Two-Phase Synthesis of Taxol[®]

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ABSTRACT: Taxol[®] is widely regarded as amongst the most famed natural isolates ever discovered, and has been the subject of innumerable studies in both basic and applied science. Its documented success as an anticancer agent, coupled with early concerns over supply, stimulated a furious worldwide effort from chemists to provide a solution for its preparation through total synthesis. Those pioneering studies proved the feasibility of retrosynthetically-guided access to synthetic Taxol, albeit in minute quantities and with enormous effort. In practice, all medicinal chemistry efforts and eventual commercialization have relied upon natural- (plant material) or biosynthetically-derived (synthetic biology) supplies. Here we show how a complementary divergent synthetic approach that is holistically patterned off of biosynthetic machinery for terpene synthesis can be used to arrive at Taxol[®].

Introduction

Taxol[®] (**1**, Figure 1) stands with penicillin as among the most famous natural products to be used in a clinical setting.[1] Registering >$9 billion in sales between 1993 and 2002[2] for use as an anticancer agent, Taxol is still prescribed today in generic form, and alternative formulations such as Abraxane[®] (albumin-bound) have generated >$5.5 billion in revenue as of January 2020.[3] Numerous other taxanes have either been approved by the FDA, or are in various stages of clinical development.[4–6] The storied history of Taxol in society began in ancient times and has been narrated in numerous books and reviews.[1,7–10] After the molecule's iconic structure was fully elucidated in 1971,[11] and clarity regarding its unique mechanism of action was revealed in 1979,[12] numbers of clinicians, formulations experts, biologists, and chemists contributed to its eventual use as a life-saving medicine in 1992.[13] Taxol has stimulated research in nearly all branches of chemical science, including medicinal, natural product, engineering, chemical biology, biochemistry, and last but not least, synthetic organic. Historically, the clinical use of **1** relied exclusively on semisynthesis,[14,15] both for the preparation of analogs (from **2**), and as the initial commercial source before the advent of a synthetic biology-based route using plant-cell cultures.[16,17]

Structurally, this heavily-oxygenated polycyclic diterpenoid presents a monumental challenge for total synthesis due to the dense orientation of functionality that render precise and predictable manipulations difficult. Any route to such a molecule must address the issue of a conformationally flexible central eight-membered ring system, which makes the neighboring reactivity of various functional groups unpredictable and substrate-dependent. In addition, the congested array of similarly-reactive secondary alcohols creates

a chemoselectivity puzzle of the highest magnitude. In the early 1990's, at least 30 teams[18] competed for the crown of finishing the synthesis first, and all completed syntheses, regardless of date, have been deservingly heralded as major (even "herculean")[1] accomplishments in the annals of organic chemistry. A relatively concise totally synthetic approach to **1** has been widely viewed as impossible, with one textbook (published in 2007) declaring that "…even an academic-type synthesis of **1** poses a major challenge, unlikely to be solved by a preparation under 30 or 40 steps in length".[9] This prediction had so far proven true, as ten distinct syntheses have been disclosed (from 1994 to 2015),[19–31] involving the effort of more than 150 chemists, to arrive at syntheses traversing through 36 to 59 isolated intermediates. Of those, seven have reported totally synthetic approaches and three have described formal syntheses that intercept known intermediates. Collectively, these efforts have resulted in the preparation of approximately 0.039 g of **1**, which sits in stark contrast to the metric ton quantities prepared yearly through plant-derived sources. Of relevance to the current study, actual taxanes (compounds containing the full carbon skeleton) are not accessed in those syntheses until late in the sequence. The difference between both the wondrous efficiency and diversity of taxanes accessed through Nature's enzymatic machinery (biosynthesis)[32] and the most valiant efforts of human chemists in the laboratory is rather striking. From a strategic perspective, three of these syntheses used naturally-occurring terpene starting materials,[19,20,23,24,27] six of them fused two chemically synthesized six-membered ring systems to form the central eight-membered ring,[21,22,25,27–31] and one built out by double annulation onto an already-constructed eight-membered ring.[26] Although these approaches follow the canonical rules of retrosynthetic analysis and establish the feasibility of accessing specifically **1**, none of them enabled divergency in their

