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Structure revision of cryptosporioptides and determination of the genetic basis for dimeric xanthone biosynthesis in fungi†

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Three novel dimeric xanthones, cryptosporioptides A–C were isolated from *Cryptosporiopsis* sp. 8999 and their structures elucidated. Methylation of cryptosporioptide A gave a methyl ester with identical NMR data to cryptosporioptide, a compound previously reported to have been isolated from the same fungus. However, HRMS analysis revealed that cryptosporioptide is a symmetrical dimer, not a monomer as previously proposed, and the revised structure was elucidated by extensive NMR analysis. The genome of *Cryptosporiopsis* sp. 8999 was sequenced and the dimeric xanthone (*dmx*) biosynthetic gene cluster responsible for the production of the cryptosporioptides was identified. Gene disruption experiments identified a gene (*dmxR5*) encoding a cytochrome P450 oxygenase as being responsible for the dimerisation step late in the biosynthetic pathway. Disruption of *dmxR5* led to the isolation of novel monomeric xanthones. Cryptosporioptide B and C feature an unusual ethylmalonate subunit: a hrPKS and acyl CoA carboxylase are responsible for its formation. Bioinformatic analysis of the genomes of several fungi producing related xanthones, *e.g.* the widely occurring ergochromes, and related metabolites allows detailed annotation of the biosynthetic genes, and a rational overall biosynthetic scheme for the production of fungal dimeric xanthones to be proposed.

Introduction

Anthraquinones and xanthones are among the most common and earliest discovered fungal secondary metabolites,¹ and they often have interesting and useful bioactivities. These compounds are polyketides, the skeletons of which are produced from acetyl and malonyl CoA by non-reducing polyketide synthases (nr-PKS).² Examples include: the anthraquinones emodin 1 and its reduced congener chrysophanol 2 which is a precursor of shamixanthone 3,³ and monodictyxanthone 4⁴ from Aspergillus nidulans.⁵ Emodin 1 is a precursor of the antifungal agent geodin 5,7 which while not strictly a xanthone, belongs to the same biosynthetic family. We have also recently isolated other xanthones such as agnestin A 6 from Paecilomyces variotii and linked it to its biosynthetic

genes.8 Cladofulvin 79 from the tomato pathogen Cladosporium

fulvum is a dimeric anthraquinone also derived from 2. Dimeric

In the course of our ongoing studies on fungal maleidride biosynthesis¹⁵ we analysed fermentations of the endophytic fungus *Cryptosporiopsis* sp. 8999, which produces the unusual octadride, viburspiran.¹⁶ This strain was also reported¹⁷ to produce a metabolite named cryptosporioptide, which was assigned the monomeric xanthone methyl ester structure 12 (Fig. 2). This structure contains an unusual ring-contracted xanthone which is difficult to rationalise biosynthetically, and an unprecedented *N*-malonyl aminal bridge. Further studies¹⁸ of this strain also led to the isolation of the corresponding free acid, named cryptosporioptide A 13, and cryptosporioptide B 14, which lacks the malonic acid ester amide bridge.

xanthones are also known, and they often have varied biological activities. ¹⁰ They include the antimalarial ascherxanthone A 8; ¹¹ the antimicrobial and anticancer dicerandrol C 9; ¹² and the mycotoxins secalonic acids B **10** and D **11** which are also known as ergochromes (Fig. 1). ¹³ Although many of the dimeric xanthones, particularly the widespread secalonic acid family, have been studied for many years, ¹⁴ key aspects of their biosynthesis such as the mechanisms and timing of the dimerisation process, and isolation and analysis of their biosynthetic gene clusters remain largely unknown.

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Fig. 1 Typical fungal anthraquinone and xanthone metabolites. Isotope labelling pattern is shown for emodin/chrysophanol with the polyketide starter unit indicated in red. The green square labels (e.g. C-12 of the secalonic acids) indicate equivalent carbons derived from the C-10 carbonyl of emodin/chrysophanol.

