above 700 nm.



Bacteriochlorophyll *a*, **1**
(BChl *a*)

NIR light of 735 nm wavelength possesses the deepest penetration depth in tissue.[3] Since bacteriochlorins possess a strong absorbance within the spectroscopic window of tissue, significant efforts were devoted to the synthesis of bacteriochlorins.[4] They were investigated as photochemotherapeutics, imaging agents, or optical labels.[5] Because of their NIR absorbance properties, their use in light-harvesting systems is appealing.[6] They have also been utilized in chemosensing systems.[7]

Synthetic bacteriochlorins can be prepared in semisynthetic approaches using naturally occurring tetrapyrroles, they can be made by total syntheses, and they can be accessed by conversion of synthetic porphyrins.[4] Semisynthetic approaches are well-established,[5a,e,8] but access to chemically more stable bacteriochlorins, the desire for better synthetic handles to fine-tune the chromophore, or production of regio- and stereochemically well-defined molecules requires fully synthetic approaches. Work by Lindsey and co-workers has recently shifted the paradigm that bacteriochlorin total syntheses are only of academic value. Their methodologies are characterized by relative simplicity, scaleability, and multiple options for

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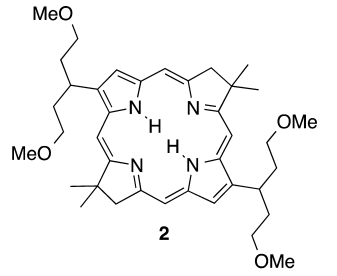
postchromophore synthesis modifications.[9] Owing to the presence of *gem*-dimethyl groups, exemplified by swallowtail bacteriochlorin **2**,[10] these chromophores are stable toward oxidation to chlorins or porphyrins, and they have shown their efficacy as photosensizers and light-harvesting pigments.[5f,6a,c,9−11]



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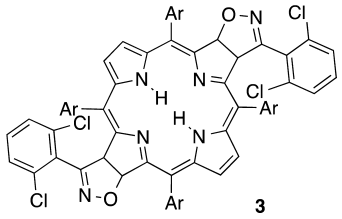

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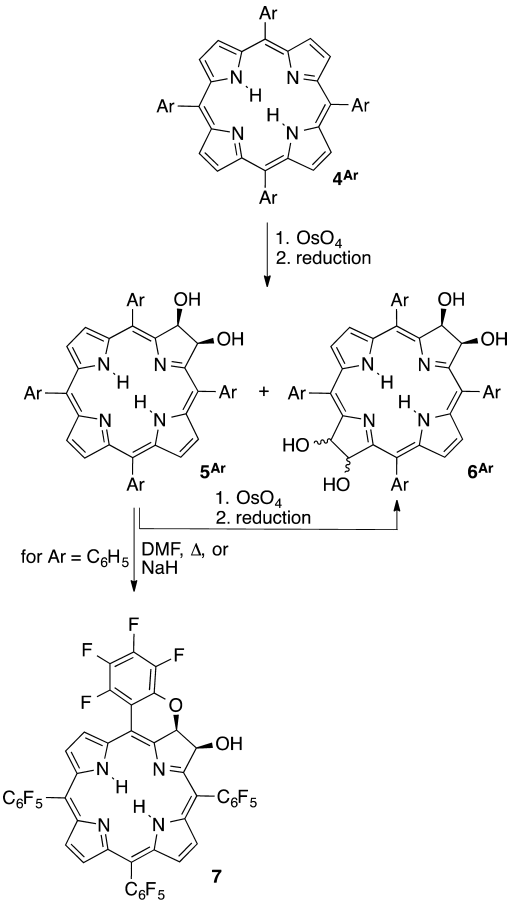
Irrespective of the progress in the total synthesis approach, the conversions of readily available porphyrins, particularly *meso*-tetraarylporphyrins,[12] still remains an attractive option to prepare bacteriochlorins in a few synthetic steps.[4] Bacteriochlorin **3** is representative for such a bacteriochlorin, made by double-1,3-dipolar cycloaddition of a nitrile oxide to a *meso*-tetraarylporphyrin.[13] Depending on the *meso*-aryl groups, even simple diimide reductions generate stable bacteriochlorins.[14] Once the hydroporphyrin chromophore was established, however, the options to modulate the chromophore in subsequent reactions were rarely explored.[15]

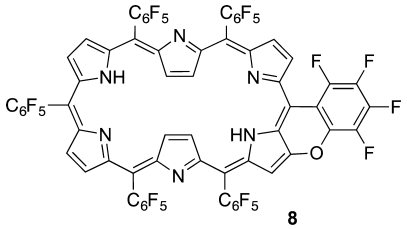
We,[16] and others,[17] described the OsO_4-mediated dihydroxylation of *meso*-arylporphyrins, such as $\mathbf{4^{Ar}}$, to generate the corresponding 2,3-*vic*-dihydroxychlorins $\mathbf{5^{Ar}}$ and 2,3-*vic*-12,13-*vic*-tetrahydroxybacteriochlorins $\mathbf{6^{Ar}}$ (Scheme 1). The regioselectivity of the second dihydroxylation reaction was rationalized.[18] We further presented functional group conversions of one or two dihydroxypyrroline moieties to, e.g., oxazole, imidazolone, or morpholine moieties, thus generating chlorin and bacteriochlorin analogues with a range of different functionalities and optical properties.[19]

We also reported a way to tune the optical properties of *meso*-tetrakis(pentafluorophenyl)-2,3-dihydroxychlorins of type $\mathbf{5^{Ar}}$ (with Ar = C_6F_5) by modest increments using a simple reaction step:[20] Upon treatment of these dihydroxychlorins with base (NaH) and/or heat in DMF, an intramolecular S_NAr reaction took place between one or two of the hydroxy groups and the *o*-F of the flanking *meso*-C_6F_5 groups, forming chromene-annulated chlorin **7** (Scheme 1) and a bis-annulated chlorin, respectively. The S_NAr reaction of *meso*-C_6F_5-substituted porphyrinoids using sulfur-, nitrogen-, or oxygen-based nucleophiles is well-known, though it generally involves intermolecular substitutions of the *p*-F atoms,[21] or, in rare cases, more than one F atom.[22] The intramolecular substitution of an *o*-F was also observed in a hexaphyrin, forming pyrrole-*N*-aryl linkages,[23] or in derivatives such as **8**.[24] Most recently, chromene- and benzodiazepine-annulated chlorin **9** was

Scheme 1. Known Syntheses of Chlorindiols $\mathbf{5^{Ar}}$ and Bacteriochlorintetraols $\mathbf{6^{Ar}}$ by OsO_4-Mediated Dihydroxylation of a *meso*-Tetraarylporphyrin[16] and Generation of Chromene-Annulated Chlorin 7[20]



prepared by stepwise manipulation of *meso*-tetrakis(pentafluorophenyl)porphyrin $\mathbf{4^{Ar}}$ (with Ar = C_6F_5).[15]



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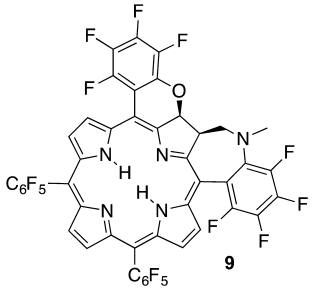

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Chromene-annulated chlorins of type **7**, like other chromophores containing *β*- to *o*-phenyl linkages,[25] are characterized by red-shifted optical spectra when compared to the spectra of the nonannulated starting material (for **7**, a shift of 16 nm was noted; for the bis-annulated chlorin a shift of 24

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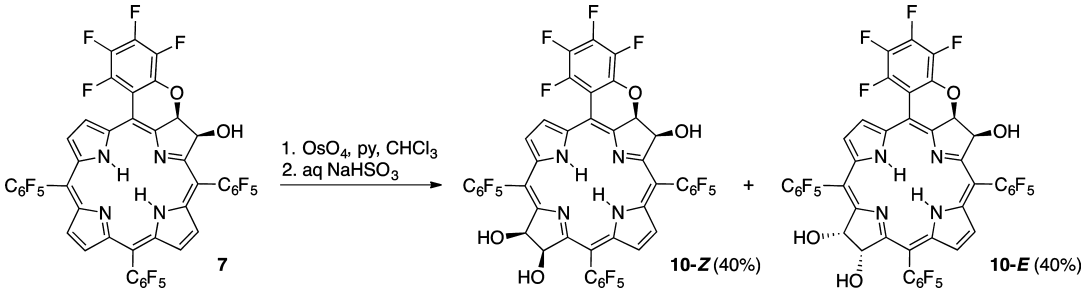
Scheme 2. Synthesis of Monochromene-Annulated Trihydroxybacteriochlorins



nm).[20] The bathochromic optical spectra were rationalized by the modulation of the chromophore conformation, induced by the annulation reaction.[26] Moreover, the annulation forces the *meso*-phenyl group into greater coplanarity with the porphyrinic chromophore, increasing π-overlap between the two aromatic moieties.

The annulation reactions in the chlorin series prompt several questions: Can the chromene-annulated chlorins be dihydroxylated, forming chromene-annulated bacteriochlorins? And once formed, can these be converted to, for example, bis-chromene-annulated bacteriochlorins? Which of the many possible isomeric bis-annulated bacteriochlorins will form? Will their UV−vis spectra also be red-shifted? This report investigates these questions experimentally, whereby several conclusions were backed by computations. We thus contribute additional members of *meso*-aryl-substituted bacteriochlorins with tunable spectra to the small class of stable, fully synthetic bacteriochlorins.

RESULTS AND DISCUSSION

Dihydroxylation of Chromene-Annulated Chlorin 7. The OsO_4-mediated dihydroxylation of tetraarylporphyrin (Scheme 1) is a two-step process:[16] First, the dihydroxychlorin osmate ester forms, followed by the reduction of the osmate ester to the diol. In the case of *meso*-C_6F_5-porphyrins, the reduction step requires a sodium bisulfite reduction step in place of the traditional hydrogen sulfide-treatment to avoid side reactions attributed to S_NAr reactions of the sulfur with the *p*-F atoms.[20] This osmylation and reduction reaction sequence applied to chromene-annulated chlorin **7** generated two compounds in a 1:1 ratio, **10-*Z*** and **10-*E***, in excellent combined yields (Scheme 2).

Both products possess identical compositions ($C_{44}H_{14}F_{19}N_4O_4$ for MH^+, as per HR-MS), consistent with the uptake of two hydroxyl groups. Their identical bacteriochlorin-like optical spectra are indicative for the expected regioselectivity of the dihydroxylation at the pyrrole opposite the chromene-linked pyrroline (see below for a detailed discussion of the UV−vis and fluorescence spectra of all compounds described).[18] The appearance of two isomeric products suggests, analogous to the tetrahydroxybacteriochlorin case,[16] the formation of two isomers: one in which the hydroxy group and the adjacent *vic*-oxygen of the annulated chromene are located on the same side of the porphyrin plane, forming isomer **10-*Z***, and one in which they are located on opposite sides, forming **10-*E*** (Figure 1).[27] Parallel to the tetrahydroxybacteriochlorin $\mathbf{6}^{Ar}$,[16] we assign the higher polarity isomer (R_f = 0.16, silica−CH_2Cl_2/1% MeOH) the **10-*Z*** configuration and the lower polarity isomer (R_f = 0.26) the **10-*E*** configuration. While the relative stereochemistry of the bacteriochlorins $\mathbf{6}^{Ar}$ was corroborated by single-crystal X-ray structures,[16] we could not obtain suitable crystals for any isomer of **10-*Z*/*E***. However, additional chemical evidence presented here provides an independent validation of our projections.

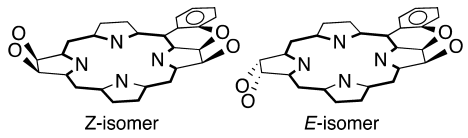


Figure 1. Nomenclature convention for the two possible stereoisomers of bis-*vic*-diol-derived bacteriochlorins.[16]

The ^1H and ^{19}F NMR spectra for the trihydroxybacteriochlorins **10-*Z*/*E*** are similar to each other and diagnostic for their connectivity, albeit not for their relative stereochemistry. Two deshielded signals per compound assigned to the inner NH protons (below −0.5 ppm) and four signals assigned to pyrrolic β-protons (in the range between 8.8 and 8.1 ppm), four pyrroline protons (in the range between 6.3 and 5.9 ppm), and three hydroxy protons (between 3.4 and 2.5 ppm, exchangeable with D_2O) complete the ^1H NMR spectra and indicate the presence of a nonsymmetric bacteriochlorin chromophore.[16] As expected, 19 fluorine atoms can be made out in their ^{19}F NMR spectra, including the multiplets in their $^1H-^{19}F$ HOESY NMR spectra that correspond to the H−F couplings of the β-H and the *o*-F atom of the neighboring annulated tetrafluorophenyl ring and that are diagnostic for the presence of the tetrafluorochromene-annulation motif.[20] Most H and F signals in their exquisitely resolved NMR spectra can be assigned (see the Supporting Information).

Synthesis of Bis-chromene-Annulated Bacteriochlorins. Heating a solution of free base bacteriochlorin triol **10-*Z*** in DMF, or using a strong base, converted the pinkish-red starting material into two light purple, more polar products, $\mathbf{11}^{H}$**-*Z*-*syn*** **and** $\mathbf{11}^{H}$**-*Z*-*anti*** (Scheme 3). These products possessed similar and typical bacteriochlorin spectra that were slightly bathochromically shifted from their starting material (for details, see below), clearly demonstrating that the bacteriochlorin chromophore was maintained in the transformation. The identical composition of both products ($C_{44}H_{13}F_{18}N_4O_4$ for MH^+, as determined by ESI+ HR-MS) indicated that they were isomers of a compound derived from the starting material by loss of HF, suggesting that a second β- to *o*-phenyl linkage had been formed, establishing a second annulated chromene moiety.[20] NMR data presented later further confirm this. Treatment of tetrahydroxybacteriochlorin **6-Z** with heat in DMF also produced the two isomeric compounds $\mathbf{11}^{H}$**-Z** in essentially identical ratios and yields as observed for the conversion of monochromene-fused bacteriochlorin **10-*Z***.