1

retrosynthetic design that could be developed into a blueprint for future analogue exploration. The goal of this study, initiated in 2007, was to answer to a fundamental question of whether an approach to terpene synthesis loosely patterned on the logic of biosynthesis, would enable a hypothetical medicinal chemistry approach to taxanes in the absence of a viable semisynthetic option. Herein we present the realization of our ultimate goal: a two-phase synthesis of Taxol[®] (**1**).
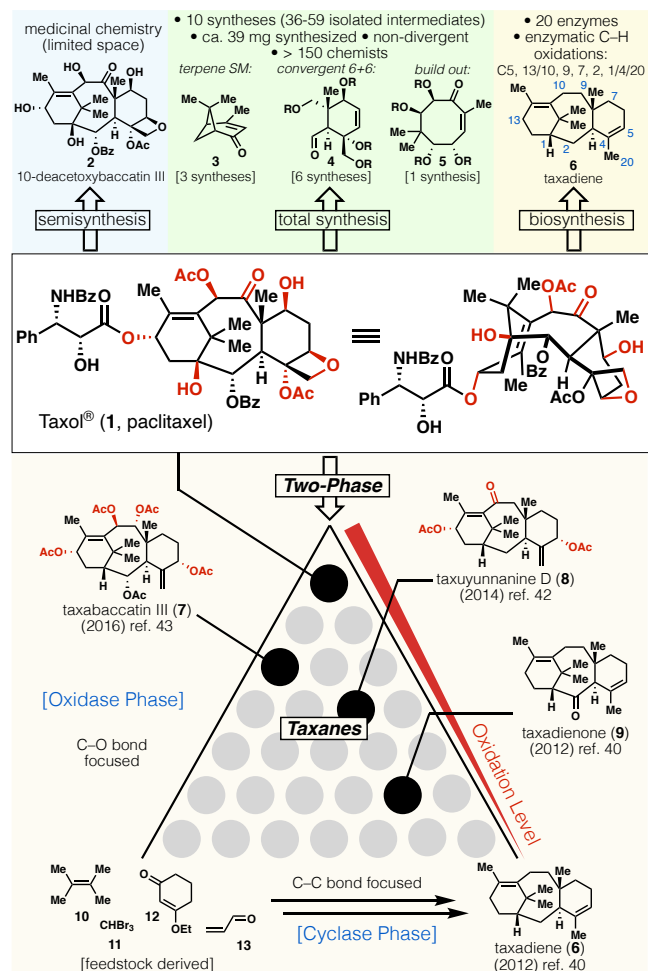

Figure 1. Approaches to the synthesis of Taxol (**1**): Semi-synthesis, canonical total synthesis, biosynthesis, and two-phase synthesis (this work).

Nature's route to complex terpenes is well-documented and enlists two conceptually different types of enzymes[32,33]. The first class of enzymes (cyclases) forges C–C bonds to generate complex hydrocarbon-based frameworks in what is known as a "cyclase-phase". These minimally oxidized terpenes are then processed by a second set of enzymes that install C–O bonds in what is known as an "oxidase-phase". This ingenious synthetic plan, despite being linear rather than convergent, benefits

strategically from near-perfect redox economy and ideality. Divergent access to analogs is encoded into this logic, as each oxidative event during the oxidase-phase potentially gives rise to different bioactivity; thus, the oxidase-phase represents a superb medicinal chemistry machinery from an evolutionary standpoint. It therefore stands to reason that mimicking this route in a chemical synthesis for structures as complex as **1** could harbor similar inherent advantages, unlike the clearly abiotic synthetic approaches to **1** that have been reported to date. In 2009, we disclosed a proof-of-concept to efficiently access highly oxidized terpenes that holistically mimics this underlying logic of biosynthesis.[34] Two-phase terpene synthesis logic, despite lacking convergency, could be applied to concise syntheses of complex systems such as ingenol,[35] phorbol,[36] thapsigargin,[37] and others.[38,39]

