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Structure and Stereospecificity of the Dehydratase Domain from the Terminal Module of the Rifamycin Polyketide Synthase

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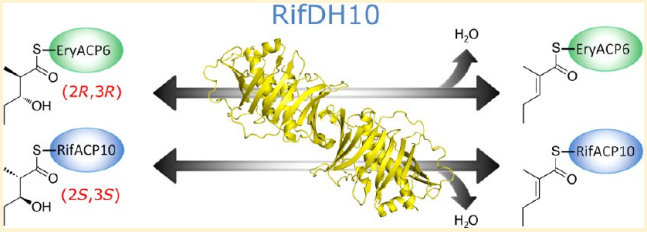
Supporting Information

ABSTRACT: RifDH10, the dehydratase domain from the terminal module of the rifamycin polyketide synthase, catalyzes the stereospecific *syn* dehydration of the model substrate (2*S*,3*S*)-2-methyl-3-hydroxypentanoyl-RifACP10, resulting in the exclusive formation of (*E*)-2-methyl-2-pentenoyl-RifACP10. RifDH10 does not dehydrate any of the other three diastereomeric, RifACP10-bound, diketide thioester substrates. On the other hand, when EryACP6, from the sixth module of the erythromycin polyketide synthase, is substituted for RifACP10, RifDH10 stereospecifically dehydrates only (2*R*,3*R*)-2-methyl-3-hydroxypentanoyl-EryACP6 to give exclusively (*E*)-2-methyl-2-pentenoyl-EryACP6, with no detectable dehydration of any of the other three diastereomeric, EryACP6-bound, diketides. An identical alteration in substrate diastereospecificity was observed for the corresponding *N*-acetylcysteamine or pantetheine thioester analogues, regardless of acyl chain length or substitution pattern. Incubation of (2*RS*)-2-methyl-3-ketopentanoyl-RifACP10 with the didomain reductase-dehydratase RifKR10-RifDH10 yielded (*E*)-2-methyl-2-pentenoyl-RifACP10, the expected product of *syn* dehydration of (2*S*,3*S*)-2-methyl-3-hydroxypentanoyl-RifACP10, while incubation with the corresponding EryACP6-bound substrate, (2*RS*)-2-methyl-3-ketopentanoyl-EryACP6, gave only the reduction product (2*S*,3*S*)-2-methyl-3-hydroxypentanoyl-EryACP6 with no detectable dehydration. These results establish the intrinsic *syn* dehydration stereochemistry and substrate diastereoselectivity of RifDH10 and highlight the critical role of the natural RifACP10 domain in chaperoning the proper recognition and processing of the natural ACP-bound undecaketide substrate. The 1.82 Å resolution structure of RifDH10 reveals the atomic-resolution details of the active site and allows modeling of the *syn* dehydration of the (2*S*,3*S*)-2-methyl-3-hydroxyacyl-RifACP10 substrate. These results suggest that generation of the characteristic *cis* double bond of the rifamycins occurs after formation of the full-length RifACP10-bound acyclic *trans*-unsaturated undecaketide intermediate, most likely during the subsequent macrolactamization catalyzed by the amide synthase RifF.



Polyketides make up an enormously diverse group of microbial natural products, many of which are important antibacterial, antifungal, immunosuppressive, and anticancer agents. The multimodular polyketide synthases (PKSs) that assemble complex polyketides are structurally and mechanistically related to the metazoan fatty acid synthases (FASs).[1−3] While FASs condense two-carbon acetate units and reduce newly formed β-ketoacyl groups in an iterative fashion, multimodular PKSs exploit an assembly line logic in which 5−25 modules (sets of enzymes similar to those in an FAS) each perform a decarboxylative chain-elongation reaction that adds successive malonyl, methylmalonyl, or ethylmalonyl building blocks to the growing polyketide and processing reactions that control the oxidation level and stereochemistry of the substituents attached to the α- and β-positions of the newly extended chain.

Type I PKS modules contain at least three independently folded catalytic domains: (1) an acyltransferase (AT) that selects a unique malonyl-, methylmalonyl-, or ethylmalonyl-CoA chain extender from the cellular acyl-CoA pool, (2) an acyl carrier protein (ACP) that acquires the extender unit from the AT through a flexible, 18 Å phosphopantetheine arm, and (3) a β-ketoacyl-ACP synthase [ketosynthase (KS)] that catalyzes the decarboxylative chain-elongation reaction between a growing polyketide transferred to the KS by the upstream module and the ACP-tethered α-carboxyacyl extender unit (the closely related *trans*-AT PKS modules lack an integrated AT domain).[4] Most modules also contain one or more processing domains, such as a ketoreductase (KR) that stereoselectively catalyzes the NADPH-dependent reduction of the β-keto group and can stereospecifically set the configuration of a neighboring α-substituent, a dehydratase (DH) that eliminates the resulting β-hydroxyl group as well as an α-proton to form an α,β-enoyl double bond, and an enoylreductase (ER) that catalyzes the stereoselective, NADPH-dependent reduction of the double bond. During polyketide assembly, growing chains remain

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covalently bound through a thioester linkage either to the phosphopantetheinyl thiol of an ACP or, transiently, to the active site cysteine residue of the KS domain, with the relatively mobile ACP domains shuttling the attached substrates among processing domains and to downstream modules. In most PKSs, the release of the fully elongated and processed polyketide is catalyzed by a dedicated thioesterase (TE) domain located at the C-terminal end of the ultimate module in the synthase, resulting in either macrolactonization or hydrolysis.

The vast majority of the more than 2000 known complex polyketides contain one or more double bonds, most of which have *trans* (*E*) geometry. A minor but nonetheless significant fraction of complex polyketides also harbor one or more *cis* (*Z*) double bonds (Figure S1 of the Supporting Information). How these *cis* double bonds are installed in polyketides such as the protein phosphatase inhibitors fostriecin[5,6] and phoslactomycin,[7] the anti-angiogenic agent borrelidin,[8] the microtubule stabilizer epothilone,[9] the microtubule polymerization inhibitor curacin A,[10] and the rifamycin family of antibacterials[11−13] remains largely unknown. Reynolds and co-workers have recently established that Plm1, the first module of the phoslactomycin PKS, most likely produces *cis*-3-cyclohexylpropenoate and that the PlmKR1 domain generates a (3*S*)-hydroxyacyl thioester intermediate that serves as the substrate for the PlmDH1 domain.[14,15]

The ansamycin antibiotic rifamycin B (Figure 1) is produced by the actinomycete *Amycolatopsis mediterranei*. The semi-

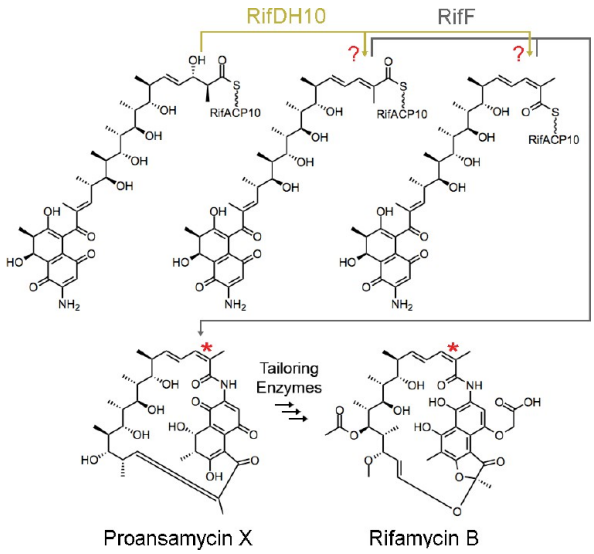

Figure 1. RifDH10 dehydrates a RifACP10-bound (2*S*,3*S*)-2-methyl-3-hydroxyacyl undecaketide generated by the paired ketoreductase domain RifKR10 in terminal module 10 of the rifamycin PKS. The amide synthase RifF catalyzes the macrolactamization of the acyclic undecaketide product to the rifamycin B precursor, proansamycin X, either before or after isomerization to form the characteristic *cis* double bond.

synthetic derivatives rifapentine, rifampicin, and rifabutin inhibit the RNA polymerase of mycobacteria and are clinically prescribed to tuberculosis patients, with rifampicin listed by the World Health Organization as one of the five essential anti-tuberculosis drugs.[16] Rifamycins are distinguished from the more common macrolide and polyene polyketides by several unique structural features, including an aminonaphthoquinone, a macrolactam ring, and a trisubstituted *cis* double bond.[17] The rifamycin biosynthetic gene cluster harbors a 10-module PKS that extends a 3-amino-5-hydroxybenzoate (AHBA) starter unit with two acetates and eight propionates.[11−13] The rifamycin PKS lacks the typical TE domain fused to terminal module 10. Instead, release of the fully processed, RifACP10-bound undecaketide is catalyzed by the separately encoded amide synthase, RifF. Although two research teams have independently reported that mutation or deletion of *rifF* leads to release of acyclic 2-methyl-2-enoyl undecaketides, these investigators reached contradictory conclusions regarding the geometry of the 15,16 double bond (rifamycin numbering) of this abortive product.[18−20] The geometry of the double bond in the fully processed RifACP10-undecaketide intermediate produced by the rifamycin PKS, which serves as the actual substrate for cyclization by amide synthase RifF, therefore remains unsettled, nor is it known whether RifDH10 itself or the cyclase RifF sets the characteristic *cis* double bond geometry of the rifamycins (Figure 1).