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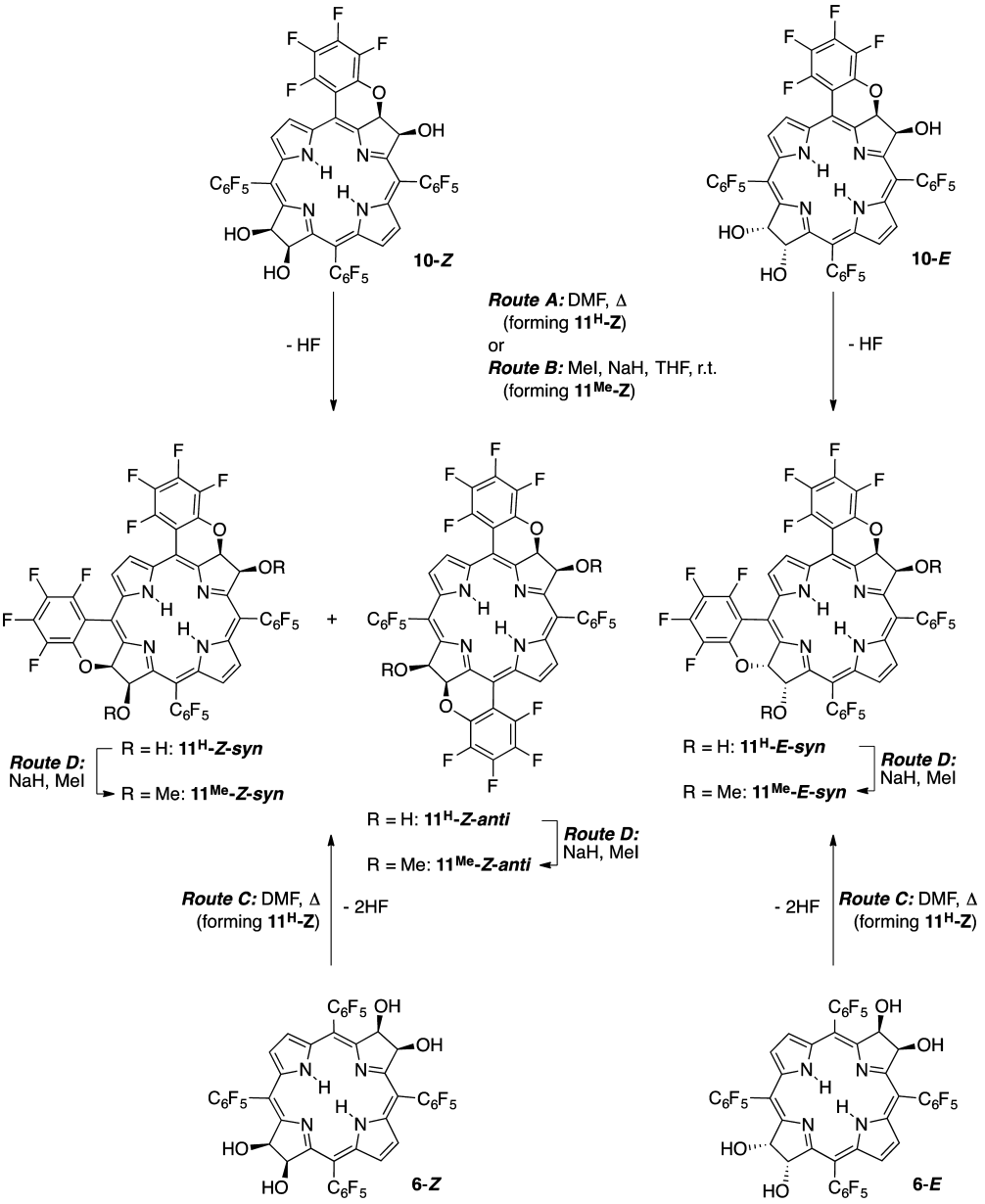
Scheme 3. Synthesis of Bis-chromene-Annulated Bacteriochlorins



Analogous to the preparation of the alkylated chromene-annulated chlorins,[16] the two isomeric bismethyl ethers **11^{Me}-*Z*** can be formed by reaction of bacteriochlorin triol **10-*Z*** with NaH/MeI (Scheme 3). An alkylation of the alcohols **11^{H}-*Z*** also generated the corresponding bismethyl ethers **11^{Me}-*Z***. The value of the formation of the bismethyl ethers lies in the chemical proof for the presence of two alcohol functionalities. Hopes that this moiety would also improve our chances of growing crystals suitable for X-ray crystallographic investigations of the compounds were largely disappointed (for the only example of a crystallographically characterized chromene-annulated hydroporphyrin, see below).

There are a total of three options for **10-*Z*** (or **10-*E***) to form a second annulated chromene moiety (Figure 2): The second chromene can be formed on the same pyrroline adjacent the first chromene, forming the *adj*-isomer, or on the opposite pyrroline. The latter can take place in two ways: Either the second linkage is established diagonally across the ring from the first linkage, forming the *anti*-isomer, or on the same side of the macrocycle, forming the *syn*-isomer. Since all possibilities can

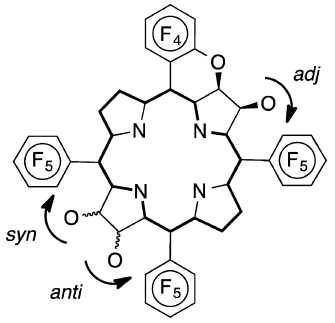


Figure 2. Nomenclature convention for the three possible regioisomers of a monochromene-annulated bacteriochlorin triol when forming a second chromene-annulated moiety, each possible for the triol *E*- and *Z*-isomers.

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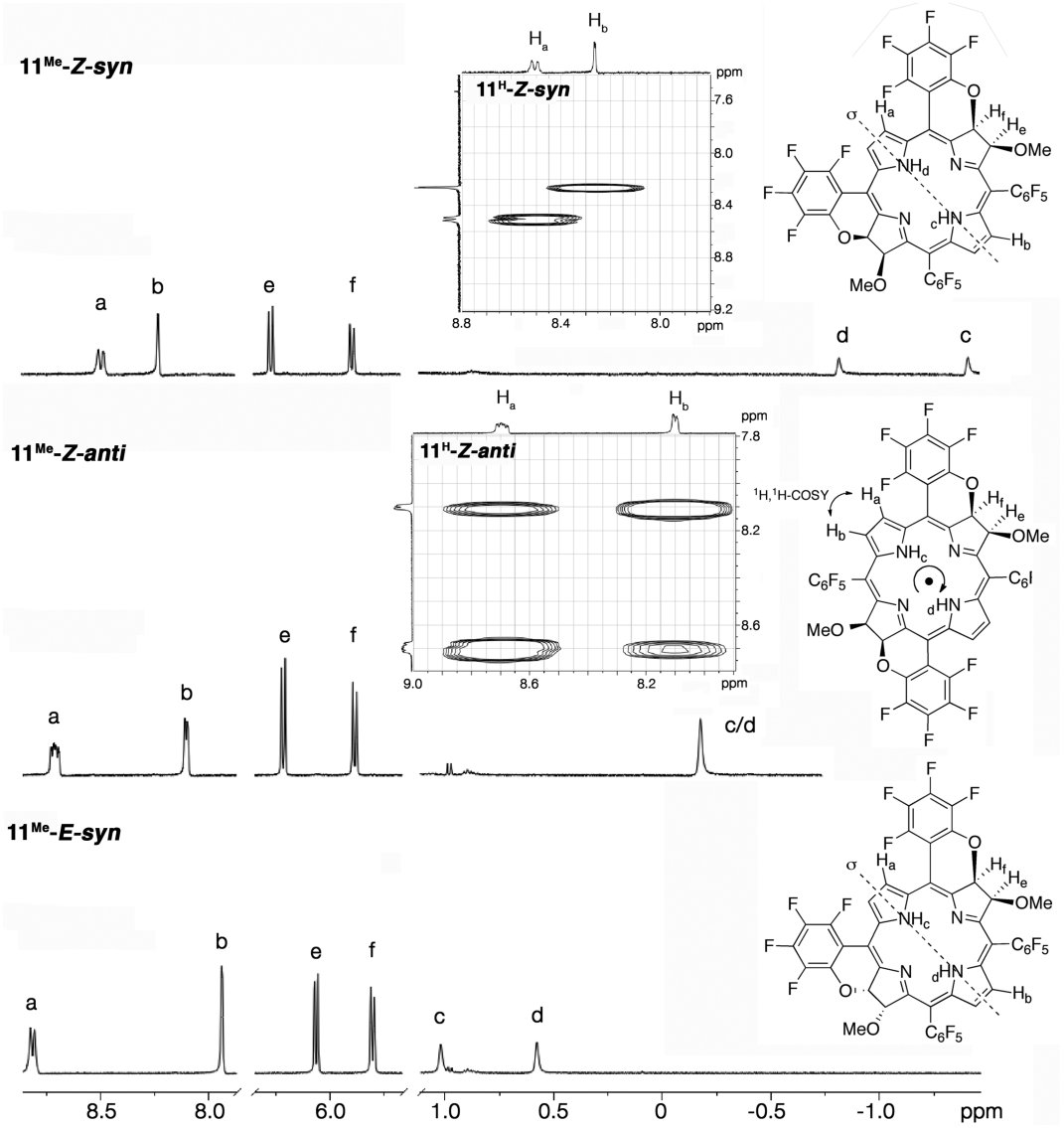

Figure 3. Select regions of the ^{1}H NMR spectra (400 MHz, $CDCl_3$) of the regio- and stereoisomeric bis-chromene-annulated bacteriochlorins **11^{Me}-*Z-syn*, 11^{Me}-*Z-anti*, and 11^{Me}-*E-syn***. Insets: Pyrrole *β*-H regions of the ^{1}H,^{1}H COSY NMR spectra (400 MHz, $CDCl_3$) of the bis-chromene-annulated bacteriochlorins **11^{H}-*Z-syn*** and **11^{H}-*Z-anti***. For the full spectra, see the Supporting Information.

theoretically take place starting with both the *Z* and the *E* isomers of the starting triols, this gives rise to the *E-syn*, *Z-anti*, or *Z-adj* isomers, etc. Therefore, the formation of the two bis-linked isomers of diol **11^{H}-*Z*** represents two out of the three possible isomers, **11^{H}-*Z-syn***, **11^{H}-*Z-anti***, or **11^{H}-*Z-adj***.

Interestingly, the *E*-isomer of trihydroxybacteriochlorin **10-*E***, when subjected to the same high temperature or strongly Brønstedt basic reaction conditions as **10-*Z***, with or without MeI present, forms only a single compound, light purple diol **11^{H}-*E***, or its dimethyl ether **11^{Me}-*E***, respectively (Scheme 3). Its composition ($C_{44}H_{13}F_{18}N_4O_4$ for MH^+, as per ESI+ HR-MS) and bacteriochlorin-like spectrum again suggest the formation of a bis-chromene-annulated bacteriochlorin. As shown by a TLC-scale experiment, treatment of tetrahydroxy-bacteriochlorin **6-*E*** with heat in DMF also produced solely **11^{H}-*E***. The computations described below provide some indications of the origin of this regioselectivity.

NMR Spectroscopic Characterization of the Isomeric Bis-chromene-Annulated-Bacteriochlorins 11-*Z*/*E*. Crystals suitable for X-ray diffraction analyses could not be grown for any of the bacteriochlorin isomers **11-*Z*/*E***. This necessitated a purely NMR-spectroscopic characterization of the connectivity of these six isomers (three connectivities, each in their alcohol and methyl ether forms). The diagnostic ^{1}H NMR spectra of the three isomers of **11^{Me}** are shown in Figure 3.

In all isomers, the annulation increases the symmetry of the molecules—all possess 2-fold rotational or axial symmetry—when compared to the nonsymmetric starting material. All signals fall into distinct regions, assigned to the pyrrole-*β*, pyrroline-*β*, and inner NH protons. The OCH_3 groups in all possible isomers are equivalent (a single s around 3.4 ppm (6H)) and therefore not diagnostic for a differentiation of the isomers. In all three isomers, the hallmark signs of the annulated tetrafluorochromene moiety are visible. Inter alia, the low-field pyrrole *β*-Hs are subject to a 9 Hz ^{6}J coupling with the *o*-F of the adjacent chromene moiety (verified by ^{1}H−^{19}F HOESY NMR spectroscopy; see the Supporting Information). The pyrroline protons appear as two d (2H each). This excludes the presence of the *adj*-isomer that would have been

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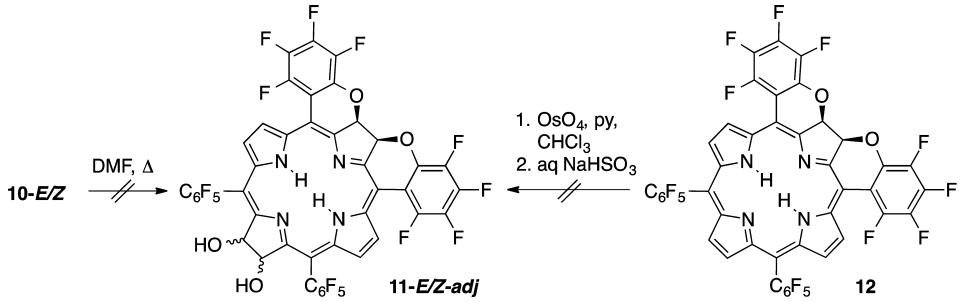
Scheme 4. Unsuccessful Formation of Bis-chromene-Annulated Bacteriochlorin *adj*-Isomer