Subsequently, isolation of an analogue **15**, in which the malonate bridge has been replaced by a succinate, was reported from the insect parasite *Cordyceps gracilloides*. Onfusingly, this was also named cryptosporioptide A.

The structure of the parent cryptosporioptide 12 was assigned on the basis of FAB-HRMS which indicated a molecular formula $\rm C_{19}H_{19}NO_{10}$. Detailed analysis of 1D and 2D ^{1}H and ^{13}C NMR spectra gave the connectivities and relative stereochemistry on which the structures were assigned. The absolute configuration was assigned by circular dichroism allied to time-dependent density functional theory (TDDFT) computational procedures. The related structures 13 and 15 were assigned on the basis of the similarity of their NMR spectra and optical rotations to those originally reported for cryptosporioptide.

We now report the isolation and structure elucidation of a novel dimeric tetrahydroxanthone metabolite **16**, methylation of which gives a compound with identical NMR properties to those reported¹⁷ for cryptosporioptide, along with related dimeric structures, **17–19** (Fig. 2). Following sequencing of the biosynthetic gene cluster and targeted gene knock-outs, the monomeric

structures, **21** and **22** were also isolated. Comparison with genome sequences of fungi known to produce xanthones and related structures, allows identification and annotation of the biosynthetic gene clusters (BCGs) for several monomeric and dimeric xanthones, *inter alia* the secalonic acids.

Results

Cryptosporiopsis sp. 8999 was grown on a range of different media. Three related metabolites were produced in good yields when the fungus was grown on brown rice (e.g. Fig. 4B). The major metabolite (900 mg kg $^{-1}$) had almost identical IR, UV and 1 H and 13 C NMR data apart from the lack of a methoxy group when compared to that reported for cryptosporioptide A 13. 17 When esterified using TMS-diazomethane, the resulting methyl ester had identical NMR data to those reported for cryptosporioptide 12 by Saleem $et\ al.$, 17 for which the reported FAB-HRMS data was 444.0781 [M + Na] $^{+}$ ($C_{19}H_{19}NO_{10}Na$). However, when the molecular weight for the derivatised compound was redetermined using FAB-HRMS and ESI-HRMS, we obtained HRMS of 801.1506 [M + Na] $^{+}$, and 778.1828 [M] $^{+}$ respectively, both consistent with a molecular formula $C_{38}H_{34}O_{18}$, and notably lacking

Fig. 2 Previous (12–15) and reassigned (16–20) structures of the cryptosporioptides.

nitrogen. The ¹H NMR spectrum showed 9 hydrogen environments, but 19 different carbon environments were observed in the ¹³C NMR spectrum consistent with a symmetrical dimer.

The presence of a tetrasubstituted aromatic ring was indicated by *ortho*-coupled hydrogens ($\delta_{\rm H}$ 7.70 and 6.43 ppm, J=8.5Hz) in the ¹H NMR spectrum, which also showed two methyl singlets ($\delta_{\rm H}$ 1.65 and 1.59 ppm), two oxygen bearing methine singlets ($\delta_{\rm H}$ 3.42 and 5.64 ppm), two low field exchangeable hydrogens ($\delta_{\rm H}$ 11.69 and 14.02 ppm) and geminally coupled methylenes ($\delta_{\rm H}$ 3.39 and 3.44 ppm, J=15.8 Hz). The ¹³C NMR spectrum also showed other signals attributable to a phenolic ring ($\delta_{\rm C}$ 159.2, 157.2, 140.6 and 106.1 ppm), four ester/enolic carbons ($\delta_{\rm C}$ 165.5, 166.7, 170.0 and 104.4 ppm) and a benzophenone carbonyl (δ_C 187.9 ppm). Signals at δ_C 56.0, 58.8, 73.9 and 78.9 ppm are consistent with the presence of an epoxide, secondary alcohol and ether. The connectivities were determined from extensive HMBC correlations which confirmed the presence of the aromatic ring, and a highly substituted cyclohexene (Fig. 3), the key signal being H-5 (5.64 ppm) which correlates with a total of eight carbons (6, 7, 8a, 9, 10a, 11, 12 and 13 at δ_C 58.8, 56.0, 170.0, 187.9, 78.9, 28.6, 18.2 and 165.5 ppm respectively). The H-5/C-13 correlation establishes the position of attachment of the malonate moiety, the other malonate carbonyl (C-15) correlating with the methoxyl ($\delta_{\rm H}$ 3.65, $\delta_{\rm C}$ 52.7 ppm). The connectivities between the two carbocyclic rings were confirmed by observation of HMBC correlations (see