Neither sequence nor structural alignments have revealed any features that correlate DH protein sequence with the *trans* or *cis* geometry of the double bond in the resultant product.[21] For example, the active site of EryDH4, which catalyzes the formation of a trisubstituted *trans* (*E*) double bond,[22,23] is structurally equivalent to that established for the DH domains of curacin PKS subunits CurF and CurH, one of which is thought to generate a *cis* double bond.[10] DH-containing modules that generate *trans* double bonds are often paired with KR domains that produce (3*R*)-hydroxyacyl products. Such KR domains are readily recognized by their characteristic amino acid sequence fingerprints.[24−27] On the other hand, there is only limited circumstantial evidence correlating KR domains that generate (3*S*)-hydroxyacyl intermediates with the generation of *cis* double bonds by their paired DH domains.[21] For example, KR domains may provide (3*S*)-hydroxyacyl substrates for the DH domains of modules 2 and 3 of the fostriecin PKS that generate *cis* double bond diketide and triketide intermediates,[6] as well as for the DH domains of modules 1 and 2 of the phoslactomycin PKS,[14,15,28] module 4 of the epothilone PKS,[29] the CurG module of the curacin PKS,[10] and module 10 of the rifamycin PKS.[11−13] Whether modules that contain both an A-type KR and a DH actually generate *cis* double bonds, however, is still largely untested, except in the case of phoslactomycin module 1 mentioned above.[14,15] As a further complication, the formation of some *cis* double bonds can involve post-PKS transformations such as dehydration[7] or double-bond isomerization.[30]

We have recently established that RifKR10, the KR domain from module 10 of the rifamycin PKS, and RifKR7 from module 7 of the same PKS each mediate the stereospecific epimerization and/or reduction of (2*R*)-2-methyl-3-ketoacyl-ACP substrates to give exclusively (2*S*,3*S*)-2-methyl-3-hydroxyacyl-ACP products.[31] The RifKR10-generated product must serve as the substrate for the paired dehydratase domain of module 10, RifDH10. Although the 3*S* configuration of this 3-hydroxyacyl substrate might superficially suggest the formation of a *cis*-2-methyl-2-enoyl-ACP product, this geometry cannot be generated by *syn* dehydration of a (2*S*,3*S*)-2-methyl-3-hydroxyacyl intermediate. In fact, all DH domains that have been stereochemically characterized to date, including EryDH4 from the erythromycin synthase,[23] NanDH2 from the nanchangmycin synthase,[32] and TylDH2 from the tylactone synthase,[27] display strict specificity for the diastereomeric

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(2*R*,3*R*)-2-methyl-3-hydroxyacyl-ACP substrates and catalyze completely stereospecific *syn* dehydration to give the corresponding *trans*-(*E*)-2-methyl-2-enoyl-ACP products. In light of not only its unusual substrate stereochemistry but also the uncertainty in the actual *cis* or *trans* geometry of its natural undecaketide product, the RifDH10-catalyzed dehydration reaction presents an intriguing and important mechanistic, stereochemical, and biosynthetic puzzle.

We now report the expression and purification of the recombinant RifDH10 domain, the determination of its protein structure to 1.82 Å resolution, and the demonstration that RifDH10 catalyzes the diastereospecific *syn* dehydration of (2*S*,3*S*)-2-methyl-3-hydroxypentanoyl-RifACP10 to give exclusively the corresponding *trans*-(*E*)-2-methyl-2-pentenoyl thioester product. Unexpectedly, the natural diastereospecificity of RifDH10 is reversed when the dehydratase is incubated with thioester substrates that are tethered to the noncognate ACP domain EryACP6 or to the corresponding pantetheinyl or *N*-acetylcysteamine (NAC) analogues, resulting in the anomalous *syn* dehydration of only the diastereomeric (2*R*,3*R*)-2-methyl-3-hydroxypentanoyl thioesters to give the corresponding (*E*)-2-methyl-2-pentenoyl thioester products.

EXPERIMENTAL PROCEDURES

Materials. Isopropyl thio-β-D-galactopyranoside (IPTG) was purchased from Invitrogen. All other chemical reagents were purchased from Sigma-Aldrich and utilized without further purification. Ni-NTA affinity resin was purchased from Qiagen. Amicon Ultra Centrifugal Filter Units [Amicon Ultra-15, 30000 molecular weight cutoff (MWCO)] were purchased from Millipore. DNA primers were synthesized by Integrated DNA Technologies. Recombinant Ery[KS6][AT6], EryACP6, RifKR7, RifKR10, TylKR1, EryKR1, EryKR6, PicTE, and Sfp were each expressed and purified as previously described.[31,33−35] Reference standards for chiral GC−MS analysis of methyl (2*S*,3*S*)-2-methyl-3-hydroxypentanoate (**4a**), methyl (2*R*,3*R*)-2-methyl-3-hydroxypentanoate (**4b**), methyl (2*R*,3*S*)-2-methyl-3-hydroxypentanoate (**4c**), and methyl (2*S*,3*R*)-2-methyl-3-hydroxypentanoate (**4d**) were each prepared synthetically or chemoenzymatically as previously described.[31,36] (*E*)-2-Methyl-2-pentenoic acid (**3**) was purchased from Sigma-Aldrich and used to prepare (*Z*)-2-methyl-2-pentenoic acid as previously described.[23] Propionyl-*N*-acetylcysteamine thioester and (2*S*,3*R*)-2-methyl-3-hydroxypentanoyl-SNAC were prepared as described previously.[36] The synthesis of acyl-*S*-NAC and acyl-*S*-pantetheine thioester substrates and products is described in the Supporting Information. (2*RS*)-2-Methyl-3-ketopentanoyl-CoA was prepared by L. Collett Pilcher as previously described,[31,37−39] purified by reversed-phase C-18 high-performance liquid chromatography (HPLC), and characterized by ^{1}H nuclear magnetic resonance and electrospray ionization mass spectrometry (ESI-MS). Synthetic genes encoding recombinant domains RifDH10 and RifACP10, optimized for expression in *Escherichia coli*, were designed and prepared by DNA2.0 and supplied in vector pJ201.

Methods. General methods were as previously described.[36,40] Growth media and conditions used for *E. coli* and standard methods for handling *E. coli in vivo* and *in vitro* were those described previously, unless otherwise noted.[40] All DNA manipulations were performed following standard procedures.[40] DNA sequencing was conducted at the University of California Davis Sequencing Facility (Davis, CA). All proteins were handled at 4 °C unless otherwise stated. Protein concentrations were determined according to the method of Bradford,[41] using Hewlett-Packard 8452A Diode Array or Thermo Evolution Array UV−vis spectrophotometers with bovine serum albumin as the standard. Sodium dodecyl sulfate−polyacrylamide gel electrophoresis (SDS−PAGE) and DNA gels were imaged and analyzed with a Bio-Rad ChemiDoc MP System. A Bio-Rad FX-Pro Plus Molecular Imager was utilized for radio thin layer chromatography (TLC) analysis. GC−MS analysis was performed on a GC−MS Hewlett-Packard Series 2 GC-MSD instrument (70 eV EI) in positive ion mode using a capillary CP-Chirasil-Dex CB column (25 m × 0.32 mm) from Agilent Technologies. For resolution and analysis of (*E*)-2-methyl-2-pentenoic acid (**3**) and (*Z*)-2-methyl-2-pentenoic acid, three different programs were used: method 1, initial oven temperature of 50 °C for 1 min, increased to 200 °C at a rate of 7.5 °C/min; method 2, initial oven temperature of 50 °C for 1 min, increased to 200 °C at a rate of 15 °C/min; method 3, initial oven temperature of 65 °C for 1 min, increased to 100 °C at a rate of 0.5 °C/min and then to a final temperature of 200 °C at a rate of 20 °C/min. For resolution and analysis of the four diastereomers of methyl 2-methyl-3-hydroxypentanoate (**4**), the following program was used: method 4, initial oven temperature of 50 °C for 1 min, increased to 90 °C at a rate of 1 °C/min and then to 200 °C at a rate of 20 °C/min. A Thermo LXQ instrument equipped with a Surveyor HPLC system and Waters Symmetry C18 column (2.1 mm × 50 mm, 3.5 μm) was utilized for HPLC−ESI-MS analysis in positive ion mode.

General Cloning Strategy. The design of rifamycin module 10 domain boundaries for cloning of RifDH10, RifDH10-RifKR10, and RifACP10-NusA is described in the Supporting Information (Figures S3−S5). Synthetic genes encoding RifDH10, RifDH10-RifKR10, and RifACP10-NusA,[42] optimized for expression in *E. coli* and flanked by suitable restriction sites, were ligated into pET28a, and the resultant plasmids were used to transform the expression host *E. coli* BL21(DE3).

RifDH10 Expression and Purification. The synthetic gene for RifDH10, flanked by 5′-NdeI and 3′-XhoI sites, was ligated into pET28a. *E. coli* BL21(DE3) transformed with the RifDH10 expression plasmid was inoculated into Luria-Bertani medium containing 50 μg/L kanamycin at 37 °C, grown to an OD_{600} of 0.4, and induced with 0.5 mM IPTG. After 12 h at 15 °C, cells were collected by centrifugation and resuspended in lysis buffer [0.5 M NaCl, 10% (v/v) glycerol, and 0.1 M 2-[4-(2-hydroxyethyl)piperazin-1-yl]ethanesulfonic acid (HEPES) (pH 7.5)]. Following sonication, cell debris was removed by centrifugation (30000*g* for 30 min). The supernatant was poured over a column of nickel-NTA resin (Thermo Scientific), which was then washed with 50 mL of lysis buffer containing 15 mM imidazole and eluted with 5 mL of lysis buffer containing 150 mM imidazole. RifDH10 was further purified using a Superdex 200 gel filtration column (GE Healthcare Life Sciences) equilibrated with 150 mM NaCl and 10 mM HEPES (pH 7.5). The eluted protein (~100 mg of purified RifDH10 from 2 L of culture) was concentrated to 15 mg/mL in the equilibration buffer and stored at −80 °C until the protein was needed. SDS−PAGE analysis of purified His_6RifDH10 protein showed an M_r of 34900 (calcd molecular mass of 34109 Da) (Figure S6 of the Supporting Information).