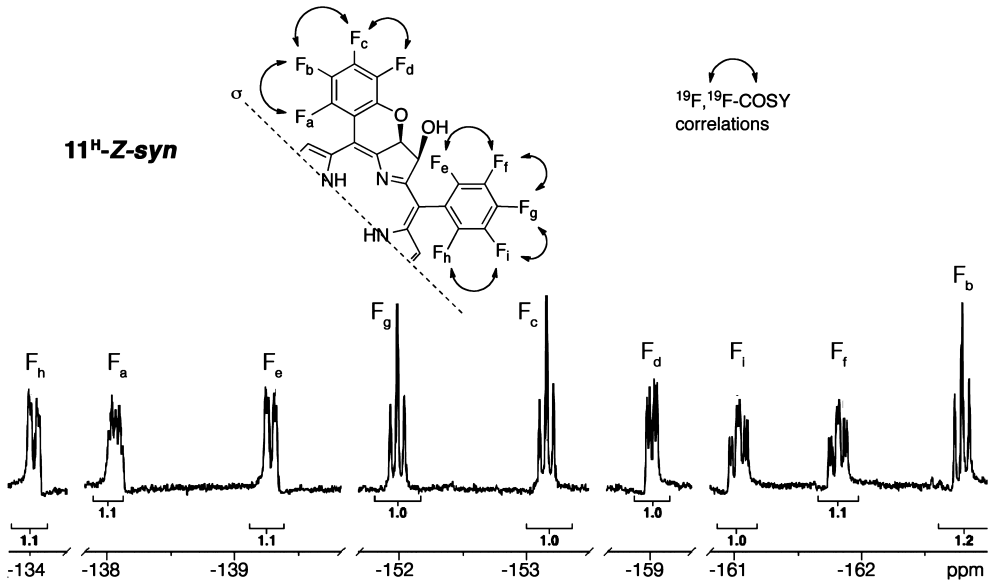
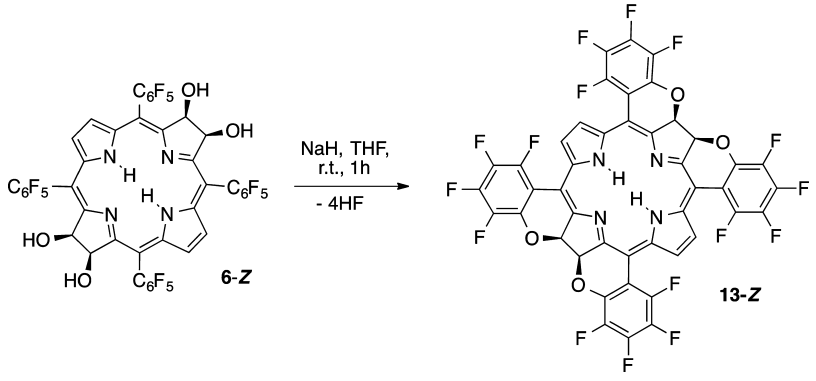


Figure 4. ^{19}F NMR spectrum (376 MHz, $CDCl_3$) of **11^{H}-*Z-syn*** and indication of observed ^{19}F,^{19}F-COSY couplings. For the full spectra, see the Supporting Information.

Scheme 5. Synthesis of Putative Tetrakis-chromene-Annulated Bacteriochlorin 13-*Z*



expected to show these protons as two singlets (also 2H each) (Scheme 4). We exclude the formation of the *adj*-bis-fusion product also on chemical grounds: Our previous work on the chromene-annulated chlorins has shown that this type of bis-fusion required much harsher conditions (NaH over 24 h) than applied here.[20]

Perhaps also an indication for the high strain inherent in known *adj*-bis-fused chlorin **12**,[20] its submission to the standard dihydroxylation conditions (1 eq OsO_4, $CHCl_3$, 10% pyridine, 25 °C, 24 h) that are well tolerated for a wide range of porphyrins, chlorins, and pyrrole-modified porphyrins[28] produced numerous degradation products. Few exhibited bacteriochlorin spectra, and none indicated (by ESI+ MS and UV−vis spectroscopy) the presence of a targeted bischromene-annulated species **11-*E/Z-adj*** (Scheme 4).

On account of the number of nonequivalent NH protons and of unique pyrrole β-protons, the *anti*- and *syn*-isomers of **11^{H}** can be clearly distinguished (Figure 3). The NH protons in both *syn*-isomers (**11^{Me}-*E/Z-syn***) are nonequivalent but are equivalent in **11^{Me}-*Z-anti***. The differences in their absolute peak positions can be rationalized by the conformational differences of the chromophores (see also the computed

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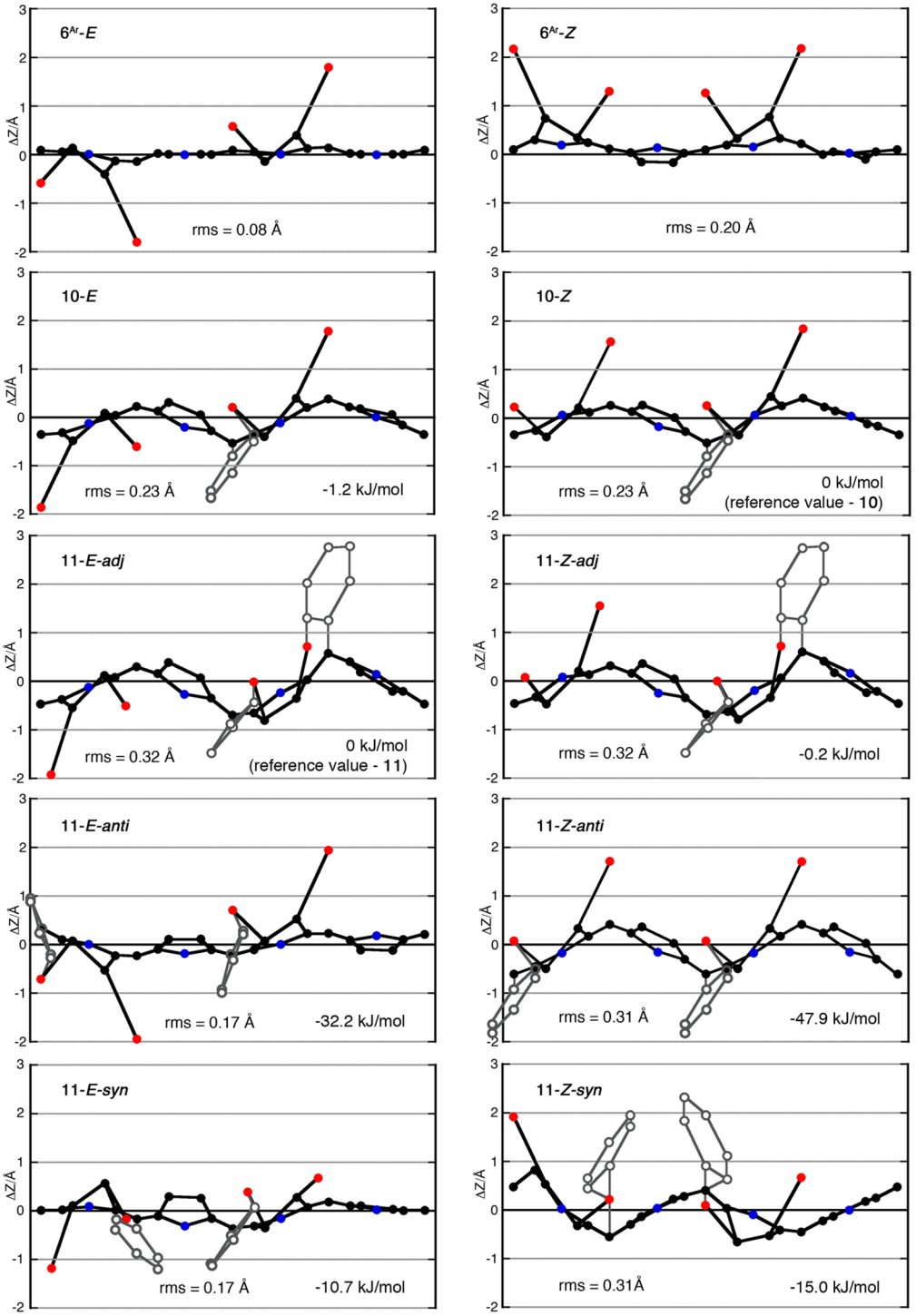

Figure 5. Out-of-plane displacement plots of the tetrahydroxybacteriochlorin macrocycle of the experimentally determined conformations of bacteriochlorins $\mathbf{6}^{\mathbf{Ar}}$-*E* (Ar = *p*-^{i}Pr-Ph)[16] and $\mathbf{6}^{\mathbf{Ar}}$-*Z* (Ar = 3,4,5-MeOPh),[16] the computationally determined conformations of the monochromene-annulated bacteriochlorins **10**-*E* and **10**-*Z*, including the annulated phenyl group, and the computationally determined conformations of all bis-chromene-annulated bacteriochlorins **11**-*E* and **11**-*Z*, including both annulated phenyl groups. The rms values listed are root-mean-square values of the deviation from planarity of the $C_{20}N_4O_4$ macrocycle from planarity. The energies are the computed relative total ΔH energies, whereby the highest energy isomer within each of the two series of compounds (**10** and **11**) were arbitrarily set to zero. The rms value was calculated as rms = $\sqrt{\frac{1}{24}(x_1^2 + x_2^2 + \ldots + x_n^2)}$ for *x* being the out-of-plane deviation of the 24 atoms of the $C_{20}N_4$ macrocycle. For details of the computations, see the Supporting Information.

conformations). In addition, both *syn*-isomers show the presence of two different pyrrolic β-protons that are not coupled to each other. On the contrary, the two different pyrrolic β-protons are coupled to each other in the *anti*-isomer.

The presence of the C_6F_5 groups enables ^{19}F NMR spectra to be used as a diagnostic tool.[20,22b,29] However, the ^{19}F−^{13}C couplings in regular {^{1}H} ^{13}C NMR spectra also complicate the interpretation of their ^{13}C NMR spectra.[30] A representative

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example for the well-resolved ^{19}F NMR spectra of the bischromene-annulated bacteriochlorins is that of **11^{H}-*Z-syn*** (Figure 4). Comparison with the well-resolved chlorin spectra,[20] in conjunction with $^{19}F-^{19}F$ COSY NMR spectra, allowed an assignment of the majority of the ^{19}F NMR signals (see the Supporting Information).

Treatment of tetrahydroxybacteriochlorin *Z*-isomer **6-*Z*** under forced fusion conditions (NaH in the absence of a nucleophile) generated a green solid. Its composition ($C_{44}H_{11}F_{16}N_4O_4$ for MH^+ as provided by ESI+ HR-MS) and its bacteriochlorin-like broadened UV−vis spectrum (λ_{max} = 754 nm, see Supporting Information) are suggestive for the formation of the tetra-annulated chromophore **13-*Z*** (Scheme 5). However, the low solubility of this material prevented its characterization by NMR spectroscopy.

Computed Conformations and Relative Energies of the Mono- and Bis-Fused Tetrahydroxybacteriochlorin Isomers Using DFT. To better understand the regiochemical outcomes of the second ring-fusion reactions of the monochromene-annulated trihydroxybacteriochlorins (Scheme 3), we computed (at the DFT level: using Gaussian 09,[31] B3LYP hybrid functional and the 6-31+G (d,p) basis set; details to the calculations presented in Supporting Information) the total energies of the six possible isomers of **11** resulting from the permutations of the ***E/Z*** and *adj/syn/anti* stereo- and regiochemical designations. We are fully aware that kinetic factors might be at least as important in the determination of the products as the relative thermodynamic stabilities of the products. However, we surmised that the largest factors differentiating the thermodynamic stabilities of the products, the distortions of the macrocycles as a result of the annulation reactions, would also be representative of the kinetic barriers in their formation. The results, shown in Figure 5, broadly mirror the experimental results, lending some credence to this supposition.

A number of general observations can be made: As expected, the nonannulated bacteriochlorins **6^{Ar}-*E*** (Ar = *p*-^{i}Pr-Ph) and **6^{Ar}-*Z*** (Ar = 3,4,5-MeOPh) are much more planar than any of the annulated systems.[16] Less obvious, all bacteriochlorins possessing the alcohol functionalities on the same side of the macrocyle plane (*Z*-isomers) are more distorted than the corresponding compounds derived from the *E*-isomers, even though the *E*-isomer of **6** are overall less stable and form in smaller amounts than the *Z*-isomers, and the separation between the two pairs of diols is much too large for any direct steric interactions.[16] In fact, overall distortions as measured by the rms values of the macrocycles are not a good predictor for the experimental observation of a compound. For instance, bis-chromene-fused isomer **11-*Z-adj*** was never experimentally observed, but its rms value is the same (0.32 Å) as that observed for **11-*Z-syn*** and **11-*Z-anti***, both of which were observed (Scheme 3).

The energies of the monofused triol isomers **10-*Z*** and **10-*E*** are nearly identical. Correspondingly, they formed in a 1:1 ratio by dihydroxylation of the annulated chlorin (Scheme 2). The energies of the various regiochemically distinct second fusion products are vastly different, with the *adj*-products possessing the highest energy, with the two **11-*Z-adj*** and **11-*E-adj*** isomers displaying essentially identical energies and conformations. All derivatives that form readily (including the parent compounds **6** and **10**) possess a dihedral angle of ∼30° between their two adjacent *β*-C−O bond axes, relaxing the steric interaction between the oxygen atoms from an eclipsed conformation but, because of the steric constraints of the pyrroline moieties, not reaching a more favorable *gauche* conformation (60° dihedral angle). In the computed **11-*adj*** isomers, the oxygen atoms are forced into a near-fully eclipsed conformation (dihedral angle of ∼4°). We see this as a major reason why they are never observed experimentally.

