corresponding halides. The use of CCl_4 and $CBrCl_3$ as radical traps for the present study proved unfeasible as did the use of thiols and Bu_3SnH because **1** was observed to react directly with these traps in the absence of CO.

For the binuclear A-frame complex **1**, the present study, including crossover and spin-trapping results, shows that two different mechanisms are operative in carbonylation, leading to acetone and butanedione as in eq 1. The system is extraordinarily sensitive to CO pressure for product selectivity. At low CO pressure (60 Torr), an intramolecular pathway to acetone formation involving methyl acetyl intermediates predominates, whereas at only slightly higher CO pressure (760 Torr), a radical process from a symmetrical diacetyl intermediate leads to 2,3-butanedione.

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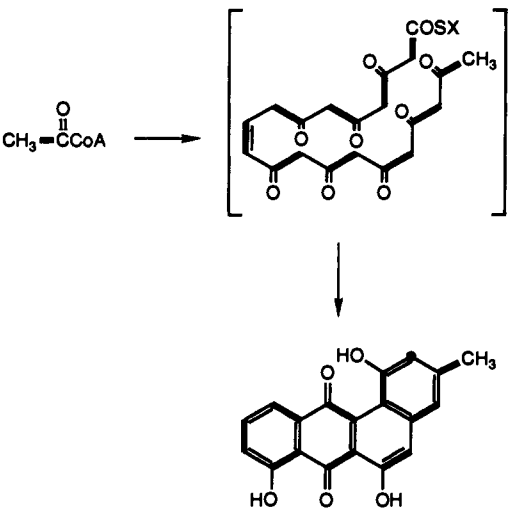
Scheme I



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Biosynthesis of the Benz[*a*]anthraquinone Antibiotic PD 116198: Evidence for a Rearranged Skeleton

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In the past 10 years the number of recognized naturally occurring benz[*a*]anthraquinones, a previously rarely encountered ring system,[1-5] has grown dramatically.[6] Three biosynthetic studies[7-10] have so far been reported, each describing a straightforward polyketide origin via derivation from a decaketide intermediate, as typified by dehydrorabelomycin, **1** (Scheme I).[9-11] We now report that the biosynthesis of the benz[*a*]anthraquinone antibiotic PD 116198, **2**, is via a decaketide polyketide derived by a novel, unexpected rearrangement of an apparent *linear* tetracyclic intermediate.

Table I. ^{13}C NMR Spectrum of PD 116198 and Incorporation of [^{13}C]Acetates

carbon	chemical shift, ppm	2a % ^{13}C[a]	2b $^1J_{CC}$, Hz
1	206.3	1.10	40.4
2	82.8	7.80	40.4
3	76.1	1.01	38.9
4	44.0	8.63	
4a	76.9	1.01	37.3
5	147.3	10.40	66.5
6	117.1	1.70	66.5
6a	138.5	6.40	52.6
7	189.0	1.21	52.7
7a	115.9	6.08	64.1
8	161.9	1.10	63.5
9	124.8	11.10	57.8
10	137.1	1.70	57.8
11	119.3	8.56	61.9
11a	133.0	0.97	61.7
12	183.4	8.56	54.1
12a	139.1	1.04	54.9
12b	77.5	6.71	37.3
13	22.4	9.61	38.8

[a] Normalized to C-8 resonance.

Spores of *Streptomyces phaeochromogenes* WP 3688, known to produce PD 116198,[12] were used to innoculate a seed broth[13] (50 mL/500-mL Erlenmeyer flask), which was incubated at 28 °C/250 rpm for 48 h. A portion of this was used to innoculate (2% v/v) production broths[13] (150 mL/1-L Erlenmeyer flask), and these were similarly incubated for 40 h. Workup involved acidification to pH 2 (1 N HCl), addition of EtOAc, and filtration over Celite. The mycelial mat was washed successively with water, EtOAc, and water. The EtOAc phases were combined, and the combined aqueous phases were extracted with additional EtOAc. After drying (Na_2SO_4) and concentrating in vacuo, the crude residue (1.6 g/1800 mL fermentation) was applied to a column

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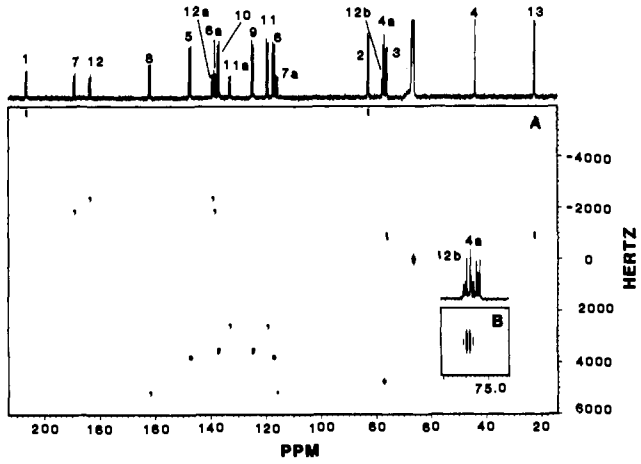
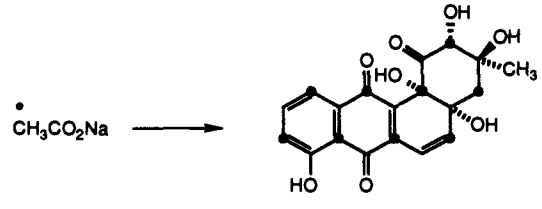


Figure 1.

of Silicar CC-4.[14] The column was eluted with CH_2Cl_2, 10% EtOAc/CH_2Cl_2, and 35% EtOAc/CH_2Cl_2. **2** eluted in the last fraction and was further purified by flash chromatography (SiO_2), eluting with 20% EtOAc/CH_2Cl_2, and then recrystallized from EtOAc (148 mg, mp 216-218 °C dec).