Apo-RifACP10-NusA Fusion Protein. The synthetic gene for RifACP10, flanked by 5′-NdeI and 3′-XhoI sites, was

initially ligated into the NdeI and XhoI sites of pET28a. Because the resultant recombinant RifACP10 was obtained only as insoluble inclusion bodies when expressed in *E. coli* BL21(DE3), we constructed the corresponding RifACP10-NusA protein. The synthetic DNA encoding RifACP10 was amplified via polymerase chain reaction from the RifACP10 construct using the primer pair of pET28a-FP (5′-ATGGGC-AGCAGCCATCATCAT-3′) and RifACP10-EcoRI-RP [5′-TATTTAAAATTCA*GAATTC*CAGCAGCTCATTCAAGTG-TGC-3′ (EcoRI site in italics)]. The resultant amplified DNA was digested with NdeI and EcoRI and ligated into the previously described plasmid,[31] RifKR10-NusA-pET28, that had been digested with NdeI and EcoRI to excise the DNA segment encoding RifKR10 and to replace it with DNA encoding RifACP10, thus giving apo-RifACP10-NusA-pET28 that was used to transform *E. coli* BL21(DE3). Recombinant His_6 tag-apo-RifACP10-NusA, harboring an HRV 3C protease cleavage site between RifACP10 and the C-terminal NusA, was expressed in soluble form by growth in Terrific Broth or in Super Broth until the OD_{600} reached 0.4−0.8. Protein expression was induced by addition of 0.2 mM IPTG, and the cell culture was continuously grown for an additional 16−18 h at 18 °C overnight. The cells were harvested by centrifugation at 4200*g* for 20 min, and the cell pellet was collected and stored at −80 °C. The frozen cells were thawed at room temperature (RT) and dissolved and lysed on ice for 30 min in starting buffer [500 mM NaCl and 50 mM phosphate (pH 7.8)] containing 1 mg/mL lysozyme, followed by sonication. The cell supernatant and the pellet were separated by centrifugation at 23000*g* for 30 min, and the supernatant was loaded on a precharged Ni-NTA column. The column was washed with starting buffer and then washing buffer [300 mM NaCl, 50 mM phosphate (pH 7.6), and 10 mM imidazole], and proteins were eluted from the Ni column with elution buffer [150 mM NaCl, 50 mM phosphate (pH 7.5), 150 mM imidazole, and 10% glycerol]. The eluted fractions were collected and concentrated with an Amicon MWCO 30000 filter, and buffer was exchanged with a PD-10 column with 150 mM NaCl, 50 mM phosphate (pH 7.5), and 10% glycerol, yielding ∼200 mg of His_6 tag-apo-RifACP10-NusA/2 L of culture. SDS−PAGE analysis of purified His_6 tag-apo-RifACP10-NusA protein showed an M_r of 70900 (calcd molecular mass of 68955 Da) (Figure S6 of the Supporting Information).

RifDH10-KR10 Fusion Protein. DNA encoding the synthetic gene for RifKR10 was amplified from the previously described expression construct[31] using the primer pair of RifKR10-NdeI-BamHI-FP [5′-ATTTTCGAATTA**CATATG**A-TGAATTTTAAA*GGATCC*CTGTACCGCGTCGACTG-3′ (NdeI site in bold and BamHI site in italics)] and pET-28a XhoI RP (5′-TCGGGCTTTGTTAGCAGC-3′). The amplified DNA fragment was digested with NdeI and XhoI followed by ligation into the pET-28a vector to give RifKR10-NdeI-BamHI-pET28a. DNA encoding RifDH10 was amplified from the expression construct described above using the primer pair of RifDH10-PAGA-BamHI-RP [5′-TAATTCGAAAAT*GGATCC*-TGCACCCGCTGGACCCGCTGCAGTGGTC-3′ (BamHI site in italics)] and pET28a-FP (5′-ATGGGCAGCAGCCAT-CATCAT-3′) followed by DNA restriction by NdeI and BamHI. The resultant DNA fragment was ligated into NdeI- and BamHI-digested plasmid RifKR10-NdeI-BamHI-pET28a. The His_6 tag-RifDH10-KR10 protein was expressed in *E. coli* BL21(DE3) and purified by the same procedures used to express the His_6 tag-apo-RifACP10-NusA protein and then further purified by size exclusion chromatography, yielding 16 mg of partially purified His_6 tag-Rif[DH10][KR10] didomain protein/2 L culture. SDS−PAGE analysis of partially purified His_6 tag-Rif[DH10][KR10] protein gave an M_r of 80100 (calcd molecular mass of 80150 Da) (Figure S6 of the Supporting Information).

Incubation of RifDH10 with (2*S*,3*S*)-2-Methyl-3-hydroxypentanoyl-RifACP10-NusA. A mixture of 500 μM (2*RS*)-2-methyl-3-ketopentanoyl-CoA, 40 μM Sfp (surfactin phosphopantetheinyl transferase),[43] and 400 μM apo-RifACP10-NusA was added to reaction buffer [150 mM NaCl and 50 mM NaH_2PO_4 (pH 7.2)] containing 20 mM $MgCl_2$ and 4 mM DTT. After incubation at 37 °C for 1 h, 300 μM RifKR7, 300 μM RifDH10, and 2 mM NADPH were added, and the mixture was incubated for an additional 1 h at RT. The final reaction volume was 500 μL. The RifACP10-NusA protein was hydrolytically released by incubation with 100 μM PicTE for 10 min at RT. The reaction mixtures were acidified with 1 M HCl to pH <3 and extracted with ethyl acetate. After solvent evaporation, the product was dissolved in 100 μL of methanol and the unsaturated diketide was analyzed by chiral GC−MS and direct comparison with authentic standards of (*E*)-2-methyl-2-pentenoic acid and (*Z*)-2-methyl-2-pentenoic acid, using both methods 1 and 2 (Figure 3).[23] In control experiments conducted in the absence of RifDH10, 20 μL of TMS-diazomethane was added to the hydrolyzed organic extract and the derived diketide methyl ester was analyzed by chiral GC−MS and direct comparison with authentic methyl (2*S*,3*S*)-2-methyl-3-hydroxypentanoate, using method 4 (Figure S7 of the Supporting Information). As previously reported, direct comparison with authentic standards **4a** and **4b** was essential because the observed retention time on the chiral column varied slightly from run to run, although the order of elution never changed.[31,36]

Incubations with TylKR1, EryKR6, and EryKR1 in place of RifKR7 were also conducted to generate the corresponding RifACP10-bound intermediates (2*R*,3*R*)-**1b**, (2*R*,3*S*)-**1c**, and (2*S*,3*R*)-**1d**. The derived hydrolysis products were analyzed by GC−MS and direct comparison with authentic standards of each diastereomer of methyl 2-methyl-3-hydroxypentanoate (**4a**−**d**) (method 4) and both (*E*)-2-methyl-2-pentenoic acid (**3**) and (*Z*)-2-methyl-2-pentenoic acid (method 2), as described for the incubations using RifKR7 (Figures S8−S10 of the Supporting Information).

Incubation of the Recombinant RifDH10-RifKR10 Didomain with Chemoenzymatically Generated (2*RS*)-2-Methyl-3-ketopentanoyl-RifACP10. A mixture of 500 μM (2*RS*)-2-methyl-3-ketopentanoyl-CoA, 40 μM Sfp, and 400 μM apo-RifACP10-NusA was added to reaction buffer [150 mM NaCl and 50 mM NaH_2PO_4 (pH 7.2)] containing 20 mM $MgCl_2$ and 4 mM DTT. After incubation at 37 °C for 1 h, 300 μM RifDH10-RifKR10 and 2 mM NADPH were added, and the mixture was incubated for an additional 1 h at RT. The final reaction volume of each assay was 500 μL. The diketide acid was hydrolytically released from RifACP10-NusA by incubation with 100 μM PicTE for 10 min at RT. The reaction mixtures were acidified with 1 M HCl to pH <3 and extracted with ethyl acetate. After solvent evaporation, the product was dissolved in 100 μL of methanol and the formation of unsaturated (*E*)-2-methyl-2-pentenoic acid was confirmed by GC−MS (method 2) and direct comparison with authentic standards of **3** and (*Z*)-2-methyl-2-pentenoic acid. For the detection of the

reduced diketide product, 20 μL of TMS-diazomethane was added and the derived diketide methyl ester, methyl (2*S*,3*S*)-2-methyl-3-hydroxypentanoate (**4a**), was identified by chiral GC−MS (method 4) and direct comparison with authentic standards (Figure 4).

Incubation of Recombinant RifDH10 with Chemoenzymatically Generated (*E*)-2-Methyl-2-pentenoyl-RifACP10 and (*E*)-2-Methylpentenoyl-EryACP6. A mixture of 500 μM (*E*)-2-methyl-2-pentenoyl-CoA, 40 μM Sfp, and either 400 μM apo-RifACP10-NusA or 200 μM apo-EryACP6 was added to reaction buffer [150 mM NaCl and 50 mM NaH_2PO_4 (pH 7.2)] containing 20 mM $MgCl_2$ and 4 mM DTT. After incubation at 37 °C for 1 h, 300 μM RifDH10 was added and the mixture was incubated for an additional 1 h at RT. The final reaction volume of each assay was 500 μL. The RifACP10-NusA or EryACP6 was hydrolytically released by incubation with 100 μM PicTE for 10 min at RT. The reaction mixtures were acidified with 1 M HCl to pH <3 and extracted with ethyl acetate. After solvent evaporation, the product was dissolved in 100 μL of methanol and 20 μL of TMS-diazomethane was added. The derived diketide methyl esters were analyzed as described above by chiral GC−MS and direct comparison with authentic standards [Figure 5 (RifACP10) and Figure S16 (EryACP6) of the Supporting Information]. In a control incubation without the added RifDH10 domain, the chemoenzymatically generated 2-methyl-2-pentenoyl-RifACP10-NusA was treated with HRV 3C protease to remove the C-terminal NusA and the molecular mass of the resulting 2-methyl-2-pentenoyl-RifACP10 was verified by LC−ESI(+)-MS, which gave an observed value of 13144 Da (calcd for $[M + H]^+$ ion of 2-methyl-2-pentenoyl-RifACP10, 13143.9 Da) (Figure S11 of the Supporting Information). LC−ESI(+)-MS was also used to confirm the formation of 2-methyl-2-pentenoyl-ACP6 (**6**), with a molecular mass (observed) of 11728 Da (calcd 11727.7 Da), compared to the peak for holo-eryACP6, with a molecular mass (observed) of 11632 Da (calcd 11631.6 Da), with the difference of 96 Da matching that expected for addition of the 2-methyl-2-pentenoyl moiety. Additional control incubations established that the isomeric (*Z*)-2-methylpentenoyl-EryACP6 was not a substrate for RifDH10.