The most stable isomers are the **11-*Z-anti*** and **11-*E-anti*** compounds, with the *Z*-isomer being ∼15 kJ/mol more stable (although their rms values are nearly identical). Surprisingly, therefore, we have not seen isomer **11-*E-anti*** experimentally. This isomer was predicted to be at least 17 kJ/mol more stable than both isomers of the **11-*syn*** pair that possess intermediate stability, with the *Z*-isomer again being more stable (but only by ∼4 kJ/mol). The *E-anti*-isomer enforces a ∼4° more eclipsed dihedral angle between the two adjacent *β*-C−O bond axes as compared to the Z-anti isomer, but it is not certain if this is the major or even sole reason for its absence in the reaction mixtures. The relative stabilities of the *anti* > *syn* > *adj* ring-fusion products was also deduced to control the formation of related *β*- to *o*-aryl linkages of porphyrin **4^{F}** under the conditions of ESI+ mass spectrometry.[32]

Optical Properties of the Chromene-Annulated Bacteriochlorins. The UV−vis spectra of the chromene-annulated bacteriochlorins are all typical bacteriochlorin spectra (Figure 6). Compared to the UV−vis spectrum of the

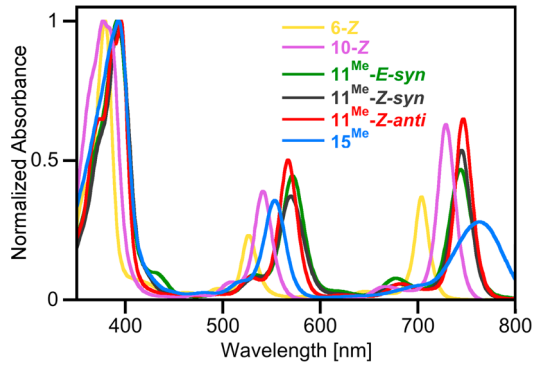

Figure 6. Normalized UV−vis spectra (CH_2Cl_2) of bacteriochlorins indicated.

tetrahydroxybacteriochlorin **6-*Z*** (λ_{max} = 705 nm),[16] mono-annulated trihydroxybacteriochlorin **10-*Z*** (λ_{max} = 729 nm) is 24 nm red-shifted. This red-shift is significantly larger than the 8 nm shift observed for when 2,3-dihydroxychlorin **5** (for Ar = C_6F_5) was annulated to form **7**. Moreover, this λ_{max} band is, relative to that of the Soret band, more intense than in tetraol **6-*Z***. The annulation-induced red-shifts are additive. Thus, the spectra of the three isomeric bis-chromene-annulated species **11^{Me}-*E-syn***, **11^{Me}-*Z-syn***, and **11^{Me}-*Z-anti*** are all an additional ∼14 nm red-shifted compared to **10-*Z***. Their spectra are with respect to the position of the bands observed very similar to each other. Their differences arise from the varying intensities of the Soret and side bands, likely reflecting their slightly differing nonplanar conformations (see above).

The fluorescence spectra of all bacteriochlorins show the typical small Stoke's shift and a bacteriochlorin-like single emission band (Figure 7).[6c,11d,33] As is also typical for bacteriochlorins (of increased conformational flexibility when compared to porphyrins and chlorins), their fluorescence yields *ϕ* are lower than those of porphyrins and chlorins. Thus, a 1% fluorescence yield is observed for tetraol **6-*Z***. Chromene

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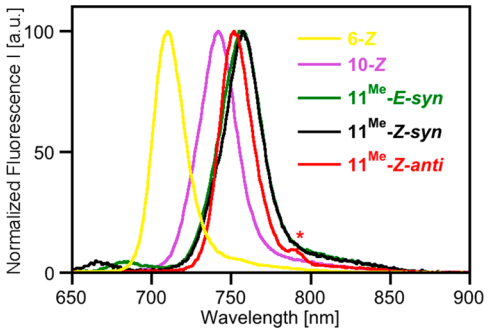

Figure 7. Normalized fluorescence spectra (CH_2Cl_2) of the bacteriochlorins indicated; * indicates impurity.

annulation increases the fluorescence yield in the annulated triols **10-*E*/*Z*** significantly, to 6%, presumably because of an increased conformational rigidity due to the ring fusion. However, the introduction of a second annulated ring does not increase the fluorescence yield further in any of the isomers of $\mathbf{11}^{H/Me}$.

Reaction of Chrome-Annulated Bacteriochlorin $\mathbf{11}^{Me}$-*Z-syn* under Acidic Conditions. In the solid state, the bis-chromene-annulated bacteriochlorins are generally stable over years and in neutral solution (in the absence of light) for weeks or at least days. However, we observed that they are slightly sensitive to prolonged exposure to acidic conditions. Thus, when bis-chromene-annulated bacteriochlorin $\mathbf{11}^{Me}$-***Z-syn***, for example, is treated under strongly acidic conditions ($BF_3 \cdot Et_2O$), a new compound is formed by a loss of MeOH from $\mathbf{11}^{Me}$-***Z-syn*** (composition of $C_{45}H_{13}F_{18}N_4O_3$ for MH^+, as determined by ESI+ HR-MS). The UV−vis spectrum of the product is similar to that of the chromene-annulated chlorins **7**, but 13 nm red-shifted (Figure 8). This suggests that a loss of

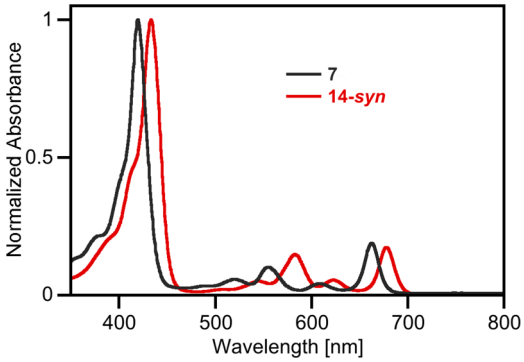

Figure 8. Normalized UV−vis spectra (CH_2Cl_2) of monochromene-annulated chlorin **7** (black trace) and bis-chromene-annulated chlorin **14-*syn*** (red trace).

MeOH across a pyrroline-β,β'-bond has taken place that converted bis-chromene-annulated bacteriochlorin $\mathbf{11}^{Me}$-***Z-syn*** to bis-annulated chlorin **14-*syn*** (Scheme 6). This interpretation was also supported by its ^1H and ^{19}F NMR data (inter alia, all spectroscopic signature for the presence of two nonequivalent chromene-annulated moieties can be distinguished: A new low-field shifted singlet (1H) at 8.16 ppm, assigned to the pyrrole β-H of the new double bond emerged) and ultimately proven by its single-crystal structure analysis (Figure 9). We previously observed an equivalent reaction on tetrahydroxy-bacteriochlorins.[16]

Single-Crystal X-ray Structure of Bis-chromene-Annulated Chlorin 14-*syn*. The crystal structure of **14-*syn***, the first solid-state structure of any of the chromene-annulated hydroporphyrins, confirms the computed and spectroscopically deduced greater coplanarity of the annulated *meso*-aryl group with the chromophore compared to the near-perpendicular arrangement of the nonannulated aryl groups (Figure 9).[20] The $C_{o\text{-aryl}}-C_{ipso}-C_{meso}-C_{\alpha\text{-pyrroline}}$ torsion angle of the chromene annulated to the pyrroline is 23° (the equivalent computed angle in **7** was computed to be 30°).[20] The corresponding torsion angle of the chromene annulated to the unsaturated portion of the molecule is at 10° smaller. As a direct result of the greater than predicted coplanarity of the aryl groups with the chromophore, the *o*-F−β-H nonbonding distances are even shorter (2.40 and 2.36 Å) than the computed distance of 2.5 Å,[20] thus also rationalizing the strong $^1H-^{19}F$ coupling observed for these two atoms that are six bonds apart. The close *o*-F−β-H contact pushes the pyrrole between the annulated rings to lie 27° out-of-plane of the remainder of the macrocycle.

Dihydroxypyrroline Ring Expansion of Chromene-Annulated Trihydroxybacteriochlorin 10-*Z/E*. We previously demonstrated that the dihydroxypyrroline moiety in dihydroxychlorins $\mathbf{5}^{Ar}$ and tetrahydroxybacteriochlorins $\mathbf{6}^{Ar}$ can be expanded to a morpholine moiety, giving rise to the class of morpholinochlorins and -bacteriochlorins, respectively.[34] Thus, when chromene-annulated trihydroxybacteriochlorin **10-*Z*** or **10-*E*** is submitted to the standard two-step, one-pot reaction conditions established for this conversion ($NaIO_4$ heterogenized on silica gel in the presence of an alcohol),[34] we observed the clean appearance of a new compound of the composition corresponding to the expected product of $\mathbf{15}^{Me}$ (formed in the presence of MeOH: $C_{46}H_{18}F_{19}N_4O_5$ for MH^+, as per ESI+ HR-MS) (Scheme 7). The ^1H and ^{19}F NMR spectra of both the dimethoxy and diethoxy compounds $\mathbf{15}^{Me}$ and $\mathbf{15}^{Et}$ clearly indicated the presence of only one isomer, the retention of the chromene annulation (strong ^6J H−F couplings), and the presence of a morpholine moiety (diagnostic signals in the high-field region for the morpholine sp^3-carbons and the diastereotopic coupling of the methylene hydrogens of the ethoxy side chains of $\mathbf{15}^{Et}$). Thus, oxidative diol cleavage and subsequent ring closure and double-acetal formation took place at the unprotected diol moiety.

The bacteriochlorin-type UV−vis spectra of $\mathbf{15}^{Me/Et}$ are as expected on the basis of precedents.[34b] They are also greatly red-shifted and broadened compared to that of the starting material, suggestive of greater nonplanarity and conformational flexibility of these compounds (Figure 6).

It was established by X-ray diffractometry that the alkoxy groups on the morpholine moiety in the morpholinochlorins and -bacteriochlorins take up an *anti*-configuration.[34] This configuration can be rationalized on steric and stereoelectronic grounds.[34a] The morpholine moiety also introduces a ruffled conformation into the macrocycle; it adopts helimeric chirality (Figure 10). As the computations revealed, chromene annulation also introduces some ruffling to the macrocycle. Thus, when the structural elements of the chromene annulation are combined with the dialkoxymorpholine ring in **15**, a low energy matching and a high energy mismatching pair of the ruffling modes can be expected, i.e., one in which the natural ruffling induced by one structural element is matched by the ruffling induced by the other and one in which they go against each other.[34b,35] As a consequence, we can predict the

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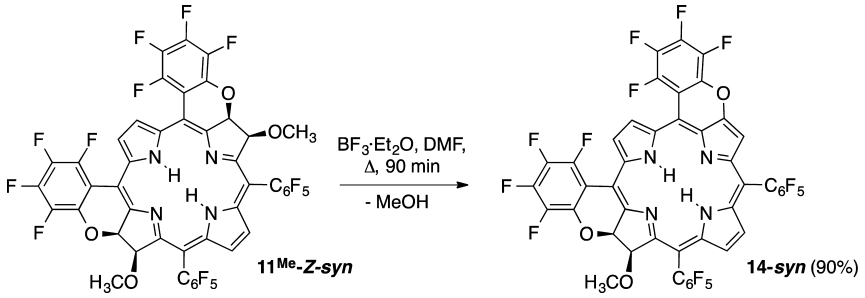
Scheme 6. Synthesis of Bis-chromene-Annulated Chlorin 14-*syn*



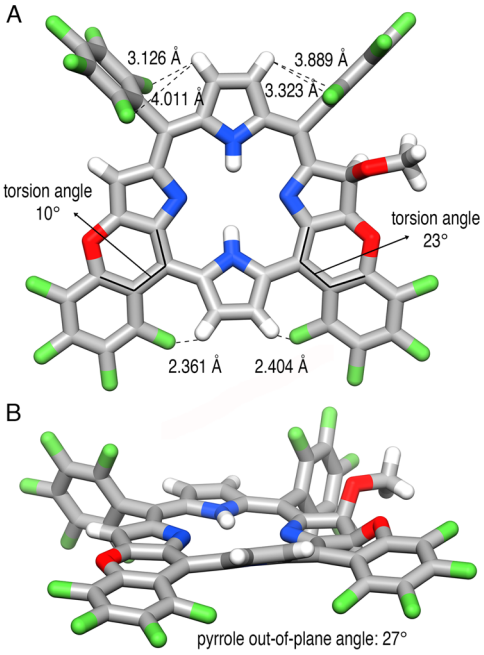


Figure 9. Stick representation of the single-crystal X-ray structure of **14-*syn*** with select bond distances and angles: (A) top view; (B) oblique view. All disorder and solvent molecules have been omitted for clarity. For details, see the Supporting Information.

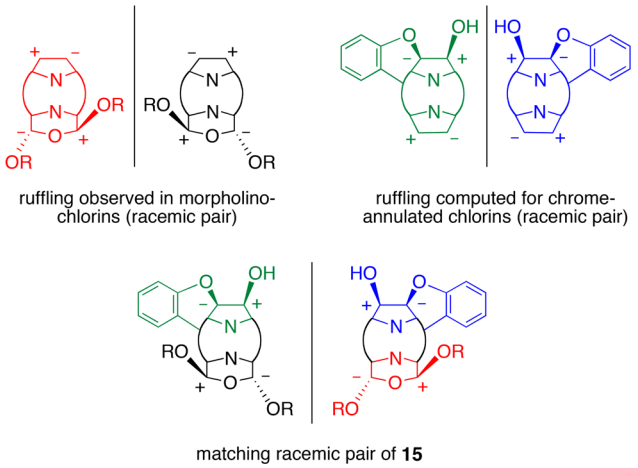


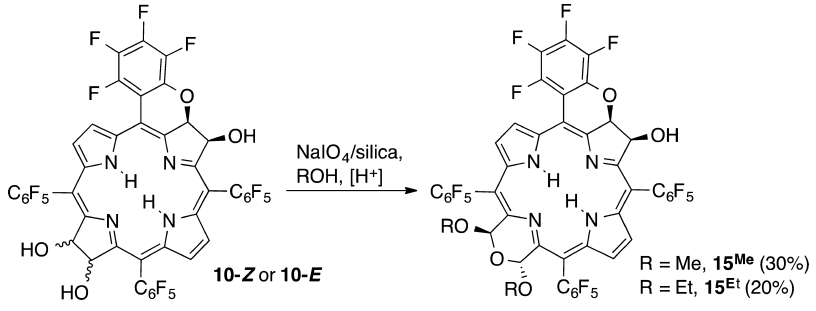
Figure 10. Deriving the possible enantiomers of **15** from the known and computed conformations of the morpholinochlorins and the chromene-annulated porphyrins, respectively.

occurrence of only the low-energy pair of enantiomeric stereoisomers shown to form, consistent with the observation in the NMR spectrum of **15** of the presence of only one diastereomer. Therefore, all five chiral elements present in morpholinobacteriochlorin **15** (four chiral centers and a chiral axis) are firmly linked to each other.