Application of this strategy to the taxanes, with **1** residing at the apex of terpene-based structural complexity, remained aspirational for the past decade. This can be visualized in Figure 1, with a hypothetical retrosynthetic pyramid for the two-phase synthesis of **1** requiring a chemist to navigate no less than nine different C–O bond forming steps from a minimally oxidized taxane precursor such as taxadienone (**9**). Initial progress towards this goal was registered in 2012 with the scalable synthesis of enantiopure **9** and taxadiene (**6**) through a concise cyclase-phase.[40] Although bioengineering approaches to **6** are known,[41] our laboratory has been a primary supplier of this molecule to numerous groups around the world (eight as of this writing). Extensive studies were then performed to decipher the innate reactivity of **6** towards allylic oxidation (installation of C–5, 10, and 13) culminating in the total synthesis of taxuyunnanine D (**8**).[42] Translating those lessons to the total synthesis of taxabaccatin III (**7**) via **9** was successful.[43] As aforementioned, the vexing arrangement of oxygenation required more than a consideration of chemo-, regio-, and stereoselectivity which Nature mastered using eons of evolution with enzymes. Scheme 1 outlines a route to **1** that overcomes such challenges.

Two-phase synthesis of Taxol[®]

Starting from simple feedstock-derived building blocks **10-13**, the cyclase-phase published in 2012[40] underwent significant optimization and was initially accomplished using flow chemistry by AMRI to deliver multigram quantities of **14**.[44] Subsequently, our collaborators (Chemveda) improved this route through the following modifications (see SI for full summary and graphical procedure): (i) use of alternative solvents for extracting volatile intermediates to simplify workup; (ii) replacement of *s*-BuLi with less expensive *n*-BuLi; (iii) use of a more easily-accessible ligand to set the stereochemistry; (iv) development of an operationally-convenient and reproducible enolate trapping sequence; (v) shorter reaction time; and (vi) development of a simple recrystallization protocol for purification.
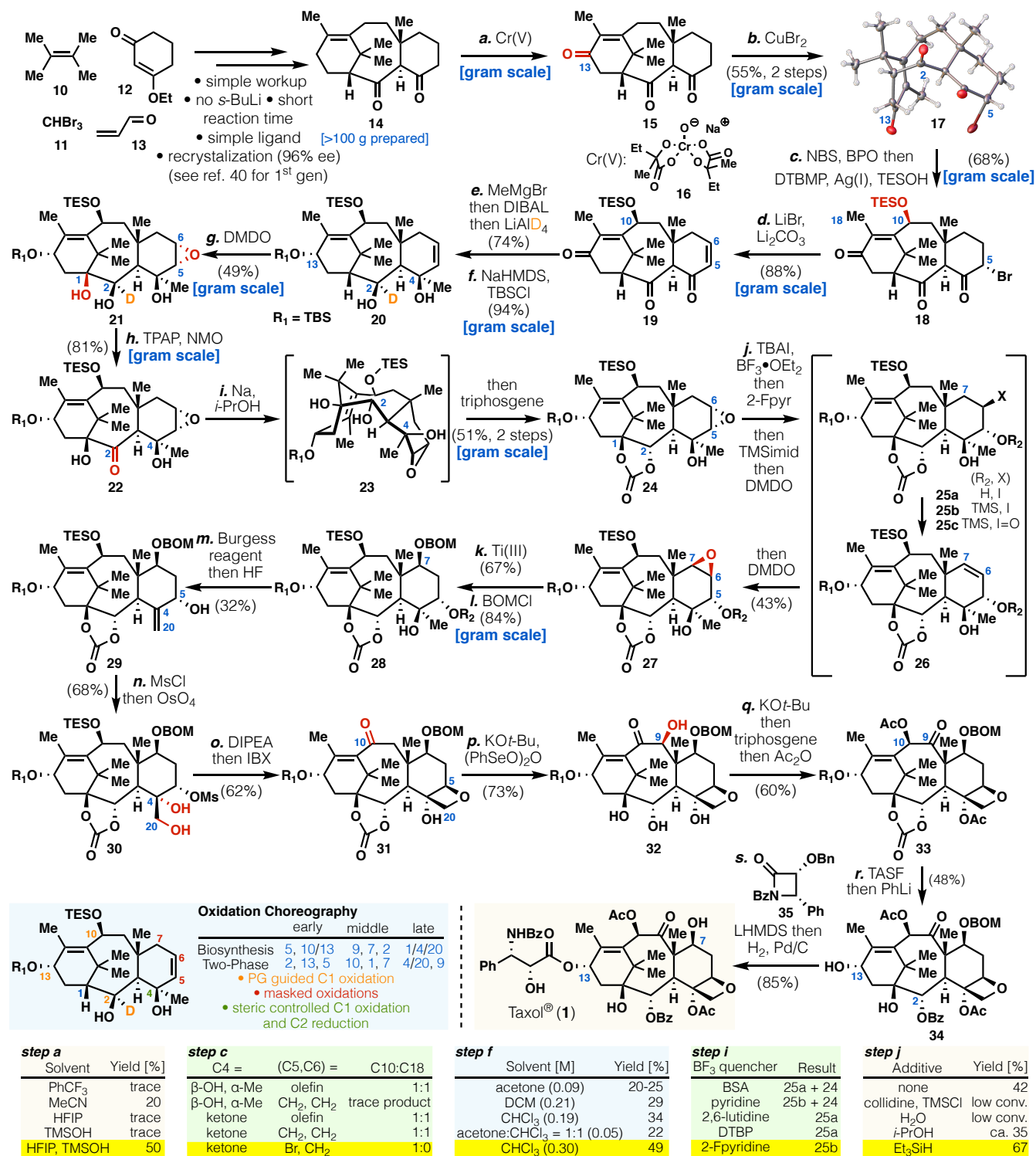
Scheme 1. Two-phase synthesis of 1. Reagents and conditions are as follows. (a) Cr(V) (**16**), HFIP, TMSOH, *t*-BuOH, 80 ºC. (b) CuBr₂, THF, rt, 55%, over 2 steps. (c) NBS, BPO, CCl₄, then DTBMP, AgOTf, TESOH, 4Å MS, PhMe, rt, 68%. (d) LiBr, Li₂CO₃, DMF, 100ºC, 88%. (e) MeMgBr, DCM, 0 ºC to rt, then DIBAL, -78 ºC, DCM, then LiAlD₄, THF, 60 ºC, 74%. (f) NaHMDS, TBSCl, THF, 0 ºC to rt, 94%. (g) DMDO, 0 ºC, 49%. (h) TPAP, NMO, DCM, rt, 81%. (h) Na, *i*-PrOH, Et₂O, rt, then triphosgene, pyr, DMAP, DCM, -78 to 0 ºC. (j) TBAI, BF₃•OEt₂, DCM, -78 ºC, then 2-Fpyr, -78 ºC, then TMSIm, rt, then DMDO, -78 ºC to rt, 43%. (k) Cp₂TiCl, Et₃SiH, THF, -78 ºC to rt, 67%. (l) BOMCl, TBAI, DIPEA, DCE, 45 ºC, 84%. (m) Burgess reagent, PhMe, dioxane, then HF, H₂O, pyr, MeCN, rt, 32%. (n) MsCl, pyr, 0 ºC to rt, then OsO₄, THF, pyr, 0 ºC to rt, 68%. (o) DIPEA, PhMe, then IBX, DMSO, H₂O, 80 ºC, 62%. (p) KO*t*-Bu, (PhSeO)₂O, THF, H₂O, -78 to 0 ºC, 73%. (q) KO*t*-Bu, THF, then triphosgene, pyr, DMAP, DCM, -78 to 0 ºC, then Ac₂O, DMAP, pyr, rt, 60%. (r) TASF, THF, rt, then PhLi, THF, -78, 48%. (s) β-lactam (**35**), LHMDS, THF, -78 ºC