TLC−Phosphorimaging Assay of the Incubation of Recombinant RifDH10 with Reconstituted Ery[KS6][AT6], EryACP6, and Recombinant KR Domains. A radio-TLC assay of the conversion of propionyl-SNAC to 2-methyl-3-hydroxypentanoic acids and 2-methyl-2-pentenoic acid by coupled incubation with reconstituted Ery[KS6][AT6] and EryACP6 in combination with EryKR6, TylKR1, EryKR1, or RifKR7 and RifDH10 was conducted as previously described.[23,31,36] For each incubation, 5 mM propionyl-SNAC and 40 μM Ery[KS6][AT6] were added to reaction buffer [50 mM NaH_2PO_4 (pH 7.2)] containing 2.5 mM TCEP and the mixture was incubated at RT. After 1 h, 200 μM holo-EryACP6, 300 μM methylmalonyl-CoA containing a trace amount of [2-^{14}C]methylmalonyl-CoA, 2 mM NADPH, and individual KR domains (300 μM) with or without 300 μM RifDH10 were added to the reaction mixture, which was then incubated for an additional 1 h. The final reaction volume of each assay was 125 μL. The reaction was quenched, and the diketide acids were hydrolytically released from EryACP6 by addition of 0.5 M NaOH (40% by volume) followed by incubation at 65 °C for 20 min. After adjustment to pH <3 with 1 M HCl and extraction with ethyl acetate, the concentrated organic extracts were dissolved in 15 μL of ethyl acetate and spotted on a silica gel TLC plate, which was developed with a 1:9 dichloromethane/ethyl acetate mixture containing 0.1% AcOH. The dried TLC plate was then visualized by phosphorimaging for 48 h (Figure S12 of the Supporting Information).

Incubation of Recombinant RifDH10 or the RifDH10-RifKR10 Didomain with Reconstituted Ery[KS6][AT6], EryACP6, and TylKR1. The incubation procedures for the *in situ* generation of (2*R*,3*R*)-2-methyl-3-hydroxyacyl-EryACP6 derivatives were based on those previously described.[31,36] In a typical assay, 5 mM propionyl-SNAC or 5 mM (2*S*,3*R*)-2-methyl-3-hydroxypentanoyl-SNAC was preincubated with 40 μM Ery[KS6][AT6] in 50 mM NaH_2PO_4 (pH 7.2) containing 2.5 mM tris-2-carboxyethylphosphine (TCEP) at RT. After 1 h, 200 μM holo-EryACP6, 300 μM methylmalonyl-CoA, 2 mM NADPH, 300 μM recombinant TylKR1, and 300 μM recombinant RifDH10 were added to the reaction mixture, which was then incubated for an additional 1 h (Figure S13 of the Supporting Information). In a second experiment, 300 μM Rif[DH10][KR10] didomain was added instead of the TylKR1 and RifDH10 pair (Figure S14 of the Supporting Information). The final reaction volume of each assay was 500 μL. The reaction was quenched, and EryACP6 was hydrolytically released from the product by addition of 0.5 M NaOH (40% by volume) and incubation at 65 °C for 20 min. Alternatively, EryACP6 was enzymatically released by incubation with 100 μM PicTE for 10 min at RT. The reaction mixtures were acidified with 1 M HCl to pH <3 and then extracted with ethyl acetate. After solvent evaporation, the product was dissolved in 100 μL of ethyl acetate or methanol and analyzed by chiral GC−MS (method 3) (Figures S13 and S14 of the Supporting Information). TMS-diazomethane (20 μL) was added to convert recovered 2-methyl-3-hydroxypentanoates to the derived 2-methyl-3-hydroxypentanoate methyl esters that were analyzed by chiral GC−MS and direct comparison with synthetic standards (method 4).[36] For the GC−MS analysis of methyl (2*E*,4*R*,5*R*)-2,4-dimethyl-5-hydroxy-2-heptenoate, the temperature program of method 3 was used (Figure S15 of the Supporting Information).

Incubation of RifDH10 with Acyl-*S*-NAC or Pantetheine Thioesters. RifDH10 (30 μM) was incubated overnight with each of the chemoenzymatically prepared 2-methyl-3-hydroxyacyl or 2,3-unsaturated enoyl-*S*-NAC or pantetheine thioester analogues (at 10 mM) in a 25 μL solution containing 150 mM NaCl, 10% (v/v) glycerol, and 150 mM HEPES (pH 7.5). After 16 h, the reaction mixture was injected onto a C_{18} reversed-phase HPLC column and monitored over a range of λ values of 200−600 nm (100% water with 0.1% TFA to 100% MeOH with 0.1% TFA, over 30 min). All products were characterized by mass spectrometry and comparison with authentic samples as appropriate (Figures S17−S24 of the Supporting Information).

RifDH10-Catalyzed Dehydration of (2*R*,3*R*)-2-Methyl-3-hydroxybutanoyl-*S*-pantetheine and Subsequent Acyl Transthioesterification to NAC. *trans*-2-Methyl-2-butenoyl-*S*-pantetheine (**11**) (20 mg) was incubated overnight in 150 mM NaCl, 150 mM HEPES (pH 7.5), 10% (v/v) glycerol, and 1 mg/mL RifDH10 in a total volume of 1 mL at 22 °C. After 16 h, the reaction mixture was injected onto a C_{18} reversed-phase HPLC column and monitored over a range of λ values of 200−600 nm (100% water with 0.1% TFA to 100% MeOH with 0.1% TFA, over 15 min). A peak that was not observed in a control reaction without RifDH10 with a λ_{max} of 232 nm was collected and concentrated. The concentrated fractions yielded

5 mg of the hydrated product, (2*R*,3*R*)-2-methyl-3-hydroxybutanoyl-*S*-pantetheine (**12b**). To confirm its stereochemistry, 3 mg of (2*R*,3*R*)-2-methyl-3-hydroxybutanoyl-*S*-pantetheine (**12b**) was resuspended in 5 mL of 50 mM $NaHCO_3$ (aqueous) and 50 mM NAC and stirred overnight. The reaction mixture was injected onto a C_{18} reversed-phase HPLC column and monitored at a range of λ values of 200−600 nm (100% water with 0.1% TFA to 100% MeOH with 0.1% TFA, over 15 min). A peak that was not observed in a control reaction without NAC with a λ_{max} of 232 nm was collected and concentrated. The compound ran in a manner identical to that of authentic (2*R*,3*R*)-2-methyl-3-hydroxybutanoyl-*S*-NAC (**9b**) on a ChiralCel OC-H column (250 mm × 4.6 mm) on a Beckman Coulter HPLC system equipped with a 20 μL loop with an isocratic flow rate of 0.6 mL/min using a 1:24 mixture of ethanol and hexanes as the mobile phase (Figure S24 of the Supporting Information).[44] Compounds were observed by 235 nm UV absorbance. Synthetic standards, prepared as previously described, were provided by S. Piasecki.[44]

Crystallization and Structure Determination. Crystals of RifDH10 grew over a period of 2 days to 1 week by sitting drop vapor diffusion at 22 °C. Drops were formed by mixing 3 μL of a protein solution [15 mg/mL RifDH10, 150 mM NaCl, and 10 mM HEPES (pH 7.5)] with 1 μL of crystallization buffer [1.1 M sodium citrate and 0.1 M HEPES (pH 6.8)]. Crystals were soaked briefly in crystallization buffer with 15% (v/v) glycerol before being frozen in liquid nitrogen. The diffraction data, collected at ALS beamline 5.0.2, were processed with iMosflm and scaled with SCALA from the CCP4 suite.[45] The structure was determined to 1.82 Å resolution by molecular replacement with PhaserMR[46] using EryDH4 [Protein Data Bank (PDB) entry 3EL6] as the search model.[21] The model generated from the molecular replacement solution was refined with Coot[47] and Refmac5.[48] Aside from the N- and C-termini, only loop residues 232−242 were not shown in the electron density maps.

RESULTS

Expression and Purification of RifDH10 and RifACP10. To investigate the mechanism and structure of RifDH10, we used a synthetic gene with codons optimized for expression in *E. coli* to express the RifDH10 domain as a discrete recombinant protein corresponding to the region from A2569 to G2872 of RifE (EMBL AAC01714.1; UniProt entry O54593; residues herein numbered 1−304), based on alignment with the previously described stand-alone EryDH4 domain[21,23] and flanked by the deduced C-terminal and N-terminal boundaries, respectively, of the RifAT10 and RifKR10 domains[12,13] (Figures S3 and S4 of the Supporting Information). After ligation of the synthetic gene into pET28a and transformation into *E. coli* BL21(DE3), the expressed recombinant RifDH10 carrying an N-terminal His_6 tag was purified by Ni(II) affinity chromatography and analyzed for purity and M_r by SDS−PAGE (Figure S6 of the Supporting Information). Attempted expression of recombinant RifACP10 corresponding to the region from L3324 to L3409 of RifE, using a synthetic RifACP10 gene with codons optimized for expression in *E. coli* (Figure S5 of the Supporting Information), gave only insoluble inclusion bodies. Instead, apo-RifACP10-NusA (hereafter simply termed apo-RifACP10) could be obtained as a soluble fusion protein carrying an N-terminal His_6 tag and a C-terminal NusA.[42] The resultant protein was readily purified by Ni(II) affinity chromatography (Figure S6 of the Supporting Information).