Dihydroxypyrroline Oxidation of Chromene-Annulated Trihydroxybacteriochlorin 10-*Z*/*E*. The oxidation of *meso*-arylporphyrins or -dihydroxychlorins to generate the corresponding *meso*-arylporpholactones is well-known.[36] We further described that the MnO_4^--mediated oxidation of dihydroxyoxazolobacteriochlorins is possible, generating oxazolochlorolactones.[28a] Thus, it is not a surprise that chromene-annulated trihydroxybacteriochlorin **10-*E*/*Z*** can be oxidatively converted to chromene-annulated chlorolactone **16** (Scheme 8), as suggested by the diagnostic mass loss associated with the replacement of a β-carbon by an oxygen atom ($C_{43}H_{10}F_{20}N_4O_4$ for MH^+, as per ESI+ HR-MS) and the appearance of a lactone $\nu_{C=O}$ stretch at 1723 cm^{-1} in the IR spectrum of the product. However, we found CrO_3 to be a better oxidant than MnO_4^- (in the form of cetyltrimethylammonium permanganate). No oxidation of the α-hydroxy chromene moiety was observed.

Two orientations of the lactone moiety in **16** are possible, giving rise to the 12-oxa-13-oxo and 13-oxa-12-oxo isomers. The ^1H and ^{19}F NMR spectra of **16** indicated that a 1:0.7

Scheme 7. Synthesis of Chromene-Annulated Morpholinobacteriochlorin 15



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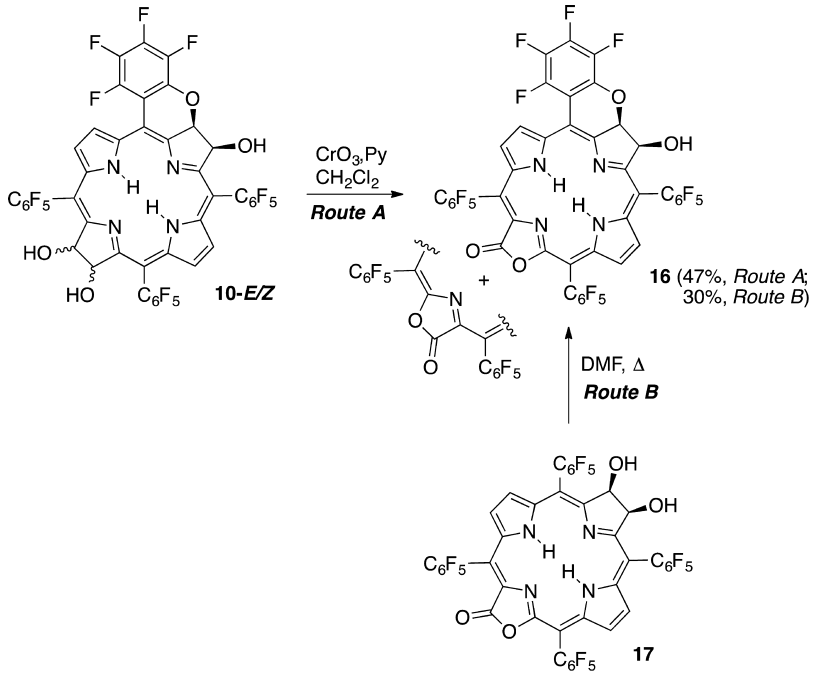
Scheme 8. Complementary Pathways toward the Synthesis of Chromene-Annulated Chlorolactone 16



mixture of the two inseparable (by silica gel flash column and plate chromatography) isomers were present, with no assignment of which isomer is which. This regioselectivity of the reaction, albeit more pronounced, was also observed in the oxidation of dihydroxyoxazolobacteriochlorins[28a] and the synthesis of bislactones.[37]

The UV−vis spectrum of chromene-annulated chlorolactone **16** is chlorin-like (Figure 11), as expected on the basis of the finding that the lactone moiety mimics the electronics of a β,β'-double bond.[36b,d] The spectrum is, following the general trend, 18 nm red-shifted compared to the spectrum of the nonannulated analogue **17**. Again, we attribute the general broadening of the spectrum and the changes in the relative ratios of the bands to conformational changes.

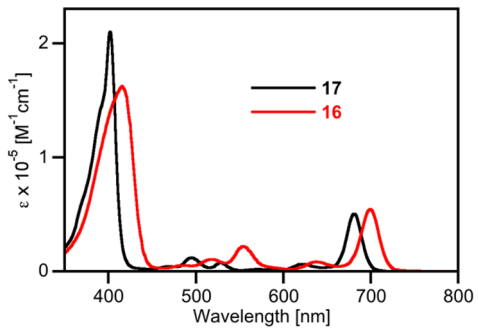


Figure 11. UV−vis spectra (CH_2Cl_2) of chromene-annulated chlorolactone **16** (red trace) and dihydroxychlorolactone **17** (black trace).

CONCLUSIONS

The generation of *meso*-C_6F_5-substituted mono- and bis-chromene-annulated bacteriochlorins by either dihydroxylation of a chromene-annulated chlorin or an intramolecular nucleophilic aromatic substitution of an *o*-fluorine atom by the alcohol functionality of a β-tetrahydroxybacteriochlorin is possible and generates stable bacteriochlorin chromophores with tuned optical spectra. We attribute this to slight variations in the conformations of the products, a supposition supported by computations that highlight the conformational changes upon annulation. The second annulation of chromene-annulated trihydroxybacteriochlorins shows, depending on the stereoisomer used, a distinct regioselectivity, a finding that we rationalized on steric grounds. A detailed analysis of the ^{19}F NMR and $^{1}H-^{19}F$ NMR spectra of these bis-annulated bacteriochlorins allowed an assignment of their connectivity. Their straightforward conversion to chromene-annulated pyrrole-modified porphyrins using dihydroxypyrroline oxidation reactions underlines the chemical stability of the annulated bacteriochlorins. Under strongly acidic conditions, however, the bis-annulated bacteriochlorins are not stable. They eliminated MeOH to produce a bis-annulated chlorin. It was characterized by single-crystal X-ray diffractometry, providing the first crystal structure of a chromene-annulated chlorin. The presence of *meso*-C_6F_5-substituents allows the preparation of a number of other derivatives to modulate their solubility or to introduce functionality into the molecule. This and their facile access, chemical robustness, and electronic tunability enhance the chance that the chromene-annulated bacteriochlorins will find utility in technical or biomedical applications.

EXPERIMENTAL SECTION

Materials and Instrumentation. 10,15,20-Tris(pentafluorophenyl)-(5′,6′,7′,8′-tetrafluoro-2*H*-chromene-annulated)-2-hydroxychlorin **7**[20] was prepared as described previously. Flash column chromatography was performed on an automated flash chromatography system on normal-phase silica columns (isocratic elution modes). The fluorescence yields (ϕ) were determined relative to those of *meso*-tetraphenylporphyrin (ϕ = 0.11 in benzene,[38] calculated to be 0.09 in CH_2Cl_2); $\lambda_{excitation} = \lambda_{Soret}$.

Computations. The computations of the energies of the most favorable conformations of the compounds chosen used DFT as implemented in the GAUSSIAN 09 program package[32] using the B3LYP hybrid functional and the 6-31+G (d,p) basis set.

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meso*-Tetrakis(pentafluorophenyl)-2(*R*),3(*S*),12(*S*),13(*R*)-tetrahydroxybacteriochlorin (6-*E*) and *meso*-Tetrakis(pentafluorophenyl)-2(*R*),3(*S*),12(*R*),13(*S*)-tetrahydroxybacteriochlorin (6-*Z*).** 5,10,15,20-Tetrakis(pentafluorophenyl)porphyrin $\mathbf{4}^{\mathbf{Ar}}$ for Ar = C_6F_5 (250 mg, 2.50×10^{-3} mol) was dissolved in $CHCl_3$ (125 mL) and freshly distilled pyridine (25 mL) in a 250 mL round-bottom flask equipped with a stir bar. The mixture was treated with 1 equiv of OsO_4 (2.50×10^{-3} mol; 26.2 mL of a stock solution of 1.0 g OsO_4 dissolved in 50 mL of pyridine). (Caution: gloves, eye protection, and fume hood must be used!) The flask was stoppered, shielded from light with aluminum foil, and stirred at ambient temperature for ∼24 h. The progress of the reaction was monitored by TLC. Once no further progress of the reaction was detectable, approximately 50% of the solvent was removed by rotary evaporation. To the crude reaction mixture, a saturated solution of $NaHSO_3$ in MeOH/H_2O (1:1) (80 mL) was added. The flask was stoppered and wrapped in aluminum foil, and the biphasic solution was vigorously stirred at ambient temperature for 2 d. Once no further progress of the reaction was detectable by TLC, the mixture was transferred into a 250 mL separatory funnel. After the addition of CH_2Cl_2 (∼50 mL), the organic fraction was separated and filtered through a short plug of diatomaceous earth (Celite). The solvent was then removed to dryness by rotary evaporation. A gentle stream of N_2 for several hours ensured that the crude material was thoroughly dried before it was purified via flash chromatography (24 g silica cartridge−CH_2Cl_2/1.0% MeOH). The lowest polarity material was tetrakis(pentafluorophenyl)porphyrin (5−10% recovery), and the second major fraction was dihydroxychlorin ***6Z, isolated in 45−50% yield as a greenish solid. Isomer **6-*E*** isomer was isolated as a higher polarity fraction in 10−15% yield and generally required a second purification step by preparative plate TLC (silica−CH_2Cl_2/2.0%MeOH). **6-*Z***: R_f (silica−CH_2Cl_2/1% MeOH) = 0.20; ^{1}H NMR (400 MHz, $CDCl_3$, δ): 8.37 (s, 2H), 8.08, (s, 2H), −2.00 (s, 1H) ppm; UV−vis (CH_2Cl_2) λ_{max} (log ε) 378 (4.70), 508 (4.25), 716 (4.32) nm; fluorescence (CH_2Cl_2) λ_{max}, nm ($\lambda_{excitation} = \lambda_{Soret}$): 728, ϕ = 0.01; ^{19}F NMR (376 MHz, $CDCl_3$, δ) −135.4 (dd, ^3J = 25.5, ^5J = 7.8 Hz, 1F), −139.6 (dd, ^3J = 25.5, ^5J = 7.8 Hz, 1F), −152.5 (t, ^3J = 20.3 Hz, 1F), −161.8 (td, ^3J = 23.1, ^5J = 7.2 Hz, 2F) ppm; HR-MS (ESI+, 100% CH_3CN) calcd for $C_{44}H_{15}F_{20}N_4O_4$ (MH^+) 1043.0768, found 1043.0760. **6-*E***: R_f (silica−CH_2Cl_2/1% MeOH) = 0.17; ^{1}H NMR (400 MHz, $CDCl_3$, δ) 8.37 (s, 2H), 7.28 (s, 2H), 6.10 (s, 2H), −2.04 (s, 1H) ppm; UV−vis (CH_2Cl_2) λ_{max} (log ε) 374 (4.96), 507 (4.43), 708 (4.74) nm; fluorescence (CH_2Cl_2) λ_{max}, nm ($\lambda_{excitation} = \lambda_{Soret}$) 712; ^{19}F NMR (376 MHz, $CDCl_3$, δ) −135.3 (dd, ^3J = 25.5, ^5J = 7.8 Hz, 1F), −139.7 (dd, ^3J = 25.5, ^5J = 7.8 Hz, 1F), −152.6 (t, ^3J = 20.3 Hz, 1F), −161.8 (td, ^3J = 23.1, ^5J = 7.2 Hz, 2F) ppm; HR-MS (ESI+, 100% CH_3CN): HR-MS (ESI+, 100% CH_3CN) calcd for $C_{44}H_{15}F_{20}N_4O_4$ (MH^+) 1043.0768, found 1043.0740.