to rt, then Pd/C, H$_2$, EtOH, 80 ºC, 85%.; HFIP, hexafluoroisopropanol; TMSOH, trimethylsilanol; NBS, *N*-Bromosuccinimide; BPO, benzoyl peroxide; DTBMP, 2,6-Di-tert-butyl-4-methylpyridine; TESOH, triethylsilanol; DIBAL, diisobutylaluminium hydride; HMDS, hexamethyldisilazane; TBSCl, *t*-butyldimethylsilyl chloride; DMDO, dimethyldioxirane; TPAP, tetrapropylammonium perruthenate; NMO, *N*-methylmorpholine *N*-oxide; pyr, pyridine; DMAP, 4-dimethylaminopyridine; TBAI, tetra-*n*-butylammonium iodide; 2-Fpyr, 2-fluoropyridine; TMSIm, *N*-(trimethylsilyl)imidazole; Cp$_2$TiCl, bis(cyclopentadienyl)titanium(iii) chloride; BOMCl, benzyl chloromethyl ether; DIPEA, *N*,*N*-diisopropylethylamine; DCE, 1,2-dichloroethane; MsCl, methanesulfonyl chloride; IBX, 2-iodoxybenzoic acid; TASF, tris(dimethylamino)sulfonium difluorotrimethylsilicate.