Stereochemistry of RifDH10-Catalyzed Dehydration of 2-Methyl-3-hydroxyacyl-RifACP10. We have recently reported that (2*S*,3*S*)-2-methyl-3-hydroxypentanoyl-RifACP10 (**1a**) can be prepared by stereospecific reduction of (2*RS*)-2-methyl-3-ketopentanoyl-RifACP10 with either RifKR7 or RifKR10 in the presence of NADPH (Figure 2a and Figure S7 of the Supporting Information).[31] The requisite RifACP10-bound 3-keto acylthioester was generated *in situ* by chemoenzymatic incubation of (2*RS*)-2-methyl-3-ketopentanoyl-CoA with apo-RifACP10 and the phosphopantetheinyl transferase Sfp.[31] Incubation of (2*S*,3*S*)-**1a** with RifDH10 gave as the exclusive dehydration product (*E*)-2-methyl-2-pentenoyl-RifACP10 (**2**), as established by enzymatic hydrolysis with PicTE, the thioesterase domain from the picromycin synthase, followed by GC−MS analysis and direct comparison of the derived (*E*)-2-methyl-2-pentenoate (**3**) with an authentic sample of **3**, as well as with the isomeric (*Z*)-2-methyl-2-pentenoic acid (Figures 2a and 3).[23] Omission of RifDH10 resulted in exclusive formation of (2*S*,3*S*)-**1a**, as confirmed by PicTE-catalyzed hydrolysis and chiral GC−MS analysis of the

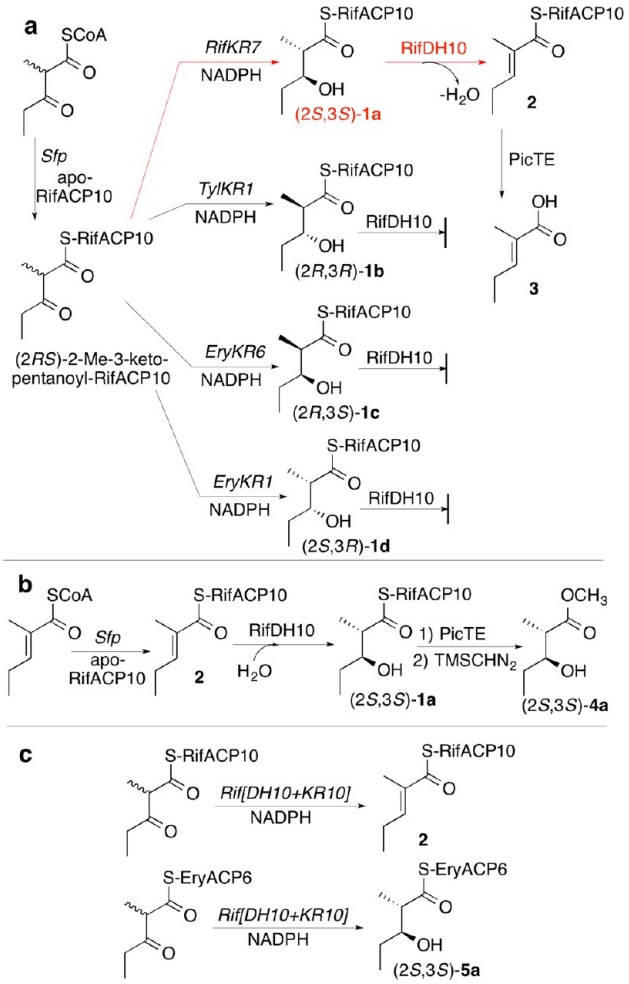

Figure 2. RifDH10-catalyzed dehydration and hydration of RifACP10-bound substrates. (a) Dehydration of (2*S*,3*S*)-2-methyl-3-hydroxypentanoyl-RifACP10 (**1a**). (b) Hydration of (*E*)-2-methyl-2-pentenoyl-RifACP10 (**2**). (c) Incubation of Rif[DH10][KR10] with RifACP10- and EryACP6-bound 2-methyl-3-ketoacyl thioesters.

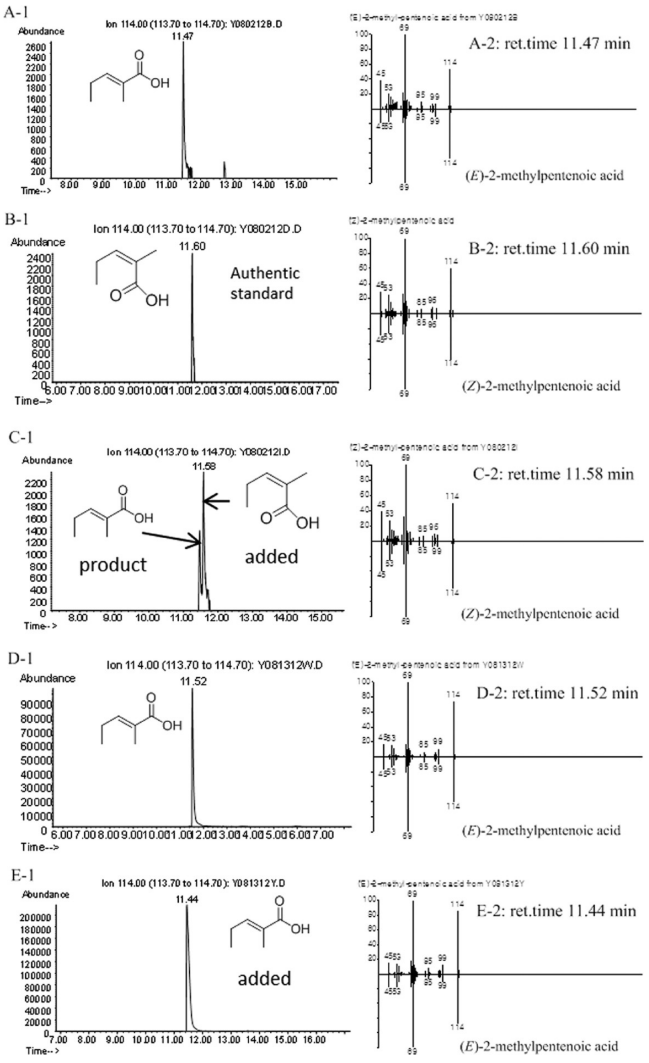

Figure 3. Chiral GC−MS analysis (method 1) of the incubation of (2*RS*)-2-methyl-3-ketopentanoyl-RifACP10-NusA with RifKR7 and RifDH10. (A and D) (*E*)-2-Methyl-2-pentenoic acid (**3**) from RifKR7-catalyzed reduction of (2*RS*)-2-methyl-3-ketopentanoyl-RifACP10-NusA followed by dehydration by RifDH10. (B) (*Z*)-2-Methylpentenoic acid authentic standard. (C) Co-injection of compounds from panels A with B. (E) Co-injection of (*E*)-2-methyl-2-pentenoic acid standard with the compound from panel D. A-1−E-1) Extracted ion current (XIC) at *m*/*z* 114 (base peak). (A-2−E-2) Mass spectra of selected peaks: (top halves) observed spectra and (bottom halves) inverted mass spectra of the reference standard.

derived methyl ester (2*S*,3*S*)-**4a**, which was identical in both retention time and mass spectrum by direct comparison with authentic **4a**, as previously observed (Figure S7 of the Supporting Information).[31] By contrast, incubations of RifDH10 under identical conditions with any of the chemoenzymatically prepared diastereomeric substrates, (2*R*,3*R*)-**1b** (TylKR1), (2*R*,3*S*)-**1c** (EryKR6), or (2*S*,3*R*)-**1d** (EryKR1),[27,36,49] resulted at most in generation of only very minor quantities (<5−10%) of **3**, most likely because of the previously reported[31] generation of minor amounts of contaminating (2*S*,3*S*)-**1a** by TylKR1 and EryKR1 upon incubation with (2*RS*)-2-methyl-3-ketopentanoyl-RifACP10 (Figures S8−S10 of the Supporting Information).

We have previously established that RifKR10 has a stereospecificity identical to that of RifKR7, reducing (2*RS*)-2-methyl-3-ketopentanoyl-RifACP10 to the corresponding (2*S*,3*S*)-2-methyl-3-hydroxypentanoyl-RifACP10 (**1a**).[31] To confirm that the observed stereochemistry of the coupled RifDH10-catalyzed dehydration reaction is not influenced by the origin of the 2*S*,3*S*-specific ketoreductase domain, we prepared a RifDH10-RifKR10 fusion protein. Incubation of Rif[DH10][KR10] with (2*RS*)-2-methyl-3-ketopentanoyl-RifACP10 and NADPH gave (*E*)-2-methyl-2-pentenoyl-RifACP10 (**2**), as established by GC−MS analysis of the derived (*E*)-2-methyl-2-pentenoic acid (**3**) (Figures 2c and 4). Analysis of the methyl ester derived from the reduced diketide intermediate **1a** confirmed the expected exclusive formation of (2*S*,3*S*)-**4a**.

***syn* Stereochemistry of RifDH10-Catalyzed Hydration of (*E*)-2-Methyl-2-pentenoyl-RifACP10.** In a complementary experiment, we also investigated the reverse RifDH10-catalyzed hydration of (*E*)-2-methyl-2-pentenoyl-RifACP10 (**2**). Incubation of chemoenzymatically prepared (*E*)-2-methyl-2-pentenoyl-RifACP10 (**2**) resulted in stereospecific *syn* hydration to give exclusively (2*S*,3*S*)-2-methyl-3-hydroxypentanoyl-RifACP10 (**1a**), as confirmed by PicTE hydrolysis, methylation, and chiral GC−MS detection of methyl (2*S*,3*S*)-**4a** (Figures 2b and 5).