10,15,20-Tris(pentafluorophenyl)-(5′,6′,7′,8′-tetrafluoro-2*H*-chromene-annulated)-2,12,13-trihydroxybacteriochlorin *Z*-Isomer 10-*Z* and 10,15,20-Tris(pentafluorophenyl)-(5′,6′,7′,8′-tetrafluoro-2*H*-chromene-annulated)-2,12,13-trihydroxybacteriochlorin *E*-Isomer 10-*E*. 10,15,20-Tris(pentafluorophenyl)-(5′,6′,7′,8′-tetrafluoro-2*H*-chromene-annulated)-2-hydroxychlorin (7) (630 mg, 6.37×10^{-4} mol) was dissolved in a 250 mL round-bottom flask equipped with a magnetic stir bar in $CHCl_3$ (125 mL) and freshly distilled pyridine (25 mL). The mixture was treated with 1.2 equiv of OsO_4 (7.64×10^{-4} mol; 9.7 mL of a stock solution of 1.0 g OsO_4 dissolved in 50 mL of pyridine). (Caution: gloves, eye protection, and fume hood are necessary!) The flask was stoppered, shielded from light with aluminum foil, and stirred at ambient temperature. The progress of the reaction was monitored by TLC and UV−vis spectroscopy. Once no further progress of the reaction was detectable (after ∼36 h), approximately 50% of the solvent was removed by rotary evaporation. To the crude reaction mixture was added a saturated MeOH/H_2O (1:1) solution of $NaHSO_3$ (80 mL). The flask was stoppered, and wrapped in aluminum foil, and the biphasic solution was vigorously stirred at ambient temperature for 3 d. Once no further progress of the reaction was detectable by TLC, the mixture was transferred into a 125 mL separatory funnel. The organic fraction was separated with CH_2Cl_2 and filtered through a short plug of diatomaceous earth (Celite). The solvent was removed to dryness by rotary evaporation. A gentle stream of N_2 for several hours ensured that the crude material was thoroughly dried; it was subsequently purified via flash chromatography (24 g silica−CH_2Cl_2/1.0% MeOH). After the recovery of the low polarity starting material 7 (5−10%), the second major fraction was bacteriochlorin **10-*E***, isolated in 40% yield (280 mg) as a bright pink solid, and the third major fraction was the isomeric bacteriochlorin **10-*Z***, isolated in 40% yield (280 mg) as a bright pink solid. **10-*E***: R_f (silica−CH_2Cl_2/1% MeOH) = 0.26; ^{1}H NMR (400 MHz, $CDCl_3$, δ) 8.79−8.75 (m, 1H), 8.24−8.22, (m, 1H), 8.16−8.14 (m, 1H), 8.12 (dd, ^3J = 4.7, ^4J = 2.0 Hz, 1H), 6.26−6.22 (m, 2H), 6.06 (t, ^3J = 7.9 Hz, 1H), 5.91−5.88 (m, 1H), 3.41 (d, ^3J = 9.0 Hz, 1H), 2.79 (d, ^3J = 3.6 Hz, 1H), 2.54 (d, ^3J = 6.5 Hz, 1H), −0.61 (s, 1H), −0.91 (s, 1H) ppm; ^{19}F NMR (376 MHz, $CDCl_3$, δ) −134.7 (dd, ^3J = 24.0, ^5J = 7.5 Hz, 1F), −135.6 (dd, ^3J = 23.6, ^5J = 8.0 Hz, 1F), −136.5 (dd, ^3J = 23.9, ^5J = 7.8 Hz, 1F), −138.1 (dd, ^3J = 23.7, ^5J = 7.7 Hz, 1F), −138.6 (dd, ^3J = 23.9, ^5J = 7.7 Hz, 1F), −140.0 (m, 1F), −140.8 (dd, ^3J = 23.9, ^5J = 7.6 Hz, 1F), −151.9 (two overlapping t, ^3J = 20.6 Hz, 2F), −152.6 (t, ^3J = 20.8 Hz, 1F), −153.8 (t, ^3J = 20.9 Hz, 1F), −158.5 (dd, ^3J = 20.9, ^5J = 9.3 Hz, 1F), −160.8 (td, ^3J = 22.3, ^5J = 8.1 Hz, 1F), −161.6 (m, 2F), −161.6 (td, ^3J = 22.4, ^5J = 7.7 Hz, 1F), −161.9 (m, 2F), −162.5 (t, ^3J = 21.7 Hz, 1F) ppm; ^{13}C NMR (100 MHz; $CDCl_3$) δ 162.5, 155.79, 155.77, 155.1, 144.2, 140.9, 140.83, 140.76, 139.1, 139.0, 138.9, 137.5, 136.6, 136.5, 136.4, 136.4, 135.8, 135.1, 135.0, 125.8, 125.7, 124.4, 122.2, 121.9, 102.2, 101.6, 100.7, 99.0, 83.1, 75.9, 73.3, 73.0, 30.8 ppm; UV−vis (CH_2Cl_2) λ_{max}/nm (log ε) 377 (5.25), 509 (4.07), 541 (4.84), 667 (3.94), 729 (5.05); fluorescence (CH_2Cl_2) λ_{max}/nm 740, ϕ = 0.06; HR-MS (ESI+, 100% CH_3CN) calcd for $C_{44}H_{14}F_{19}N_4O_4$ (MH^+) 1023.0712, found 1023.0675. **10-*Z***: R_f (silica−CH_2Cl_2/1% MeOH) = 0.16; ^{1}H NMR (400 MHz, $CDCl_3$, δ) 8.86−8.81 (m, 1H), 8.33−8.31 (m, 1H), 8.22 (dd, ^3J = 4.9, ^4J = 1.8 Hz, 1H), 8.26 (dd, ^3J = 4.8, ^4J = 1.9 Hz, 1H), 6.31−6.28 (m, 1H), 6.25 (d, ^3J = 6.5 Hz, 1H), 6.06 (t, ^3J = 7.9 Hz, 1H), 5.91 (t, ^3J = 7.1 Hz, 1H), 3.44 (d, ^3J = 8.8 Hz, 1H), 2.83 (d, ^3J = 4.3 Hz, 1H), 2.66 (d, ^3J = 7.3 Hz, 1H), −0.85 (s, 1H), −1.09 (s, 1H) ppm; ^{19}F NMR (376 MHz, $CDCl_3$, δ) −134.8 (dd, ^3J = 23.9, ^5J = 7.4 Hz 1F), −135.5 (dd, ^3J = 23.7, ^5J = 8.0 Hz, 1F), −135.9, (dd, ^3J = 24.1, ^5J = 7.6 Hz 1F), −138.1 (dd, ^3J = 24.0, ^5J = 7.6 Hz, 1F), −138.6 (dd, ^3J = 24.0, ^5J = 7.6 Hz, 1F), −139.7 (m, 1F), −141.3 (dd, ^3J = 24.1, ^5J = 7.3 Hz, 1F), −151.7 (t, ^3J = 20.8 Hz, 1F), −152.0 (t, ^3J = 20.9 Hz, 1F), −153.0 (t, ^3J = 20.9 Hz, 1F), −153.8 (t, ^3J = 21.0 Hz, 1F), −158.5 (dd, ^3J = 20.9, ^5J = 9.3 Hz, 1F), −160.6 (td, ^3J = 22.4, ^5J = 7.5 Hz, 1F), −161.2 to −161.4 (m, 2F), −161.5 (td, ^3J = 22.4, ^5J = 7.6 Hz, 1F), −162.0 (td, ^3J = 22.4, ^5J = 7.1 Hz, 1F), −162.2 (td, ^3J = 22.4, ^5J = 7.4 Hz, 1F), −162.5 (t, ^3J = 21.7 Hz, 1F) ppm; ^{13}C NMR (100 MHz; $CDCl_3$): δ 160.1, 157.2, 156.4, 154.1, 136.5, 136.3, 134.2, 124.74, 124.6, 123.4, 123.4, 123.0, 83.1, 77.3, 77.2, 77.0, 76.7, 75.3, 73.4, 73.4; UV−vis (CH_2Cl_2) λ_{max} (log ε) 378 (5.21), 510 (3.99), 541 (4.81), 667 (3.83), 729 (5.02) nm; fluorescence (CH_2Cl_2) λ_{max}: 740 nm, ϕ = 0.06; HR-MS (ESI+, 100% CH_3CN) calcd for $C_{44}H_{14}F_{19}N_4O_4$ (MH^+) 1023.0712, found 1023.0720.

15,20-Bis(pentafluorophenyl)-bis(5′,6′,7′,8′-tetrafluoro-2*H*-chromene-annulated)-3,12-dihydroxybacteriochlorin *Z*-Isomer 11^H-*Z*-*syn* and 10,20-Bis(pentafluorophenyl)-bis-(5′,6′,7′,8′-tetrafluoro-2*H*-chromene-annulated)-3,13-dihydroxybacteriochlorin *Z*-Isomer 11^H-*Z*-*anti*. Chromene-annulated trihydroxybacteriochlorin **10-*Z*** (50 mg, 4.89×10^{-5} mol) was dissolved in DMF (50 mL) in a 100 mL round-bottom flask equipped with a magnetic stir bar. It was heated to reflux for 40 min. The progress of the reaction was monitored by TLC and UV−vis spectroscopy. Once no further progress of the reaction was detectable, the solvent was removed in vacuo and the residue was thoroughly dried under a gentle stream of N_2 for 1 d. The crude material was purified by preparative plate chromatography (silica−CH_2Cl_2/30% hexanes) to provide the products $\mathbf{11^H}$-***Z*-*anti*** in 40% yield (15 mg) and $\mathbf{11^H}$-***Z*-*syn*** in 15% yield (8 mg), both as purple solids. $\mathbf{11^H}$-***Z*-*anti***: R_f (silica−CH_2Cl_2/10% hexanes) = 0.47; ^{1}H NMR (400 MHz, $CDCl_3$, δ) 8.71−8.68 (m, 1H), 8.10 (dd, ^3J = 4.7, ^4J = 1.8 Hz, 1H), 6.21 (s, 2H), 2.84 (br s, 1H), −0.09 (br s, 1H) ppm; ^{19}F NMR (376 MHz, $CDCl_3$,

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δ) −134.5 (dd, ^3J = 23.9, ^5J = 8.1 Hz, 1F), −138.0 to −138.1 (m, 1F), −139.3 (dd, ^3J = 24.1, ^5J = 6.9 Hz, 1F), −152 (t, ^3J = 20.9 Hz, 1F), −153.2 (t, ^3J = 21.03 Hz, 1F), −159 (dd, ^3J = 20.9, ^5J = 9.2 Hz, 1F), −161 (td, ^3J = 22.4, ^5J = 7.7 Hz, 1F), −161.8 (td, ^3J = 22.5, ^5J = 7.3 Hz, 1F), −162.8 (t, ^3J = 21.7 Hz, 1F) ppm; ^{13}C NMR (100 MHz; $CDCl_3$): δ 156.6, 153.3, 136.4, 133.2, 124.7, 122.6, 101.8 ppm; UV−vis (CH_2Cl_2) λ_{max} (log ε) 373 (5.05), 394 (5.23), 428 (4.22), 529 (4.16), 568 (4.95), 680 (4.04), 748 (5.06) nm; fluorescence (CH_2Cl_2) λ_{max} 759 nm, ϕ = 0.06; HR-MS (ESI+, 100% CH_3CN) calcd for $C_{44}H_{13}F_{18}N_4O_4$ (MH^+): 1003.0649, found: 1003.0640. **11^{H}-*Z-syn***: R_f (silica−CH_2Cl_2/10% hexanes) = 0.21; ^{1}H NMR (400 MHz, $CDCl_3$, δ) 8.51 (br d, ^6J = 9.2 Hz, 2H), 8.26 (d, ^4J = 1.9 Hz, 2H), 6.31−6.25 (m, 4H), 2.97 (br s, 2H), −0.72 (s, 1H), −1.30 (s, 1H) ppm; ^{19}F NMR (376 MHz, $CDCl_3$, δ) −135.5 (dd, ^3J = 23.8, ^5J = 7.8 Hz, 1F) −138.1 (dd, ^3J = 23.9, ^5J = 7.3 Hz, 1F), −139.8 to −139.9 (m, 1F), −151.9 (t, ^3J = 20.8 Hz, 1F), −153.7 (t, ^3J = 20.9 Hz, 1F), −158.4 (dd, ^3J = 20.9, ^5J = 9.4 Hz, 1F), −160.7 (td, ^3J = 22.4, ^5J = 7.7 Hz, 1F), −161.6 (td, ^3J = 22.4, ^5J = 7.3 Hz, 1F), −162.6 (t, ^3J = 21.7 Hz, 1F) ppm; UV−vis (CH_2Cl_2) λ_{max} (log ε) 392 (5.30), 539 (4.20), 570 (4.88), 686 (4.04), 745 (5.05) nm; fluorescence (CH_2Cl_2) λ_{max} 761 nm, ϕ = 0.03; HR-MS (ESI+, 100% CH_3CN) calcd for $C_{44}H_{13}F_{18}N_4O_4$ (MH^+) 1003.0649, found 1003.0634.

15,20-Bis(pentafluorophenyl)-bis(5′,6′,7′,8′-tetrafluoro-2*H*-chromene-annulated)-3,12-dihydroxybacteriochlorin *E*-Isomer 11^{H}-*E-syn*. Triol **10-*E*** (50 mg, 4.89 × 10^{-5} mol) was dissolved in DMF (50 mL) in a 100 mL round-bottom flask equipped with a magnetic stir bar, and it was heated to reflux for 40 min. The progress of the reaction was monitored by TLC and UV−vis spectroscopy. Once no further progress of the reaction was detectable, the solvent was removed in vacuo and the residue was thoroughly dried under a gentle stream of N_2 for 1 d. The crude material was purified by preparative plate chromatography (silica−CH_2Cl_2/30% hexanes) to provide **11^{H}-*E-syn*** as the major product in 45% yield (22 mg) as purple solid. **11^{H}-*E-syn***: R_f (silica−CH_2Cl_2/10% hexanes) = 0.67; ^{1}H NMR (400 MHz, $CDCl_3$, δ) 8.83 (br d, ^6J = 7.0 Hz, 2H), 7.96 (d, ^4J = 2.0 Hz, 2H), 6.15 (br. d, ^3J = 5.8 Hz, 2H), 6.06 (d, ^3J = 6.0 Hz, 2H), 2.75 (br s, 1H), 0.97 (s, 1H), 0.55 (s, 1H) ppm; ^{19}F NMR (376 MHz, $CDCl_3$, δ) −136.3 (dd, ^3J = 23.7, ^5J = 7.7 Hz, 1F), −138.4 (dd, ^3J = 24.0, ^5J = 7.4 Hz, 1F), −140.0 to −140.1 (m, 1F), −151.8 (t, ^3J = 20.9 Hz, 1F), −153.8 (t, ^3J = 21.0 Hz, 1F), −158.1 (dd, ^3J = 21.0, ^5J = 9.3 Hz, 1F), −160.5 (td, ^3J = 22.3, ^5J = 7.6 Hz, 1F), −161.3 (td, ^3J = 22.4, ^5J = 7.7 Hz, 1F), −162.2 (t, ^3J = 21.8 Hz, 1F) ppm; UV−vis (CH_2Cl_2) λ_{max} (log ε) 390 (5.27), 532 (4.23), 570 (4.95), 678 (4.11), 746 (4.98) nm; fluorescence (CH_2Cl_2) λ_{max} 760 nm, ϕ = 0.05; HR-MS (ESI+, 100% CH_3CN) calcd for $C_{44}H_{13}F_{18}N_4O_4$ (MH^+) 1003.0649, found 1003.0668.