In this way, *ca*. 110 grams of **14** were prepared in a simple batch protocol. Lessons from previous studies on the selective C–H activation of allylic C–H bonds in the taxane core suggested that oxidation at C–13 would be feasible. It was found that the solvent played a decisive role in controlling the regioselectivity (as three allylic positions can be oxidized) and conversion to enone **15** using the Cr(V)-based oxidant **16**.[42,45] As shown in the inset table for step a, a mixture of HFIP/TMSOH (2:1) was utilized to afford **15**, which could be carried on directly to the next reaction with minimal purification. This tri-carbonyl-bearing scaffold was selectively brominated at C–5 rather than C–1, C–3, C–10, or C–14 using CuBr$_2$, delivering **17** (whose structure was undoubtably confirmed by X-ray crystallography) in 55% isolated yield (19-gram scale). Bromination at this stage was essential, as it served as a placeholder for the eventual C–5 and C–7 oxidations and also drove subtle conformational shifts that enabled complete selectivity in the ensuing C–H allylic oxidation at C–10 (see inset table for step c, and SI for discussion). Radical-based oxidation of C–10 took place smoothly following our 2014 protocol,[42] proceeding through a dibromide (C–5/10) that could be selectively displaced at C–10 with TESOH in the presence of Ag(I) to deliver **18** in 68% isolated yield (gram-scale). Elimination of the C–5 bromide under standard conditions (LiBr/Li$_2$CO$_3$) afforded di-enone **19** in 88% isolated yield on gram-scale. To set the stage for the pivotal C–1 oxidation, the last carbon atom of the taxane core was installed, the C–13 stereochemistry was set, and a deuterium atom was strategically placed onto C–2; that is, taxane **20** was produced from **19** by sequential addition of MeMgBr and DIBAL (to reduce C–13), and then LiAlD$_4$ (to reduce C–2) followed by TBS installation in 67% yield over two transformations (gram-scale). The remarkable site-selectivity in functionalizing **19** was enabled by exploiting the unique steric and electronic features associated with each carbonyl group. A complex matrix of experiments across multiple taxanes (see SI) revealed substrate **20** to be ideally suited to chemo- and stereoselective oxidation events using DMDO in step g to deliver epoxy-triol **21** in 49% yield as a single diastereomer (gram-scale). The solvent (CHCl$_3$, which presumably enhances the reactivity of DMDO through H-bonding) and concentration choice were essential (see inset table for step g)[46,47] as was the precise functionality expressed in taxane **20**. Thus, if C–2 bearing alcohol did not have the β-stereochemistry (presumably prevents C–2 from directing oxidation elsewhere)[48] and α-deuterium incorporation, or if C–4 did not bear full substitution, rapid oxidation back to the C–2 ketone took place with little to no observable hydroxylation at C–1 (see SI).