Fig. 3 Selected correlations observed in 2D NMR spectra of cryptosporioptide A dimethyl ester 17. Secalonic acid numbering used. See Table S7 (ESI†) for full details.

ESI Fig. S15†) from both H-5 (5.64 ppm) and H-4 (6.43 ppm) to the C-9 ketone ($\delta_{\rm C}$ 187.9 ppm), and nOes between the 12-methyl and H-4 in the aromatic ring. The relative stereochemistry C-5 to C-7 and C-11 was established by nOes between H-5 and H-7 and the 11- and 12-methyls.

While the absolute configuration of the original cryptosporioptide structure was established by comparison of the measured circular dichroism (CD) with that predicted by computational methods, the complete revision of the structure renders this assignment invalid, and indeed suggests caution should be exercised when applying these methods which are being increasingly used for configurational assignment. The absolute configuration at the C-10a stereogenic centres of secalonic acid B 10 and related structures, e.g. dicerandrol C 9 have been assigned on the basis of a positive $n-\pi^*$ CD band at 330-340 nm as 10aR and 10aS respectively (note change in CIP designation due to priority inversion for CO2Me and CH₂OAc). ²⁰⁻²² The absolute configuration of dicerandrol C 9 has also been confirmed by total synthesis.23 Cryptosporioptide A dimethyl ester 17 has a reported CD (341 nm, $\Delta \varepsilon = + 5.0$)¹⁷ which is consistent with the 10aR configuration. Thus cryptosprioptide can be designated as 5R,6S,7S,10aR.

Finally, the connectivity between the individual xanthone monomers was established by an intra-dimer nOe between 1-OH and H-3. The point of dimerisation was confirmed by isolation of monomers 21 and 22 following KO of DmxR5, the cytochrome P450 responsible for oxidative coupling (see below). Thus the previously reported structures 12, and 13 have been revised to 17 and 16 respectively, and we propose renaming them cryptosporioptide A dimethyl ester, and cryptosporioptide A respectively. We have not observed any trace of the methyl ester 17 in any of our extracts, and the reported isolation of 17 as a natural product is possibly an artefact of the purification involved (Sephadex LH20 eluted with methanol).

The remaining two dimeric metabolites, cryptosporioptides B **18** and C **19**, differ from cryptosporioptide A **16** in the malonyl subunit, their UV and NMR spectra being otherwise identical (see ESI Tables S1 and S2 \dagger). HRMS showed their molecular formulae to be $\rm C_{38}H_{34}O_{18}$ and $\rm C_{40}H_{38}O_{18}$ respectively. The NMR spectra showed the latter **19** to be also essentially symmetrical

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with signals attributable to the ethylmalonate moieties ($\delta_{\rm H}$ 3.29, 2H, m; 1.81, 4H, m; and 0.85, 6H, m). Doubling of some signals was observed, probably due to facile epimerisation of the ethylmalonyl substituent, giving diastereomers at C-13. The spectra for 18 are more complex with many signals doubled due to the presence of only one ethylmalonate moiety removing the symmetry. Again on the basis of the close similarities of the NMR spectra, the *C. gracilloides* metabolite¹⁹ 15 has been renamed as cryptosporioptide D 20.