15,20-Bis(pentafluorophenyl)-bis(5′,6′,7′,8′-tetrafluoro-2*H*-chromene-annulated)-3,12-dimethoxybacteriochlorin *Z*-Isomer 11^{Me}-*Z-syn* and 10,20-Bis(pentafluorophenyl)-bis-(5′,6′,7′,8′-tetrafluoro-2*H*-chromene-annulated)-3,13-dimethoxybacteriochlorin *Z*-Isomer 11^{Me}-*Z-anti*. Bacteriochlorin triol **10-Z** (50 mg, 4.89 × 10^{-5} mol) was, under N_2, dissolved in 50 mL of THF in a 100 mL round-bottom flask equipped with a magnetic stir bar. First, CH_3I (0.10 mL, 32-fold molar excess) was added by syringe. (Caution: gloves and fume hood are necessary!) Second, excess NaH (∼50 mg of a 60% emulsion in mineral oil) was added in portions. The reaction mixture was allowed to stir for ∼1 h at ambient temperature. The progress of the reaction was monitored by TLC. After all of the starting material was consumed, the reaction was quenched by slow addition of a concd aq NH_4Cl solution, the mixture was transferred into a separatory funnel, and the product was extracted with CH_2Cl_2. The organic phase was evaporated to dryness by rotary evaporation, and the residue was purified via preparative plate chromatography (silica−CH_2Cl_2/30% hexanes) to provide the products **11^{Me}-*Z-anti*** in 30−35% yield (15−17 mg) and **11^{Me}-*Z-syn*** in 8−12% yield (4−6 mg) as purple solids. **11^{Me}-*Z-anti***: R_f (silica−CH_2Cl_2/50% hexanes) = 0.30; ^{1}H NMR (400 MHz, $CDCl_3$, δ) 8.72−8.69 (m, 1H), 8.10 (dd, ^3J = 4.7, ^4J = 1.6 Hz, 1H), 6.21 (d, ^3J = 6.8 Hz, 1H), 5.89 (d, ^3J = 6.8 Hz, 1H), 3.30 (s, 3H), −0.18 (s, 1H) ppm; ^{19}F NMR (376 MHz, $CDCl_3$, δ) −135.6 (dd, ^3J = 23.5, ^5J = 7.9 Hz, 1F), −137.9 (dd, ^3J = 24.1, ^5J = 7.4 Hz, 1F), −140.0 (m, 1F), −151.7 (t, ^3J = 20.9 Hz, 1F), −154.0 (t, ^3J = 20.9 Hz, 1F), −158.7 (dd, ^3J = 20.9, ^5J = 9.3 Hz, 1F), −161.2 (td, ^3J = 22.3, ^5J = 8.0 Hz, 1F), −161.4 (td, ^3J = 22.5, ^5J = 7.5 Hz, 1F), −163.2 (t, ^3J = 21.8 Hz, 1F) ppm; UV−vis (CH_2Cl_2) λ_{max} (log ε) 374 (5.04), 396 (5.23), 529 (4.15), 566 (4.93), 680 (4.00), 745 (5.04) nm; fluorescence (CH_2Cl_2) λ_{max} 750 nm, ϕ = 0.06; HR-MS (ESI+, 100% CH_3CN) calcd for $C_{46}H_{17}F_{18}N_4O_4$ (MH^+) 1031.0962, found 1031.0948. **11^{Me}-*Z-syn***: R_f (silica−CH_2Cl_2/50% hexanes) = 0.18; ^{1}H NMR (400 MHz, $CDCl_3$, δ) 8.49 (br d, ^6J = 9.3 Hz, 2H), 8.23 (s, 2H), 6.27 (d, ^3J = 7.4 Hz, 2H), 5.89 (d, ^3J = 7.5 Hz, 2H), 3.34 (s, 6H), −0.81 (s, 1H), −1.41 (s, 1H) ppm; ^{19}F NMR (376 MHz, $CDCl_3$, δ) −134.8 (dd, ^3J = 23.3, ^4J = 7.6 Hz, 1F), −138.2 to −138.3 (m, 1F), −139.1 (dd, ^3J = 23.8, ^4J = 7.0 Hz, 1F), −151.9 (t, ^3J = 20.8 Hz, 1F), −153.5 (t, ^3J = 21.0 Hz, 1F), −159.4 (dd, ^3J = 20.6, ^4J = 9.20 Hz, 1F), −161.4 to −161.6 (m, 2F), −163.4 (t, ^3J = 21.8 Hz, 1F) ppm; UV−vis (CH_2Cl_2) λ_{max} (log ε) 392 (5.23), 534 (4.14), 570 (4.80), 680 (3.98), 745 (4.96) nm; fluorescence (CH_2Cl_2) λ_{max} 756 nm, ϕ = 0.03; HR-MS (ESI+, 100% CH_3CN) calcd for $C_{46}H_{17}F_{18}N_4O_4$ (MH^+) 1031.0962, found 1031.0977.

15,20-Bis(pentafluorophenyl)-bis(5′,6′,7′,8′-tetrafluoro-2*H*-chromene-annulated)-3,12-dimethoxybacteriochlorin *E*-Isomer 11^{Me}-*E-syn*. Prepared in 45−50% yield (25 mg) as a purple solid from bacteriochlorin triol **10-*E*** (50 mg, 4.89 × 10^{-5} mol) as described for **11^{Me}-*Z-syn/anti***. **11^{Me}-*E-syn***: R_f (silica−CH_2Cl_2/50% hexanes) = 0.19; ^{1}H NMR (400 MHz, $CDCl_3$, δ) 8.81 (br d, ^6J = 7.2 Hz, 2H), 7.94 (s, 2H), 6.06 (d, ^3J = 6.2 Hz, 2H), 5.80 (d, ^3J = 6.2 Hz, 2H), 3.26 (s, 6H), 1.02 (s, 1H), 0.58 (s, 1H) ppm; ^{19}F NMR (376 MHz, $CDCl_3$, δ) −136.4 (dd, ^3J = 23.6, ^5J = 7.7 Hz, 1F), −138.2 (dd, ^3J = 24.0, ^5J = 7.3 Hz, 1F), −140.4 (m, 1F), −151.6 (t, ^3J = 20.9 Hz, 1F), −154.1 (t, ^3J = 21.0 Hz, 1F), −158.3 (dd, ^3J = 20.9 Hz, ^5J = 9.3 Hz, 1F), −160.9 to −161.1 (m, 2F). −162.7 (t, ^3J = 21.8 Hz, 1F) ppm; ^{13}C NMR (100 MHz; $CDCl_3$): δ 157.8, 151.8, 135.0, 134.0, 128.1, 127.1, 120.6, 103.2, 98.3, 84.5, 82.1, 59.0 ppm; UV−vis (CH_2Cl_2) λ_{max} (log ε) 392 (5.24), 533 (4.20), 570 (4.89), 678 (4.13), 744 (4.92) nm; fluorescence (CH_2Cl_2) λ_{max} 755 nm, ϕ = 0.05; HR-MS (ESI+, 100% CH_3CN) calcd for $C_{46}H_{17}F_{18}N_4O_4$ (MH^+) 1031.0962, found 1031.0927.

15,20-Bis(pentafluorophenyl)-bis(5′,6′,7′,8′-tetrafluoro-2*H*-chromene-annulated)-3-methoxychlorin (14-*syn*). Bacteriochlorin **11^{Me}-*Z-syn*** (20 mg, 0.02 mmol) was placed in 50 mL round-bottom flask, and DMF (5 mL) and $BF_3{\cdot}Et_2O$ (2 mL) were added. It was connected to a reflux condenser, and the reaction mixture was refluxed for 1.5 h. TLC monitored disappearance of the starting materials. Once no further progress of the reaction was observed, the reaction was allowed to cool, and CH_2Cl_2 (20 mL) was added after the reaction mixture returned to room temperature. The organic fraction was separated and washed with distilled water (3 × ∼ 50 mL) and dried over anhydrous Na_2SO_4. The solvent was evaporated under reduced pressure and further dried with a gentle stream of N_2. The crude material was purified via flash chromatography (silica−50% CH_2Cl_2/hexanes). The major fraction was the product **14-*syn*** that was isolated in 90% yield. **14-*syn***: R_f (silica−CH_2Cl_2/50% hexanes) = 0.65; ^{1}H NMR (400 MHz; $CDCl_3$, δ) 9.34 (s, 1H), 8.99 (s, 1H), 8.66 (s, 1H), 8.42 (s, 1H), 8.16 (s, 1H), 6.25 (s, 1H), 6.13 (s, 1H), 3.36 (s, 3H), −0.09 (s, 1H), −0.59 (s, 1H) ppm; ^{19}F NMR (400 MHz; $CDCl_3$, δ) −135.6 (t, ^3J = 11.8 Hz, 1F), −136.2 (dd, ^3J = 22.1, ^5J = 7.4 Hz, 1F), −136.7 (dd, ^3J = 24.1, ^5J = 6.8 Hz, 1F), −137.7 (m, 2F), −140.0 (dd, ^3J = 22.5, ^5J = 9.1 Hz, 1F), −151.3 (m, 2F), −153.0 (t, ^3J = 21.0, 1F), −154.5 (t, ^3J = 21.0, 1F), −158.6 (dd, ^3J = 20.6, ^5J = 8.2 Hz, 1F), −159.3 (dd, ^3J = 20.9, ^5J = 9.1 Hz, 1F), −160.9 (m, 4F), −161.8 (t, ^3J = 22.0 Hz, 1F), −163.1 (t, ^3J = 21.7 Hz, 1F) ppm; ^{13}C NMR (100 MHz; $CDCl_3$): δ 157.4, 156.2, 154.7, 148.8, 140.1, 137.1, 135.3, 134.9, 130.1, 128.9, 127.7, 125.2, 123.8, 105.2, 98.0, 83.7, 82.2, 59.1, 29.7 ppm; UV−vis (CH_2Cl_2) λ_{max} (log ε) 433.1 (5.08), 545.5 (3.79), 583.5 (4.24), 623.0 (3.82), 678 (4.31) nm; fluorescence (CH_2Cl_2) λ_{max} 684 nm; HR-MS (ESI+, 100% CH_3CN) calcd for $C_{45}H_{13}F_{18}N_4O_3$ for (MH^+) 999.0700, found 999.0764.

5,10,15,20-Tetrakis(5′,6′,7′,8′-tetrafluoro-2*H*-chromene-annulated)bacteriochlorin *Z*-Isomer (13-*Z*). Bacteriochlorin tetraol **6-*Z*** (50 mg, 0.05 mmol) was, under N_2, dissolved in 50 mL of

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THF in a 100 mL round-bottom flask equipped with a magnetic stir bar. Excess NaH (~50 mg of a 60% emulsion in mineral oil) was added in portions. The reaction mixture was stirred for ~1 h at ambient temperature. The disappearance of the starting material was monitored by TLC. Once all starting material was consumed, the reaction was quenched by slow addition of a concd aq NH_4Cl solution, the mixture transferred into a separatory funnel, and the product extracted with CH_2Cl_2. The organic phase was evaporated to dryness by rotary evaporation. Upon reduction of the solvent, putative product **13-*Z*** precipitated as a highly insoluble greenish powder and isolated by filtration. UV−vis (CH_2Cl_2) λ_{max} (rel I) 407 nm (1.0), 434 (0.85), 591 (0.34), 688 (0.10), 756 (0.35) nm; HR-MS (ESI+, 100% CH_3CN) calcd for $C_{44}H_{11}F_{16}N_4O_4$ (MH^+) 963.0525, found 963.0536.

10,15,20-Bis(pentafluorophenyl)-(5′,6′,7′,8′-tetrafluoro-2*H*-chromene-annulated)-3-hydroxydimethoxymorpholinobacteriochlorin (15^{Me}). Triol **10-*Z*** (or **10-*E***, or a mixture of both) (50 mg, 4.89×10^{-5} mol) was dissolved in $CHCl_3$ (30 mL) at rt in a 50 mL round-bottom flask equipped with a magnetic magnetic stir bar, a N_2 inlet, and a bubbler and was shielded from ambient light with aluminum foil. Excess MeOH (~1.0 mL) was added, and the solution was purged with N_2. Silica−$NaIO_4$ (~0.3 g) was added to the stirring reaction mixture. Additional oxidant (~0.10 g) was added until all starting material was consumed (reaction monitored by TLC, ~ 12 h). Upon completion, the mixture was filtered (glass frit M) and the filter cake washed with $CHCl_3$. The filtrate was evaporated to dryness by rotary evaporation and was purified via preparative plate chromatography (silica−CH_2Cl_2/30% hexanes) to provide $\mathbf{15^{Me}}$ in 30% yield (15 mg) as a reddish pink solid. $\mathbf{15^{Me}}$: R_f (silica−CH_2Cl_2/10% hexanes) = 0.80; ^{1}H NMR (400 MHz, $CDCl_3$, δ) 8.68−8.64 (m, 1H), 8.04 (br dd, ^3J = 4.4, ^4J = 1.5 Hz, 1H), 7.95 (br dd, ^3J = 4.7, ^4J = 1.2 Hz, 2H), 6.36 (s, 1H), 6.33 (s, 1H), 6.20−6.15 (m, 2H), 3.21 (s, 3H), 3.08 (s, 3H), 2.86 (d, ^3J = 4.0 Hz, 1H), 0.39 (s, 1H), 0.19 (s, 1H) ppm; ^{19}F NMR (376 MHz, $CDCl_3$, δ) −135.9 (^3J = dd, 23.8, ^5J = 7.8 Hz, 1F), −136.3 (dd, ^3J = 23.8, ^5J = 7.5 Hz, 1F), −136.7 (dd, ^3J = 23.7, ^5J = 7.8 Hz, 1F), −137.0 (dd, ^3J = 23.7, ^5J = 7.4 Hz, 1F), −137.2 (dd, ^3J = 23.8, ^5J = 7.6 Hz, 1F), −138.5 (dd, ^3J = 23.9, ^5J = 7.5 Hz, 1F), −140.8 to −140.9 (m, 1F), −151.5 (t, ^3J = 20.9 Hz, 1F) −151.8 (q, ^3J = 20.0 Hz, 2F), −153.7 (t, ^3J = 21.0 Hz, 1F), −158.2 (dd, ^3J = 20.9, ^5J = 9.4 Hz, 1F), −160.5 (td, ^3J = 22.3, ^5J = 7.8 Hz, 1F), −160.8 to −161.1 (m, 4F), −161.5 (td, ^3J = 22.4, ^5J = 7.3 Hz, 1F), −162.4 (t, ^3J = 21.7, 1F) ppm; ^{13}C NMR (100 MHz, $CDCl_3$, δ) 154.8, 154.4, 147.5, 143.3, 137.2, 135.6, 134.0, 125.7, 123.4, 122.1, 103.7, 102.2, 102.1, 99.0, 95.8, 95.5, 83.0, 73.6, 54.6, 64.5 ppm; UV−vis (CH_2Cl_2) λ_{max} (log ε) 392 (5.27), 553 (4.84), 763, (4.74) nm; HR-MS (ESI+, 100% CH_3CN) calcd for $C_{46}H_{18}F_{19}N_4O_5$ (MH^+) 1067.0974, found 1067.0943.