Stereochemistry of RifDH10-Catalyzed Dehydration of 2-Methyl-3-hydroxyacyl Thioester Analogues. Although these results are all congruent with the previously established 2*S*,3*S* stereospecificity of RifKR10,[31] which generates the natural substrate for RifDH10, the observed *syn* dehydration of a (2*S*,3*S*)-2-methyl-3-hydroxyacyl-ACP substrate by RifDH10 to give the corresponding (*E*)-2-methyl-2-enoylacyl-ACP product is biochemically unprecedented. Thus, all other mechanistically characterized DH domains catalyze *syn* dehydration of only the diastereomeric (2*R*,3*R*)-2-methyl-3-hydroxyacyl-ACP substrates to give (*E*)-2-methyl-2-enoyl-ACP products,[23,32] while a (3*S*)-hydroxyacyl intermediate has been implicated in the formation of a *cis*-enoyl thioester in the biosynthesis of phoslactomycin (although the overall stereochemistry of the latter dehydration has not been determined).[15] To explore any influence of RifACP10 on the overall stereochemistry of the RifDH10-catalyzed reaction, we therefore also examined the stereospecificity of RifDH10-catalyzed dehydration of diketide thioester substrates that are covalently tethered to alternative thioester analogues of RifACP10. To our surprise, we found that replacement of RifACP10 with the heterologous EryACP6 domain, obtained from module 6 of the erythromycin PKS, resulted in an unexpected complete alteration of the diastereospecificity of RifDH10, without any effect on either the intrinsic *syn* stereospecificity of the dehydration reaction or the *trans* geometry of the resulting unsaturated product (Figure 6). Thus, although RifDH10 was unable to dehydrate chemoenzymatically prepared (2*S*,3*S*)-2-methyl-3-hydroxyacyl-EryACP6 (**5a**), as established by the TLC−phosphorimaging assay (Figure S12 of the Supporting Information), RifDH10 did catalyze the *syn* dehydration of the diastereomeric *anti*-(2*R*,3*R*)-2-methyl-3-hydroxyacyl-EryACP6 (**5b**), which could be generated *in situ* by coupled incubation of the Ery[KS6][AT6] didomain from module 6 of the erythromycin PKS, EryACP6, and TylKR1 (from module 1 of the tylactone PKS) with propionyl-SNAC, methylmalonyl-CoA, and NADPH, as previously described.[23,27,36,49] The reaction gave exclusively (*E*)-2-methyl-2-pentenoyl-EryACP6 (**6**), whose structure and stereochemistry were established by hydrolysis with 0.5 M NaOH for 20 min at 65 °C and GC−MS analysis of the derived methyl ester **3** (Figure 6a and Figure

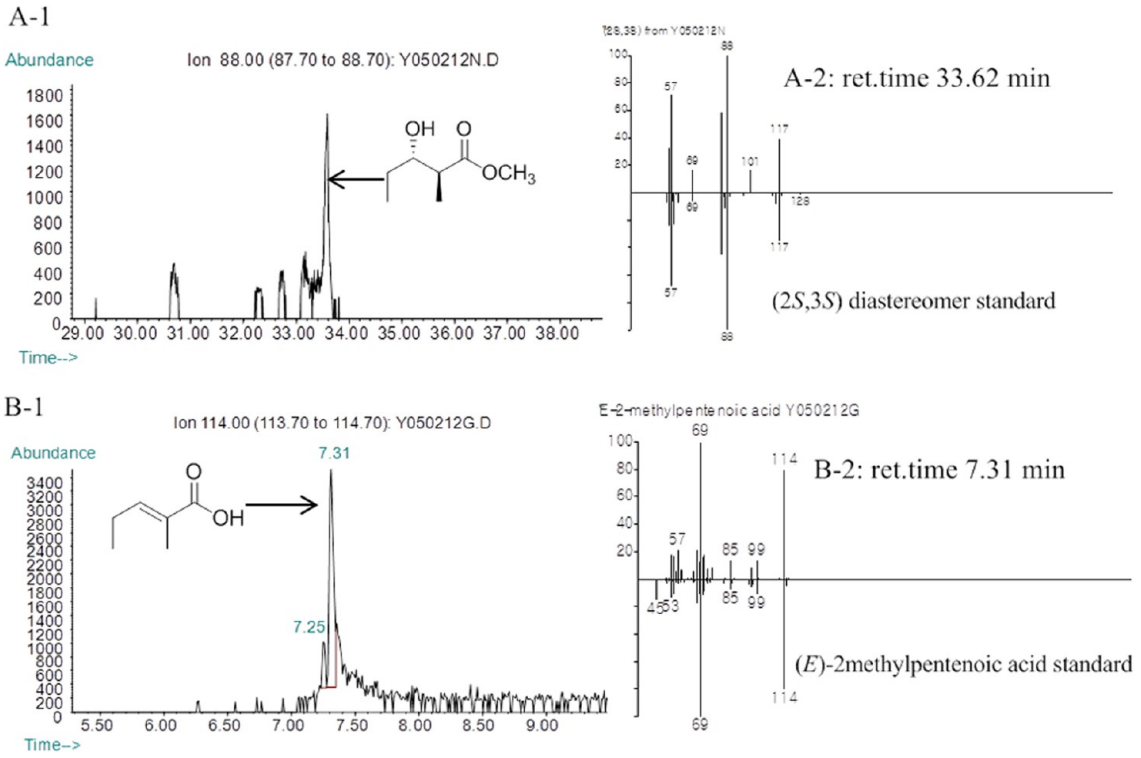

Figure 4. Chiral GC–MS analysis of the incubation of (2*RS*)-2-methyl-3-ketopentanoyl-RifACP10-NusA with RifDH10-KR10 (methods 2 and 4). (A-1) Extracted ion current (XIC) at *m*/*z* 88 (base peak for **4a**) (method 4). (B-1) Extracted ion current (XIC) at *m*/*z* 114 (base peak for **3**) (method 2). (A-2 and B-2) Mass spectra of selected peaks: (top halves) observed spectra and (bottom halves) inverted mass spectra of the reference standard. (A) (2*S*,3*S*)-**4a** produced by RifDH10-KR10. (B) (*E*)-2-Methylpentenoic acid (**3**) produced by RifDH10-KR10.

S13 of the Supporting Information). Similarly, an analogous incubation in which (2*S*,3*R*)-2-methyl-3-hydroxypentanoyl-SNAC was substituted for propionyl-SNAC gave exclusively (*E*)-(4*R*,5*R*)-2,4-dimethyl-5-hydroxy-2-heptenoyl-ACP6, as established by GC–MS analysis of the derived methyl ester (Figure S15 of the Supporting Information). On the other hand, RifDH10 did not dehydrate either of the diastereomeric EryACP6-bound *syn* thioesters, (2*R*,3*S*)-**5c** or (2*S*,3*R*)-**5d** (Figure 6a and Figure S12 of the Supporting Information). RifDH10 also catalyzed the reverse *syn* hydration of (*E*)-2-methyl-2-pentenoyl-EryACP6 (**6**), chemoenzymatically prepared *in situ*, as previously described[23] to give methyl (2*R*,3*R*)-2-methyl-3-hydroxypentanoyl-EryACP6 (**5b**), whose structure and stereochemistry were established by PicTE-catalyzed hydrolysis and methylation, followed by chiral GC–MS analysis and direct comparison of the derived methyl ester (2*R*,3*R*)-**4b** with authentic standards of each of the four diastereomeric diketide methyl esters (Figure 6b and Figure S16 of the Supporting Information).

A parallel series of incubations of RifDH10 with the corresponding pantetheine and NAC thioesters also resulted in *syn* dehydration and hydration of only the anomalous (2*R*,3*R*)-2-methyl-3-hydroxyacyl thioester diastereomers and their corresponding (*E*)-2-methyl-2-enoylacyl thioesters (Figure 6c and Figures S17–S23 of the Supporting Information). Thus, incubation of RifDH10 with (2*R*,3*R*)-2-methyl-3-hydroxypentanoyl-*S*-pantetheine (**7b**), prepared by diastereospecific reduction of (2*RS*)-2-methyl-3-ketopentanoyl-*S*-pantetheine with TylKR1[26,44,50] and a coupled enzymatic NADPH-regenerating system,[44] gave exclusively (*E*)-2-methyl-2-pentenoyl-*S*-pantetheinate (**8**), as established by HPLC analysis and direct comparison with authentic synthetic standards (Figure 6c and Figures S19 and S20 of the Supporting Information). In agreement with this result, incubation of RifDH10 with (*E*)-2-methyl-2-butenoyl-*S*-pantetheine (**11**) yielded exclusively the *syn* hydration product (2*R*,3*R*)-2-methyl-3-hydroxybutanoyl-*S*-pantetheine (**12b**) (Figure 6d and Figures S22 and S24 of the Supporting Information). The isomeric (*Z*)-2-methyl-2-butenoyl-*S*-pantetheine (**13**) did not undergo RifDH10-catalyzed hydration. RifDH10 did not dehydrate diastereomeric diketide *S*-pantetheinate (2*S*,3*S*)-**7a**, (2*R*,3*S*)-**7c**, or (2*R*,3*S*)-2-methyl-3-hydroxypentanoyl-*S*-pantetheine (**7d**). Analogous results were also obtained using the corresponding NAC thioester analogues. Thus, RifDH10 catalyzed the *syn* dehydration of only (2*R*,3*R*)-2-methyl-3-hydroxypentanoyl-*S*-NAC (**9b**) to give the corresponding (*E*)-2-methyl-2-pentenoyl-*S*-NAC (**10**) (Figure 6c and Figure S19 of the Supporting Information). We also examined the effects of acyl chain length and substitution pattern, observing that RifDH10 catalyzed the reversible dehydration of (3*R*)-hydroxybutanoyl-*S*-pantetheine (Figures S21 and S24 of the Supporting Information) and the hydration of (*E*,*E*)-2,4-hexadienoyl-*S*-pantetheine (Figure S23 of the Supporting Information).