The data obtained by workers at Warner-Lambert yielded a structure, exclusive of stereochemistry, identical with yoronomycin.[13] Through a series of 1D and 2D NMR experiments (including LR-HETCOSY,[15] difference NOE, and NOESY), we have confirmed the structure of **2** and determined its relative stereochemistry, as shown.[16]

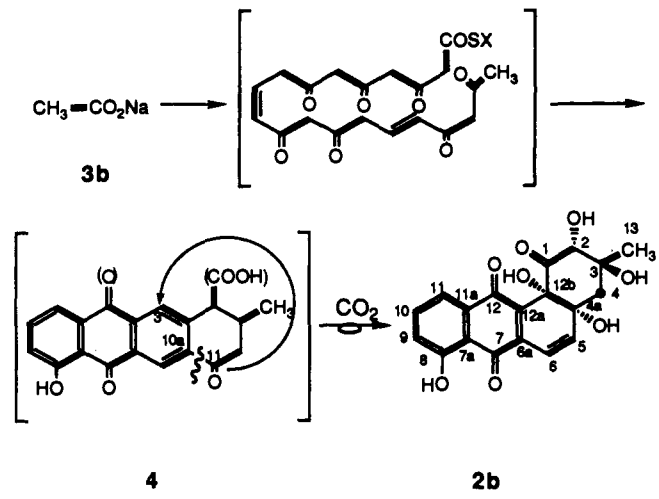
Initial biosynthetic experiments with tracer amounts of sodium [2-^{14}C]acetate fed to production broths at 18 h, alone and mixed with unlabeled acetate, established conditions for feedings of acetate labeled with stable isotopes. Sodium [2-^{13}C]acetate (481 mg), **3a**, mixed with sodium [2-^{14}C]acetate (0.5 μCi), was fed to two production broths. The crude product (138 mg) was purified as described to yield 9.5 mg of **2a** (1.6% incorporation of **3a**), which was analyzed by ^{13}C NMR spectroscopy (100.6 MHz, dioxane-d_8),[17] yielding the labeling pattern indicated in Table I. Based on a 25% recovery of the **2a**, an average enrichment of 9.2% was anticipated.[18]



3a **2a**

The labeling pattern of **2a** was consistent with the paradigm represented by Scheme I. To confirm this, Na[1,2-$^{13}C_2$]OAc, **3b**, was next fed. A total of 721 mg of **3b**, mixed with 0.65 μCi of Na[2-^{14}C]OAc, was fed to three production broths, and this yielded 10.7 mg of pure **2b** (1% incorporation of **3b**). The ^{13}C NMR spectrum (Figure 1) of **3b** showed 18 resonances with doublets flanking the natural abundance singlets, indicating nine intact precursor acetate units, and one lone enriched singlet. However, contrary to expectations, the singlet was due to C-4, and on the basis of pairing resonances from their J_{CC} values (Table I), the D-ring labeling pattern was clearly inconsistent with Scheme I! The coupling patterns for C-4a and C-12b were not first order, due to the closeness of their chemical shifts (76.9 and 77.5 ppm, respectively), and were diagnostic for their being coupled to each other. The correctness of all the assigned pairings was confirmed by both ^{13}C{^{13}C}COSY and ^{13}C 2D INADEQUATE (spectrum shown in Figure 1) experiments.

Scheme II



4 **2b**

PD 116198 clearly is not derived by a simple folding and condensation of a decaketide directly to the angular benz[*a*]-anthraquinone skeleton. This is in direct contrast to the pathway previously reported for three other benz[*a*]anthraquinones.[7-10] The data presented here are consistent with initial condensation to a linear tetracyclic structure, schematically represented by **4**, and subsequent cleavage of the C-10a/C-11 bond (between two precursor acetates) followed by bond formation between C-3 and C-11 (Scheme II). A more detailed understanding of this unusual pathway is being pursued.

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(18) The average ^{13}C enrichment per position was 7.3%.

A Catalytic Method for the Reduction of Esters to Alcohols†

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While transition-metal catalysis has been successfully applied to the hydrosilylation of olefins, alkynes, and many carbonyl compounds,[2] the hydrosilylation of esters remains relatively unknown. Investigations using γ-irradiation[3a] and metal halides such

† This paper is dedicated to our friend and colleague Professor K. Barry Sharpless on the occasion of his 50th birthday.
(1) (a) National Science Foundation Predoctoral Fellow, 1989-1992. (b) Recipient of a fellowship from the Division of Organic Chemistry of the American Chemical Society, sponsored by the Dow Chemical Company.
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