10,15,20-Bis(pentafluorophenyl)-(5′,6′,7′,8′-tetrafluoro-2*H*-chromene-annulated)-3-hydroxydiethoxymorpholinobacteriochlorin (15^{Et}). Prepared in 20% yield (10 mg) as a reddish pink solid from triol **10-*Z*** or **10-*E*** (50 mg, 4.89×10^{-5} mol), excess EtOH (~1.0 mL), and silica−$NaIO_4$[39] (~0.3 g) as described for $\mathbf{15^{Me}}$: R_f (silica−CH_2Cl_2/10% hexanes) = 0.80; ^{1}H NMR (400 MHz, $CDCl_3$, δ) 8.69−8.65 (m, 1H), 8.08−8.06 (m, 1H), 7.99−7.96 (m, 2H), 6.53−6.52 (m, 1H), 6.42−6.41 (m, 1H), 6.24−6.21 (m, 1H), 6.19−6.17 (m, 1H), 3.60−3.55 (m, 1H), 3.49−3.43 (m, 1H), 3.33−3.28 (m, 2H), 2.91−2.88 (m, 1H), 1.06−1.00 (m, 3H), 0.94−0.90 (m, 3H), 0.29 (s, 1H), 0.08 (s, 1H) ppm; ^{19}F NMR (376 MHz, $CDCl_3$, δ) −135.8 (dd, ^3J = 23.8, ^5J = 7.8 Hz, 1F), −136.0 (dd, ^3J = 23.9, ^5J = 7.8 Hz, 1F), −136.4 (dd, ^3J = 23.7, ^5J = 7.7 Hz, 1F), −136.7 (dd, ^3J = 23.8, ^5J = 7.4 Hz, 1F), −136.9 (dd, ^3J = 23.8, ^5J = 7.6 Hz, 1F), −138.5 (dd, ^3J = 23.9, ^5J = 7.5 Hz, 1F), −140.8 (m, 1F), −151.7 (t, ^3J = 20.8 Hz, 1F), −151.9 (t, ^3J = 20.8 Hz, 1F), −153.9 (t, ^3J = 20.8 Hz, 1F), −158.3 (m, 1F), −160.6 (td, ^3J = 22.3, ^5J = 6.3 Hz, 1F), −161.0 to −161.2 (m, 3F), −161.4 (td, ^3J = 22.3, ^5J = 8.1 Hz, 1F), −161.6 to −161.7 (m, 1F), −162.5 (t, ^3J = 21.7 Hz, 1F) ppm; ^{13}C NMR (100 MHz, $CDCl_3$, δ) 154.9, 154.2, 147.3, 143.5, 136.9, 135.7, 134.7,134.2, 126.6, 126.5, 125.6, 123.5, 122.1, 103.9, 102.0, 101.9, 98.9, 94.7, 94.5, 82.9, 73.6, 63.3, 63.1, 14.7 ppm; UV−vis (CH_2Cl_2) λ_{max} (log ε) 392 (5.24), 553 (4.77), 755, (4.66) nm; HR-MS (ESI+, 100% CH_3CN) calcd for $C_{48}H_{22}F_{19}N_4O_5$ (MH^+) 1095.1287, found 1095.1300.

10,15,20-Bis(pentafluorophenyl)-(5′,6′,7′,8′-tetrafluoro-2*H*-chromene-annulated)-3-hydroxychlorolactone (1:0.7 Mixture of the 12-Oxa-13-oxo- and 13-Oxa-12-oxo-isomers I and II, Unknown Which Compound Is Which Isomer) (16). Route A: **10-*E/Z*** (50 mg, 4.89×10^{-2} mmol) was dissolved in a 50 mL round-bottom flask equipped with a stir bar in pyridine (2 mL). The mixture was treated with ~10 equiv of CrO_3 (50 mg, 0.5×10^{-3} mol. The flask was stoppered, shielded from light with aluminum foil, and stirred at ambient temperature. The disappearance of the starting material and appearance of the product was monitored by TLC. Once no further progress of the reaction was detectable (after ~30 min), 25 mL of CH_2Cl_2 was added, and the mixture was transferred into a 125 mL separatory funnel and extracted with water (3 × 25 mL). The organic fraction was separated with CH_2Cl_2 and filtered through a short plug of diatomaceous earth (Celite). The solvent was removed to dryness by rotary evaporation. A gentle stream of N_2 for several hours ensured that the crude material was thoroughly dried. The crude material was purified via flash chromatography (silica, CH_2Cl_2/50% hexanes). Product **16** was isolated in 47% yield (23 mg) as a purple solid. Route B: *meso*-Tetrakis(pentafluorophenyl)-2,3-dihydroxy-12-oxa-13-oxochlorin **17**[40] (40 mg, 4.03×10^{-5} mol) was dissolved in DMF (50 mL) in a 100 mL round-bottom flask equipped with a magnetic stir bar. It was heated to reflux for 40 min. The disappearance of the starting material was monitored by TLC and UV−vis spectroscopy. Once no further progress of the reaction was detectable, the solvent was removed in vacuo and the residue was dried under a gentle stream of N_2 for 1 d. The crude material was purified by preparative plate chromatography (silica−CH_2Cl_2/30% hexanes) to provide **16** as an inseparable mixture of two diastereomers in 30% (12 mg) yield as a red solid: R_f (silica−CH_2Cl_2/1% MeOH) = 0.88; ^{1}H NMR (400 MHz, $CDCl_3$, δ) 8.92 (ddd, $^6J_{H-F}$ = 9.7, ^3J = 5.2, ^4J = 1.6 Hz, $1H^I$), 8.82 (ddd, $^6J_{H-F}$ = 9.9, ^3J = 5.0, ^4J = 1.9 Hz, $0.7H^{II}$), 8.64 (br dd, ^3J = 4.9, ^4J = 0.5 Hz, $0.7H^{II}$), 8.56 (br dd, ^3J = 4.9, ^4J = 0.5 Hz, $1H^I$), 8.50 (br dd, ^3J = 4.7, ^4J = 1.1 Hz, $0.7H^{II}$), 8.46−8.43 (m, $1.7H^{I\&II}$), 8.20 (br dd, ^3J = 4.5, ^4J = 1.7 Hz, $1H^I$), 6.38−6.36 (m, $0.7H^{II}$), 6.33−6.31 (m, $1.7H^{I\&II}$), 6.27−6.26 (m, $1H^I$), 3.00 (br d, ^3J = 3.44 Hz, $0.7H^{II}$), 2.87 (br d, ^3J = 2.87 Hz, $1H^I$), −0.04 (s, $1H^I$), −0.06 (s, $1H^I$), −0.82 (s, $0.7H^{II}$), −0.85 (s, $0.7H^{II}$) ppm; ^{19}F NMR (376 MHz, $CDCl_3$, δ) −135.0 (dd, ^3J = 23.3 Hz, ^5J = 7.6 Hz, $0.7F^{II}$), −135.2 (dd, ^3J = 23.5, ^5J = 7.8 Hz, $1F^I$), −136.5 (dd, ^3J = 22.0, ^5J = 5.4 Hz, $0.7F^{II}$), −136.8 (dd, ^3J = 23.1, ^5J = 6.9 Hz, $1F^I$), −137.4 (dd, ^3J = 21.7, ^5J = 4.7 Hz, $1F^I$), −137.8 (dd, ^3J = 23.5, ^5J = 6.6 Hz, $0.7F^I$), −138.1 (td, ^3J = 24.9, ^5J = 6.6 Hz, $1.4F^{2xII}$), −138.3 to −138.4 (m, $1.7F^{I\&II}$), −138.6 (dd, ^3J = 23.7, ^5J = 7.0 Hz, $1F^I$), 139.5 (dd, ^3J = 23.3, ^5J = 6.5 Hz, $1.7F^{2xII}$), −140.5 (m, 1F), −150.5 (td, ^3J = 20.8, ^5J = 12.5 Hz, $1.6F^{I\&II}$), −150.7 (t, ^3J = 20.9, $0.7F^{II}$), −151.1 (t, ^3J = 20.9 Hz, $1F^I$), −151. Five (td, ^3J = 20.9, ^5J = 11.2 Hz, $1.7F^{I\&II}$), −152.5 (q, ^3J = 21.0 Hz, $1.7F^{I\&II}$), −157.8 (dd, ^3J = 20.9, ^5J = 9.5 Hz, $1F^I$), −158.2 (dd, ^3J = 20.9, ^5J = 9.4 Hz, $0.7F^{II}$), −160.0 to −160.3 (m, $1.6F^{I\&II}$), −160.6 to −161.1 (m, 5F), −161.4 to −161.7 (m, $4.4F^{I\&II}$), −162.0 (t, ^3J = 21.7 Hz, $0.7F^{II}$) ppm; ^{13}C NMR (100 MHz, $CDCl_3$, δ) 165.9, 162.9, 160.3, 157.9, 155.1, 153.7, 153.1, 141.5, 139.2, 138.9, 137.9, 135.3, 134.4, 128.7, 128.6, 128.4, 128.3, 126.8, 125.5, 125.3, 124.1, 124.0, 122.5, 110.7, 107.2, 106.3, 103.2, 100.6, 99.6, 90.5, 83.8, 82.6, 73.6, 73.1 ppm; UV−vis (CH_2Cl_2) λ_{max} (rel I) 413 (1.0), (0.06), 518 nm 554 nm (0.14), 638 (0.05), 700 (0.38) nm; HR-MS (ESI+, 100% CH_3CN) calcd for $C_{43}H_{10}F_{19}N_4O_4$ (MH^+) 1007.0397, found 1007.0364.

5,10,15,20-Tetrakis(pentafluorophenyl)-*cis*-2,3-dihydroxy-12-oxa-13-oxoporphyrin (17). Compound previously known only as osmate ester.[40] Porpholactone **15** (100 mg 1.0×10^{-4} mol) was dissolved in a 250 mL round-bottom flask equipped with a stir bar in $CHCl_3$ (125 mL) and freshly distilled pyridine (25 mL). The mixture treated with 1.2 equiv of OsO_4 (1.2×10^{-4} mol; 1.5 mL of a stock solution of 1.0 g OsO_4 dissolved in 50 mL of pyridine). (Caution: gloves, eye protection, and fume hood are necessary!) The flask was stoppered, shielded from light with aluminum foil, and stirred at ambient temperature. The disappearance of the starting material/appearance of the product was monitored by TLC and UV−vis spectroscopy. Once no further progress of the reaction was detectable (after ~24 h), approximately 50% of the solvent was removed by

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rotary evaporation. To the crude reaction mixture was added saturated MeOH/H_2O (1:1) solution of $NaHSO_3$ (40 mL). The flask was stoppered and wrapped in aluminum foil, and the biphasic solution was vigorously stirred at ambient temperature for 2 h, whereupon the mixture was transferred to a 125 mL separatory funnel. The organic fraction was washed with CH_2Cl_2 and filtered through a short plug of diatomaceous earth (Celite). The solvent was removed to dryness by rotary evaporation. A gentle stream of N_2 for several hours ensured that the crude material was thoroughly dried. The crude material was purified via flash chromatography (4 g silica–CH_2Cl_2/1.0% MeOH). After the recovery of the low polarity starting material **15** (5–10%), the second major fraction was diol **17**, isolated in 50–55% yield (48 mg) as a green solid: R_f (silica–CH_2Cl_2/1% MeOH) = 0.48; ^{1}H NMR (400 MHz, $CDCl_3$, δ) 8.68 (br d, ^3J = 5.1 Hz, 1H), 8.57 (br dd, ^3J = 4.7, ^4J = 1.7 Hz, 1H), 8.51 (br dd, ^3J = 4.9, ^4J = 0.3 Hz, 1H), 8.32 (br dd, ^3J = 4.6, ^4J = 1.3 Hz, 1H), 6.15–6.07 (m, 2H), 3.31 (d, ^3J = 7.5 Hz, 1H), 3.02 (d, ^3J = 7.2 Hz, 1H), −1.29 (s, 1H), −1.64 (s, 1H) ppm; ^{19}F NMR (376 MHz, $CDCl_3$, δ) −134.9 (dd, ^3J = 23.8 Hz, ^5J = 7.6 Hz, 1F), −135.2 (dd, ^3J = 23.8 Hz, ^5J = 7.5 Hz, 1F), −137.1 (overlaping dd, ^3J = 22.4 Hz, ^5J = 6.4 Hz, 2F), −138.7 (dd, ^3J = 23.5 Hz, ^5J = 7.0 Hz, 1F), −139.0, (dd, ^3J = 23.4 Hz, ^5J = 6.7 Hz, 1F), −139.4 (td, ^3J = 24.7 Hz, ^5J = 7.3 Hz, 2F), −150.5 (t, ^3J = 20.8 Hz, 1F), −151.4 to −151.6 (m, 3F), −160.8 (td, ^3J = 21.9 Hz, 7.1 Hz, 2F), −161.1 to −161.3 (m, 4F), −161.5 to −161.7 (m, 2F) ppm; UV–vis (CH_2Cl_2) λ_{max}/nm (log ε) 402 (5.32), 495 (4.08), 526 (3.85), 621 (3.8), 681 (4.70); HR-MS (ESI−, 100% CH_3CN) calcd for $C_{43}H_9F_{20}N_4O_4$ (MH^+) 1025.0304, found 1025.0310.

X-ray Single-Crystal Diffractometry. Details of the data collection and structural parameters for the structure elucidation of **14-*syn***, including CIF file, descriptions of disorder and hydrogen atom treatment, and software packages used, can be found in the Supporting Information. The crystallographic data have been deposited with the Cambridge Crystallographic Data Centre under no. CCDC 1429883. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b00273.

Reproduction of the UV–vis, fluorescence, and ^{1}H, ^{13}C, and ^{19}F NMR spectra of all novel compounds, experimental details for the crystal structure determinations of **14-*syn***, iand details for the computations (PDF)

X-ray crystallographic data for compound **14-*syn*** (CIF)

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Notes

The authors declare no competing financial interest.

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