Incubation of the Rif[DH10][KR10] fusion protein with chemoenzymatically prepared (2*RS*)-2-methyl-3-ketopentanoyl-EryACP6 gave only the corresponding product of reduction by RifKR10, (2*S*,3*S*)-2-methyl-3-hydroxypentanoyl-EryACP6 (**5a**), with no detectable dehydration product, in contrast to the processing of the RifACP10-bound substrate, which resulted in both reduction and dehydration to give the corresponding (*E*)-2-methyl-3-pentenoyl-RifACP10 product, as described above. In a like manner, although Rif[DH1]-[KR10] produced alcohol (2*S*,3*S*)-**5a** by diastereospecific reduction of (2*R*)-2-methyl-3-ketopentanoyl-EryACP6, gener-

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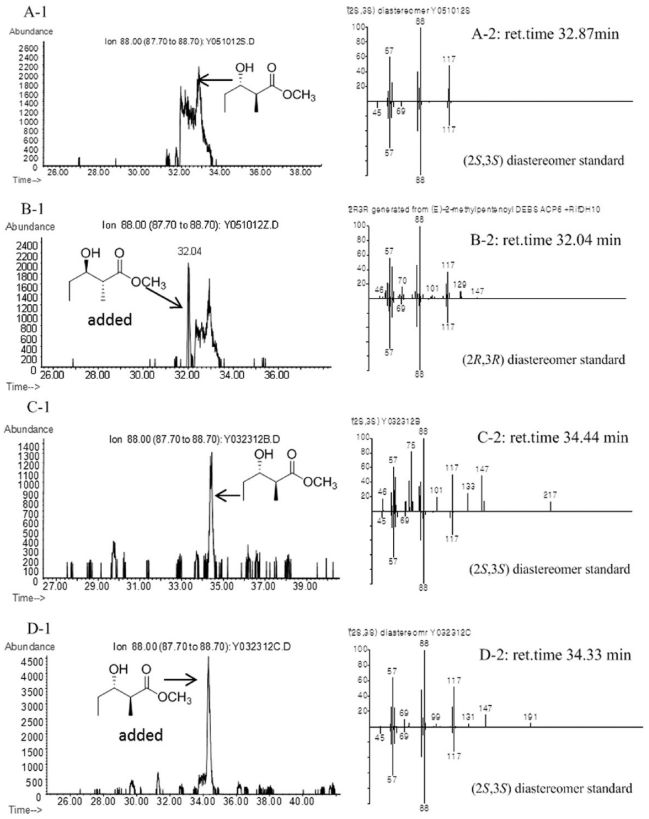

Figure 5. Chiral GC–MS analysis (method 4) of the incubation of (*E*)-2-methyl-2-pentenoyl-RifACP10-NusA with RifDH10. (A-1–D-1) Extracted ion current (XIC) at *m*/*z* 88 (base peak). (A-2–D-2) Mass spectra of selected peaks corresponding to diastereomers of methyl 2-methyl-3-hydroxypentanoate: (top halves) observed spectra and (bottom halves) inverted mass spectra of the reference standard. (A and C) (2*S*,3*S*)-**4a** generated by RifDH10. (B) Compound from panel A with (2*R*,3*R*)-**4b**. (D) Compound from panel C with (2*S*,3*S*)-**4a**. Detailed analysis of the full mass spectra of all peaks detected in panel A-1 between 31.00 and 34.00 min showed only the presence of the single (2*S*,3*S*)-**4a**.

ated *in situ* by decarboxylative condensation of propionyl-SNAC and methylmalonyl-CoA catalyzed by Ery[KS6][AT6] plus EryACP6, none of the corresponding dehydration product could be detected (Figure 2c and Figure S14 of the Supporting Information).

Structure of RifDH10. To improve our understanding of the protein structural basis for the dehydration reaction catalyzed by RifDH10, its structure was determined to 1.82 Å resolution (Figure 7 and Table 1). RifDH10 is structurally highly homologous to the other previously determined DH domains, including EryDH4 and the four DH domains from CurF, CurH, CurJ, and CurK of the curacin PKS [PDB entries 3EL6, 3KG6, 3KG7, 3KG8, and 3KG9, respectively, and root-mean-square deviations (rmsd) of 1.2, 1.8, 2.0, 2.3, and 1.7 Å, respectively].[10,21] RifDH10 possesses a characteristic double-hotdog fold and dimerizes through an interface largely created by its ~25 N-terminal residues (Figure 7a). The catalytic dyad, comprised of a histidine (H50) and an aspartic acid (D220), almost perfectly superimposes with the dyads of each of the other DH structures (Figure 7b). A hydrogen bonding network beginning with the phenolic hydroxyl of Y164 may increase the pK_a of the active site aspartate, thereby allowing it to act as a general acid for the dehydration reaction. A similar hydrogen

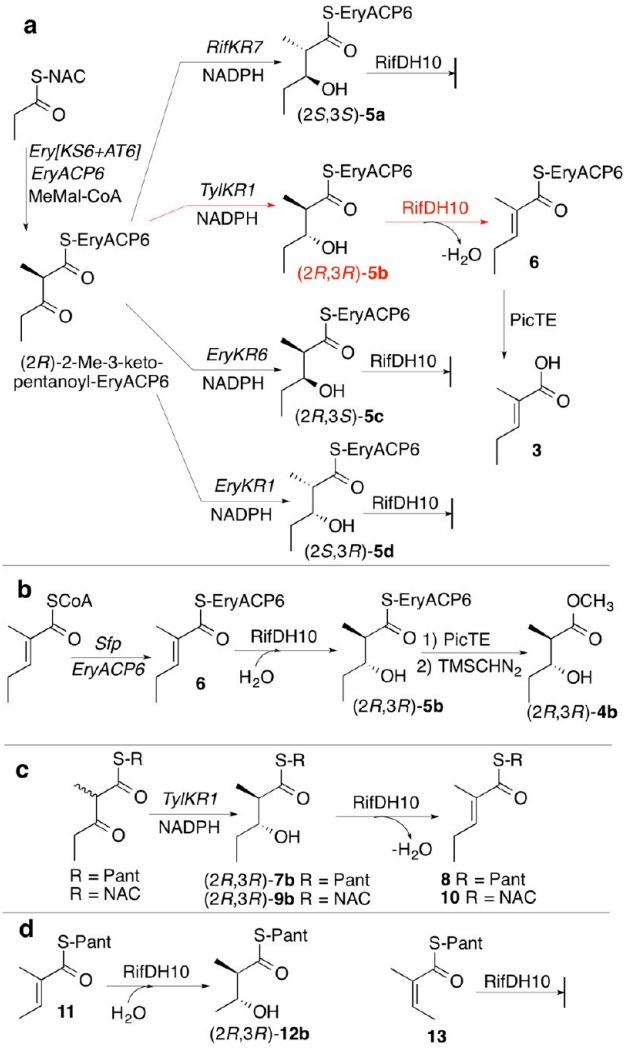

Figure 6. RifDH10-catalyzed dehydration and hydration of acyl thioester analogues. (a) Dehydration of (2*R*,3*R*)-2-methyl-3-hydroxypentanoyl-EryACP6 (**5b**). (b) Hydration of (*E*)-2-methyl-2-pentenoyl-EryACP6 (**6**). (c) Dehydration of (2*R*,3*R*)-2-methyl-3-hydroxypentanoyl-*S*-pantetheine (**7b**) and -*S*-NAC (**9b**) analogues. (d) Incubation of RifDH10 with (*E*)-**11** and (*Z*)-**13**.

bonding network is conserved in five of the six known DH structures, which employ either a glutamine or histidine (H224 in RifDH10) to bridge the network between Y164 and the catalytic aspartate. The exception is the CurH DH, in which an arginine occupies the corresponding site.

DISCUSSION

RifDH10 is only the second PKS DH domain for which both the protein structure and the stereospecificity of the dehydration reaction have been experimentally determined.[23] Consistent with the high degree of similarity in overall protein architecture between RifDH10 and EryDH4, as well as the essentially identical relative positioning of their conserved active site histidine and aspartate residues, we have established that both dehydratases catalyze *syn* elimination of water to give *trans*-unsaturated, trisubstituted carboxylic acid thioesters. On the other hand, these two closely related dehydratases actually catalyze the dehydration of effectively enantiomeric *syn*-2-methyl-3-hydroxyacyl substrates. Catalysis of each dehydration reaction is believed to involve deprotonation of C2 of the

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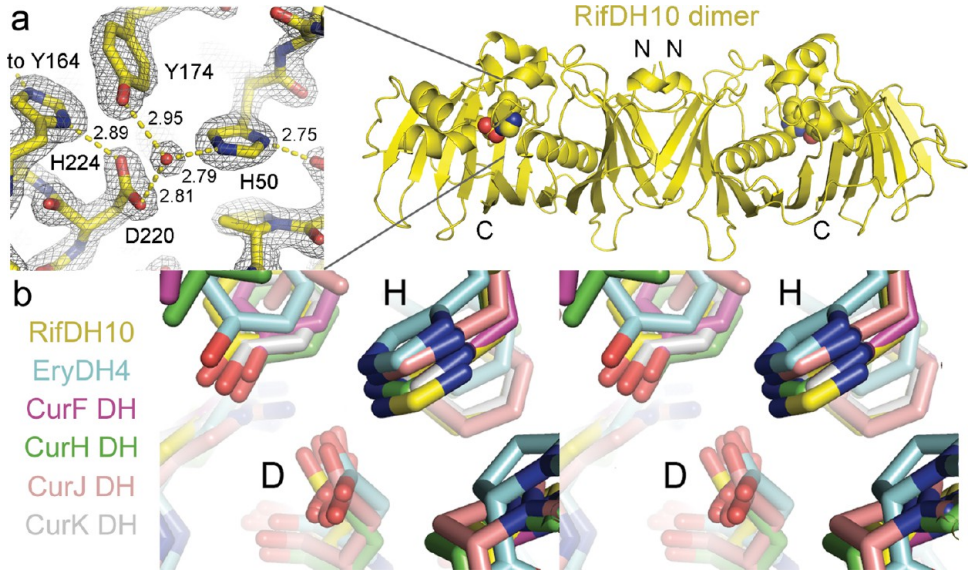

Figure 7. Structure of RifDH10 at 1.82 Å resolution. (a) The $2F_o - F_c$ electron density map (contoured at 1.8 rmsd) shows a water molecule, bound to the catalytic histidine (H50) and aspartate (D220), as well as a nearly invariant Y174, which is representative of the water molecule eliminated through a *syn* dehydration reaction. H224 and Y164 may help increase the pK_a of D220 through a hydrogen bonding network. (b) Stereodiagram of the superposition of the active sites of RifDH10, EryDH4, CurF DH, CurH DH, CurJ DH, and CurK DH, showing the catalytic His (H) and Asp (D) residues.