The second half of the synthesis began with TPAP-mediated oxidation of C–2 (**22**, 85% isolated yield, gram-scale). Thermodynamic reduction of the ketone using Na/*i*-PrOH followed by addition of triphosgene to epoxy-triol **23** furnished carbonate **24** in 51% isolated yield (gram-scale) with the C–5/6 epoxide left completely unscathed. As with the oxidation in step g, the stereochemistry and right balance of sterics at C–4 again played an important role in enabling this outcome, presumably due to its staggered conformation relative to the C–2 α-keto radical intermediate during the reduction. The stage was now set for a redox-relay event to stereoselectively install the C–7 oxygen atom. This maneuver was achieved without isolation of unstable intermediates in one-flask through a carefully designed sequence involving the addition of orthogonally reactive and volatile reagents. In the event, taxane **24** was exposed to TBAI/BF$_3$•OEt$_2$ to regioselectively (*via* stereoelectronic guidance) afford the corresponding iodohydrin **25a**, followed by addition of 2-fluoropyridine to sequester boron-salts (the use of unsubstituted pyridine returned **24**). As indicated in the inset table, the use of other additives and alternative bases led to low yields, stemming from incomplete reaction (**26**) and/or reformation of **24**. Immediate capping at C–5 with a TMS group (TMS-imidazole), followed by addition of DMDO, led to iodine-oxidation and spontaneous *syn*-elimination of iodoso **25c** to liberate olefin **26**, which could be further stereoselectively oxidized to epoxy-taxane **27** in 43% isolated yield. Elimination through **25c** was essential, as E2-elimination of the corresponding iodide **25b** did not take place due to steric hindrance around C–7. It is important to note that this sequential addition design proved to be essential in practice, as **25a** was found to revert to **24** upon isolation. Ti-mediated, sterically-guided, regioselective reductive lysis of the epoxide in the presence of Et$_3$SiH followed by BOM installation proceeded in 56% isolated yield to furnish **28** (gram-scale). The use of triethyl silane as reductive quenching agent in Ti-mediated epoxide reduction is, to the best of our knowledge, without precedent, and increased both the yield and robustness of the transformation (see inset table for step j). The tertiary alcohol at C–4, which played a pivotal role in numerous transformations, was dismantled through Burgess dehydration, followed by addition of HF•py to afford allylic alcohol **29** in 32% yield. Next, the C–5 hydroxyl group was activated with MsCl and the resulting allylic mesylate (which could not be isolated due to its instability) was immediately subjected to dihydroxylation using OsO$_4$ to deliver oxetane-precursor diol **30** in 68% isolated yield. Oxetane formation was achieved using a hindered amine base (DIPEA), and subsequent addition of IBX directly oxidized the C–10 allylic -OTES group to the C–10 enone, forming **31** in 62% isolated yield. C–9 oxidation took place first, using a modification of Holton's conditions[20] (KO*t*-Bu and water/(PhSeO)$_2$O) to deliver **32** (with the cyclic carbonate cleaved) in 73% yield. Redox-isomerization (KO*t*-Bu) and quadruple acylation to reinstall the cyclic carbonate and acetylate C–4/10 proceeded smoothly to afford taxane **33**. Tandem desilylation at C–13 and addition of PhLi gave rise to baccatin III bearing a BOM group at C–7 (**34**) in 48% isolated

yield. The total synthesis of **1** could be completed by Ojima-acylation[49] using β-lactam **35** and the Li-alkoxide of **34**, followed by hydrogenation in 85% isolated yield. The use of **35**, which has not been utilized in the context of taxane synthesis before,[50] enabled more direct access to **1**. This sequence could be performed through the isolation and purification of 22 intermediates and has been used to prepare 35.2 mg of **1**.

Discussion

It is worth contrasting the strategy employed in Nature with the pioneering syntheses that preceded this work. As aforementioned, the biological two-phase approach to **1** is rather linear, requiring no fewer than 20 different enzymes (2 in the cyclase-phase and 18 in the oxidase-phase).[32,33,51] Each transformation takes place in high yield and intermediates are individually sequestered leading to incredible efficiency and scalability. Conventional retrosynthetic analysis would teach that a more convergent approach to **1** should be a better solution for procurement in the laboratory. Perhaps in the future, newly designed convergent approaches will prove optimum. Yet, as history has proven, such designs so far did not succeed in meaningfully adding to either the supply of **1** or as a practical approach for medicinal chemistry explorations. The former issue stems from the sheer number of manipulations required by all syntheses (including our work) and the latter results from the fact that taxanes (compounds bearing the complete carbon skeleton) are not accessed until late into those syntheses, an issue the present approach overcomes. To be sure, of the 10 syntheses reported, actual taxanes are only accessed after isolation of as few as 19 intermediates,[21] and as many as 37.[26] Such issues cannot be resolved by creative engineering solutions, as Takahashi has shown with the fully automated formal synthesis of **1** that delivered 0.0001g of baccatin III after 44 transformations.[27] While the current synthesis offers no benefit in terms of overall yield, it does however provide a conceptual blueprint for how a viable medicinal chemistry evaluation could take place without semi-synthetic approaches. Furthermore, since multigram quantities of the full taxane skeleton are accessed at a very early stage (step e), this could serve as a new platform for further analogue synthesis combined with the known structure-activity relationships of **1** (as demonstrated with **6**, **7**, and **8**).[52,53] Since taxanes only exhibit useful bioactivity when a C–13 sidechain is present, it is notable that our route mirrors biosynthesis in that the proper oxidation is installed at C–13 very early in the synthesis (step a) rather than at a late-stage as in most of the past routes (see Scheme 1 oxidation choreography for a summary). The strategic advance of this two-phase retrosynthesis is reinforced by the fact that all of the methods employed to access **1** were, in principle, known and available to past practitioners. The robust nature of these reactions ensured that two-thirds of the transformations in this synthesis could be conducted on a gram-scale.