While the biosynthetic pathways towards monomeric xanthones and related compounds such as geodin 5 have been investigated previously, there is much less information on the dimeric systems despite these having been the subject of intensive study over many years.10 The main question is the timing of ring cleavage to give the xanthone moiety relative to dimerisation. The recently reported20 co-occurrence of the monomeric blennolides (e.g. ergochrome B) with their symmetrical dimer, secalonic acid B 10 supports, but does not unequivocally prove that during secalonic acid biosynthesis, xanthone formation precedes dimerisation. In those systems where the anthraguinonoid carbonyl (i.e. C-10) is retained, it is often found as a methyl ester as in the secalonic acids (note C-12 in SA numbering), or partially reduced to a hydroxymethyl equivalent, e.g. in dicerandrol C 9, or fully reduced to a methyl group as in the ascherxanthones, e.g. 8 and cryptosporioptides 16-20. Other questions include: which of the original anthraquinone rings retains the cleaved carbonyl C-10 (C-12 in SA nomenclature) - that containing the polyketide starter unit as in secalonic acids, e.g. 10 and cryptosporioptides or the non-starter ring as in, e.g. ascherxanthones 8; and the location of the site of dimerisation (Fig. 1).

With these questions in mind, the 54 Mbp draft genome of Cryptosporiopsis sp. 8999 was obtained using Illumina MiSeq and assembled and annotated using Newbler v29. The total number of contigs was 2166 with an N50 of 204 Kb. Bioinformatic studies using antiSMASH24 identified ten BGCs containing non-reducing polyketide synthase (nr-PKS) genes. A putative gene cluster for xanthone biosynthesis25 was readily identified by BLAST analysis using protein sequences from: the shamixanthone 3/monodictyphenone 4 BGC from Aspergillus nidulans;5,6,26 the agnestin 6 BGC from Paecilomyces variotii;8 the recently (but partially, vide infra) described secalonic acid 10 BGC from Claviceps purpurea;27 the geodin 5 BGC from Aspergillus terreus;7 and the cladofulvin 7 BGC from Cladosporium fulvum.9 Development of a transformation system, targetted knockout of the putative cryptosporioptide (dmx) PKS using the bipartite method of Neilsen and coworkers, 28 and subsequent observation of abolition of all cryptosporioptide production (Fig. 4) proved this assignment to be correct. We then used the cryptosporioptide BGC to screen the genomes of other fungi for similar clusters. Penicillium oxalicum29 and Aspergillus aculeatus30 are both known to produce secalonic acid D 11,31 and their genomes have been sequenced.32 In both cases we found a BGC (P. oxa, A. acu Table 1) featuring homologs of many of the genes in the dmx BGC.

The *dmx* BGC spans approximately 84 Kb surrounding *dmxPKS* which encodes a fungal nr-PKS homologous to the monodictyphenone PKS (MdpG, 67% identity) from *A. nidulans*⁶

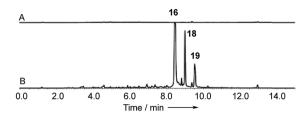


Fig. 4 Knockout of dmxpks1. (A) LCMS analysis (DAD) of organic extract of Cryptosporiopsis sp. 8999 $\Delta dmxpks1$ strain fermented on brown rice; (B) LCMS analysis (DAD) of organic extract of wild type Cryptosporiopsis sp. 8999 fermented on brown rice. LCMS method 50-90% CH₃CN:H₂O gradient, 15 min.

and the analogous polyketide synthases encoded by the geodin 5 (*ged*), agnestin 6 (*agn*), cladofulvin 7 (*cla*) and secalonic acid 10, 11 (*sec*) clusters (Table 1, Fig. 5). Homologies to all genes which encode proteins required for the synthesis of emodin 1 (*dmxpks*, *dmxR1*, *dmxR15* and *dmxR16*) are present, as are the genes required for the synthesis of chrysophanol 2 (*dmxR7*, *dmxR17* and *dmxR18*). The geodin pathway, which does not proceed *via* chrysophanol 2, lacks homologs of *dmxR17* and *dmxR18*.