Table 1. Crystallographic Data and Refinement Statistics[a]

Data Collection	
space group	$P3_2$
cell dimensions *a*, *b*, *c* (Å)	77.2, 77.2, 97.9
resolution (Å)	50−1.82
R_{merge}	0.075 (0.807)
$I/\sigma(I)$	10.6 (2.0)
no. of reflections	55103 (4134)
completeness (%)	99.1 (99.9)
redundancy	5.3 (4.8)
Wilson *B* value (Å^2)	40.1
Refinement	
resolution (Å)	50−1.82
no. of reflections	55103 (4134)
R_{work}/R_{free}	0.211/0.254
no. of atoms	4444
protein	4134
water	310
average *B* factor (Å^2)	
protein	40
water	46
rmsd	
bond lengths (Å)	0.003
bond angles (deg)	0.759
Ramachandran statistics (%)	
preferred regions	95.8
allowed regions	4.2
outliers	0.0

[a]Values in parentheses are data for the highest-resolution shell (1.92−1.82 Å).

substrate by the imidazole side chain of H50 that acts as the general base, with either stepwise or concerted elimination of water promoted by protonation of the C3 hydroxyl by the carboxylic acid side chain of D220 (Figure 7b). These conserved active site residues have been shown to be essential not only in EryDH4[51] and in the dehydratase domain of animal FAS[52] but also in the corresponding type II FabZ dehydratase proteins of bacterial fatty acid biosynthesis.[53] The topological relationship of the active site histidine and aspartate residues is consistent only with net *syn* elimination of water from the substrate. Crotonase (enoyl-CoA hydratase), a mechanistically closely related enzyme from the fatty acid *β*-oxidation pathway, although differing from PKS and FAS DH domains in both active site residues and overall protein structure, has also been shown to catalyze reversible concerted *syn* addition of water to *trans*-enoyl-CoA substrates.[39,54]

In spite of all these mechanistic and structural similarities to other characterized DH domains, RifDH10 is unique in catalyzing the diastereospecific *syn* dehydration of a (2*S*,3*S*)-2-methyl-3-hydroxyacyl-RifACP10 substrate. This is in contrast to the demonstrated specificity of EryDH4, TylDH2, and NanDH2, all of which utilize only (2*R*,3*R*)-2-methyl-3-hydroxyacyl-ACP substrates, as well as the specificity of the DH domain of yeast FAS for (3*R*)-hydroxyacyl-ACP substrates.[55] Intriguingly, the intrinsic preference of RifDH10 for the (2*S*,3*S*)-2-methyl-3-hydroxyacyl thioesters is only evident when the substrate is tethered to its native acyl carrier protein, RifACP10. By contrast, RifDH10-catalyzed dehydration of the corresponding noncognate EryACP6 as well as the NAC and pantetheine thioester analogues is specific for the corresponding (2*R*,3*R*)-2-methyl-3-hydroxyacyl diastereomers, while in no case do either the (2*R*,3*S*)- or (2*S*,3*R*)-2-methyl-3-hydroxyacyl derivatives undergo dehydration. This reversal of substrate specificity is unprecedented. Although several EryKS domains have been shown to exhibit strong preferences for their cognate ACP domains in both intramodular condensation reactions and intermodular chain transfers,[35,56,57] and the stereoselectivity of KR-catalyzed reductions can require or be enhanced by tethering of 3-ketoacyl thioester substrates to an ACP domain,[36,50] this is the first example of the complete reversal of the diastereospecificity of a biochemical reaction based on the nature of the thioester conjugate.

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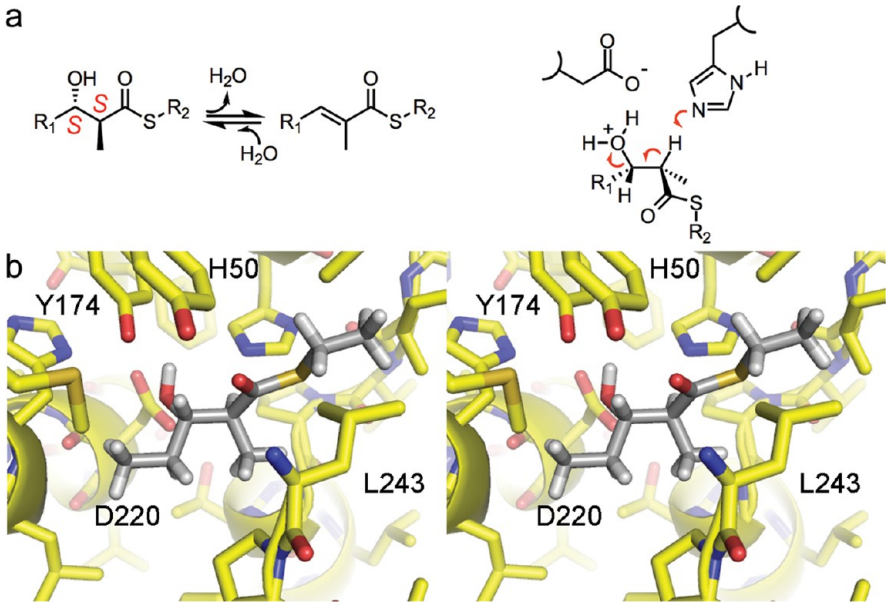

Figure 8. RifDH10-catalyzed dehydration. (a) *syn* dehydration of a (2*S*,3*S*)-2-methyl-3-hydroxyacyl thioester substrate generates a *trans* (*E*) double bond. (b) Stereodiagram showing the (2*S*,3*S*)-2-methyl-3-hydroxyacyl thioester substrate modeled into the active site of RifDH10. See Figure S2 of the Supporting Information for modeling of diastereomeric thioesters into the active site.

Several interlocking lines of argument support the biosynthetic relevance of the observed strict preference for the RifACP10-linked, (2*S*,3*S*)-2-methyl-3-hydroxyacyl thioester substrate. (1) RifACP10 is derived from the same parent module of the rifamycin synthase as is RifDH10 and therefore must represent the native carrier for dehydration of the natural ACP-bound acyclic undecaketide substrate within Rif module 10. (2) RifKR10, the paired KR domain that is also harbored in Rif module 10, generates exclusively the (2*S*,3*S*)-2-methyl-3-hydroxyacyl thioester, independent of the nature or origin of the attached ACP domain. Under natural conditions, therefore, RifDH10 should encounter only the (2*S*,3*S*)-2-methyl-3-hydroxyacyl undecaketide that will be tethered to RifACP10. (3) While most of the substrate analogues that have been tested *in vitro* with RifDH10 are diketide derivatives, longer chain acyl thioester substrates have no effect on the observed stereospecificity of RifDH10. (4) It highly unlikely that the *in vitro* results are artifacts and that the natural reaction on the undecaketide substrate would generate a *cis* double bond on the basis of both the highly conserved active site geometry of RifDH10, including the precise positioning of the catalytic histidine and aspartate residues in a topology that has been shown to catalyze *syn* dehydration by several other DH domains, and the exclusive formation and rehydration of *trans*-α,β-unsaturated trisubstituted enoyl thioesters. (5) If these *in vitro* results were simply the spurious consequence of the use of a deconstructed *in vitro* enzyme system, one would expect to see a simple degradation in overall diastereospecificity, rather than the observed complete reversal of the diastereospecificity that is cleanly correlated with the use of RifDH10 within its natural context.

The *syn* stereochemistry of the DH-catalyzed dehydration reaction is thus an intrinsic catalytic property that is rooted in the topological placement of the active site histidine and aspartate residues. This reaction stereochemistry should not be influenced by simple variations in the structure and stereochemistry of the substrate. While it is not unusual to observe degradation in substrate stereospecificity with the use of alternative substrates, to the best of our knowledge it is unprecedented to encounter a complete reversal in the apparent diastereospecificity that is a consequence of a change in the nature of the thioester conjugate. Although both the (2*S*,3*S*)- and (2*R*,3*R*)-2-methyl-3-hydroxyacyl thioesters can be modeled into the RifDH10 active site, with productive alignments of both the *syn*-related C2 proton and the C3 hydroxyl group with the corresponding H50 and D220 residues, the attached pantetheinyl moieties would be differently positioned in each case (Figure 8). While there is as yet no protein structure of a DH−ACP complex, several lines of evidence have supported the postulated existence of strong interactions between DH domains and their cognate ACP domains. Both pull-down and surface plasmon resonance experiments have shown a high affinity of the *Helicobacter pylori* ACP (HpACP) for the HpFabZ protein, with a K_d of 10 nM.[58] Similarly, *in silico* protein ligand docking and molecular dynamics simulations have been used to model complexes involving specific interactions of EryDH4 and holo-EryACP4.[59] We surmise that substitution by the noncognate EryACP6, which has a sequence that is only 43% identical to that of RifACP10, or by the simpler NAC and pantetheine analogues results in the loss of critical RifDH10-RifACP10 interactions that are essential for the proper positioning of the tethered substrate within the active site, thereby permitting *syn* dehydration of the anomalously bound, diastereomeric (2*R*,3*R*)-2-methyl-3-hydroxyacyl thioester analogues.

Our results strongly indicate that during the course of rifamycin biosynthesis the combined action of the RifKR10 and RifDH10 domains from the terminal module of the rifamycin PKS naturally generates an acyclic (*E*)-2-methyl-2-enoyl undecaketide. We therefore suggest that isomerization of the (*E*)-2,3-double bond of the initially formed RifACP10-bound undecaketide intermediate to the corresponding *cis* geometry that is characteristic of both the cyclized intermediate proansamycin X and the ultimately derived rifamycin B probably most likely occurs during the subsequent macro-

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lactamization reaction that is catalyzed by the discrete amide synthase RifF.

■ ASSOCIATED CONTENT

Supporting Information

Structures of polyketides containing *cis* double bonds, modeling of reduced diketides into the RifDH10 active site, design of recombinant RifDH10 and RifACP10, GC−MS data for incubations of RifACP10- and EryACP6-bound substrates with RifDH10, LC−MS data for incubations of *S*-pantetheine and *S*-NAC thioesters with RifDH10, and preparation of *S*-pantetheine thioesters. This material is available free of charge via the Internet at http://pubs.acs.org.

Accession Codes

The atomic coordinates and crystallographic structure factors for RifDH10 have been deposited in the Protein Data Bank as entry 4LN9.

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Author Contributions

D.G. and Y.-O.Y. contributed equally to this work.

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Notes

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■ ABBREVIATIONS

ACP, acyl carrier protein; AT, acyltransferase; DH, dehydratase; ER, enoylreductase; Ery, 6-deoxyerythonolide B synthase; FAS, fatty acid synthase; GC−MS, gas chromatography−mass spectrometry; KR, ketoreductase; KS, ketosynthase; NAC, *N*-acetylcysteamine; Nan, nanchangmycin synthase; PKS, polyketide synthase; Rif, rifamycin synthase; TE, thioesterase; Tyl, tylactone synthase.

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