Conclusion and Outlook

It is worth recounting some of the key lessons, tactics, and maneuvers that enabled the current route to **1**. As with the biosynthetic two-phase approach, this synthesis focuses mostly on the oxidase phase and thus the precise choreography of *O*-installation was critical not only to access the target. C–2 was chosen as the first oxygenation not only due to the

retrosynthetic simplification it enabled during the cyclase phase but also because of its critical role in bioactivity.[52] Oxidation of C–13, 5 and 10 gave the best material throughput in this order. These oxidations were rapidly completed based on our previous work[42,43] and failed attempts (see SI) to the stage for the key C–1 oxidation. The challenge of installing C–1 and C–7 could be addressed in unison through careful selection of neighboring functionality and redox-relay through a C–5/6 epoxide group. The C–7 oxidation state was installed through a carefully designed redox relay originating from the C–4 ketone, the C–5 bromide, the C–5/6 epoxide, the C–6 iodide, the $\Delta^{6,7}$-olefin, the C–6/7-epoxide, and finally to the C–7 alcohol. As the supporting information detail, multiple generations of strategies were evaluated before finalizing this pathway. This is clearly a weakness of the two-phase design with regards to one of the most densely functionalized terpenes known. In biosynthesis, enzymatic hydroxylation events accomplished through eons of evolution don't necessitate protecting groups or functional group manipulations and are largely impervious to subtle substrate modifications. C–4 and C–20 benefited from simple dihydroxylation of an olefin, and the pioneering work of Holton[20] guided the final C–9 oxidation (and stereochemistry thereof).

While this synthesis does employ protecting groups (C–5, C–7, C–10, and C–13) their effect was maximized by strategic selections and allocations so that analogous functional groups were well differentiated throughout the synthesis – e.g. simultaneous installation of an –OTES group upon C–H oxidation (C–10) or tandem removal during oxidation (C–10) in the presence of –OTBS (C–13). The silyl groups at C–13 and C–10 did play a pivotal role in shielding the bridgehead olefin from oxidation. Unconventional means of protecting functionality and directing reactivity were also employed including the use of deuterium (kinetic isotope effect) at C–2,[54] a bromine atom at C–5, a tertiary alcohol at C–4, and an epoxide at C–5/6. The dense functionality innates to **1** enabled unique positionally selective reactions such as the reactivity of a tricarbonyl (step e), the oxidation at C–1 (step g), and the stability and reactivity of epoxide intermediates (steps h-j). Reactive intermediates (c, j, n, and q) could also be utilized through consecutive operations in order to achieve challenging transformations with minimal labor.

As aforementioned, we began our campaign to access Taxol® (**1**) to answer a fundamental thought-experiment: Would a holistically-biomimetic approach enable an unified medicinal synthetic campaign involving divergent access to natural and non-natural taxanes at various oxidation patterns? In one sense, if **1** were pursued by a large pharma company in the absence of a natural supply, this route would indeed enable such a study (where mg quantities of each analog are needed). On the other hand, the blueprint laid out herein, required deeply-choreographed empirically derived manipulations unique to each substrate's reactivity. Thus, extensive effort would be required and process chemists might choose a different path to the final target. At the end of the day, chemical synthesis to *specifically* access **1** will likely never be competitive with a fully enzymatic approach. To avoid unnecessary concession steps that beleaguer all syntheses of **1**, we predict that far more improved medicinal chemistry-based approaches to novel taxanes could be accomplished using a hybrid approach that

employs synthesis to generate carbon frameworks (for example containing unnatural motifs) and enlists synthetic biology for chemo- and site-specific oxidations. In the meantime, the present synthesis demonstrates that two-phase synthesis can open the possibility of divergent access to taxanes, in contrast to classical synthetic strategies.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website.

Detailed experimental procedures and analytical data (PDF)

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GRAPHICAL ABSTRACT

- Divergent, two-phase strategy
- Site-selective C–H [O]
- 22 isolated intermediates