Oxidative ring-opening of chrysophanol 2 is specified by dmxR6 which encodes a Baeyer-Villiger monooxygenase (BVMO) homologous to those encoded by the mdp, ged, agn and sec clusters where this transformation is required. Notably cladofulvin, which is a dimeric anthraquinone, does not require this chemistry and the cla cluster lacks a dmxR6 homolog. Beyond this point the content of the clusters varies significantly.

The *dmx* BGC has a series of unique genes not present in the other clusters such as *dmxR2*, *dmxR8*, *dmxR11-13* and *dmxL1-3*. In particular *dmxL2* encodes a highly reducing PKS (hr-PKS) homologous to the lovastatin diketide synthase³³ and squalestatin tetraketide synthase.³⁴ The gene *dmxL1* encodes an acyl-CoA carboxylase. The gene *dmxR5* encodes a cytochrome P450 enzyme homologous to ClaM which is known to dimerise nataloe-emodin to form cladofulvin 7.^{35,36} This gene is missing from the clusters of the monomeric compounds, but is present in the *sec* cluster (CPUR_05419). Finally, *dmxR13* encodes an *O*-acyl transferase, and again this is absent from the other clusters.

In order to gain evidence for the function of these genes we devised knockout experiments. Disruption of dmxR6 (BVMO) gave high titres of chrysophanol 2 as expected, showing that dimerisation occurs after anthraquinone ring cleavage and xanthone formation (Fig. 6). Deletion of dmxR5 (putative dimerase) abolished dimer production and two novel metabolites with similar UV spectra to the cryptosporioptides but with molecular weights consistent with monomers were isolated (Fig. 7). Full NMR analysis (see ESI†) confirmed that these were hemi-cryptosporioptide 21 ($C_{19}H_{18}O_9$), and an analogue 22 ($C_{19}H_{18}O_9$) containing a tertiary alcohol at C-6 which was isolated as a mixture of epimers at C-5.

When monomer 21, but not 22, was re-fed to the $\Delta dmxPKS$ mutant, cryptosporioptide A 16 production was restored (Fig. 8), confirming this as a pathway intermediate.

Table 1 The cryptosporioptide dimeric xanthone (dmx) cluster and similarities of encoded proteins with those of the monodictyphenone (mdp), geodin (ged), agnestin (agn), cladofulvin (cla) and secalonic acid (sec, P. oxa and A. acu) clusters

| Chemistry | Predicted function | Dmx | mdp | % ID | Ged | % ID | Agn | % ID | Cla | % ID | Sec | % ID | P. oxa | % ID | А. аси | % ID |
|-----------------------|-------------------------------|--------|-------|---------|-------------------|---------|---------|---------|--------------------|---------|-------------------------|----------------------|-----------------|---------------|-----------------|--------------|
| | Non-reducing PKS | DmxPKS | MdpG | 66.6 | GedC | 65.1 | Agnpks1 | 66.4 | ClaG | 53.6 | 05437 | 58.5 | 09237 | 62.4 | AacuL | 62.8 |
| Steps to | Hydrolase/thioesterase | DmxR1 | MdpF | 68.5 | GedB | 68.7 | AgnL7 | 65.1 | ClaF | 55.3 | 05436 | 65.5 | 09238 | 64.7 | AacuM | 64.1 |
| emodin | Decarboxylase | DmxR15 | MdpH1 | 60.1 | GedI | 67.0 | AgnL1 | 62.8 | ClaH1 ^d | 75.7 | 05434 | 76.0 | 09234 | 61.4 | AacuI | 62.2 |
| hydroquinone | Anthrone oxidase | DmxR16 | MdpH2 | 41.2 | GedH | 42.4 | AgnL2 | 46.7 | ClaH2 ^e | 32.7 | 05435 | 37.6 | 09232 | 61.2 | AacuG | 60.5 |
| | Oxidoreductase | DmxR7 | MdpK | 58.2 | GedF | 59.4 | AgnL4 | 62.6 | ClaK | 48.9 | 05430 | 51.8 | - | | | _ |
| Steps to | Dehydratase | DmxR17 | MdpB | 64.1 | _ | — | AgnL8 | 60.4 | ClaB | 60.8 | 05428 | 69.6 | 09236 | 58.5 | AacuK | 57.2 |
| chrysophanol 2 | Reductase | DmxR18 | MdpC | 79.7 | _ | _ | AgnL6 | 70.5 | ClaC | 76.1 | 05429 | 85.6 | 09239 | 71.6 | AacuN | 61.1 |
| BVMO | Baeyer–Villiger oxidase | DmxR6 | MdpL | 46.1 | GedK | 44.9 | AgnL3 | 65.3 | _ | _ | 05427 | 53.7 | 09233 | 62.1 | АасиН | 59.9 |
| C-5S reductase | SDR | DmxR3 | _ | _ | _ | _ | _ | _ | _ | | 05418 | 58.0 | _ | _ | AacuD | 64.8 |
| Dimerase | Cytochrome P450 | DmxR5 | _ | | _ | _ | - | - | ClaM | 33.3 | 05419 | 39.7 | 09230 | 44.7 | АасиЕ | 45.5 |
| C-5 hydrox. | Monooxygenase | DmxR9 | MdpD | 68.5 | _ | _ | _ | _ | _ | _ | 05423 | 55.8 | 09229 | 55.8 | AacuC | 56.6 |
| dmx, agn and sec only | Hypothetical | DmxR10 | _ | | _ | _ | AgnL5 | 46.0 | _ | _ | 05417 05425 05426 | 20.0 21.3 21.8 | 09240, 09241 | 46.0, 46.9 | AacuO, AacuP | 47.3 47.6 |
| ged and sec only | Methyltransferase | _ | _ | _ | GedG | - | _ | _ | _ | _ | 05424 | | 09242 | _ | AacuQ | _ |
| <i>dmx</i> only | Hypothetical | DmxR11 | _ | _ | _ | _ | _ | _ | _ | | _ | _ | _ | _ | - | _ |
| | SDR | DmxR12 | _ | - | — | _ | _ | _ | - | _ | _ | _ | - | _ | _ | |
| | O-Acyltransferase | DmxR13 | _ | _ | _ | _ | _ | _ | _ | _ | _ | | - | _ | _ | _ |
| | Cytochrome P450 | DmxL3 | _ | - | _ | | _ | _ | _ | | _ | | _ | _ | | _ |
| | Highly-reducing PKS | DmxL2 | _ | _ | _ | | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ |
| | Acyl CoA carboxylase | DmxL1 | _ | _ | - | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ |
| | SDR | DmxR8 | — | _ | - | _ | — | _ | _ | _ | _ | _ | _ | - | _ | _ |
| | Putative transferase | DmxR2 | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | - | _ | _ |
| | Acyl-CoA synthase | _ | MdpI | - | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ |
| mdp only | Glutathione S- transferase | _ | MdpJ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | | _ |
| ged only | Glutathione S- transferase | _ | _ | _ | GedE | _ | | | | | | | | | | |
| | O-Methyltransferase | _ | _ | | GedA | _ | _ | | _ | _ | _ | _ | _ | | _ | |
| | Dihydrogeodin oxidase | _ | _ | _ | GedJ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ |
| | Sulochrin halogenase | _ | _ | _ | GedL | _ | _ | _ | _ | _ | _ | _ | _ | _ | _ | |
| cla only | Oxidoreductase/SDR | _ | _ | _ | _ | _ | _ | _ | ClaN | _ | _ | _ | _ | _ | | _ |
| sec only | Hypothetical | _ | _ | _ | _ | _ | - | _ | _ | _ | 05420 | _ | 09235 | = | AacuJ | _ |
| | Monooxygenase | _ | _ | _ | _ | _ | _ | _ | _ | _ | 05431 | _ | | | | _ |
| | SDR (C-5 <i>R</i> reductase) | _ | _ | _ | _ | _ | _ | _ | | | _ | _ | 09231 | | AacuF | _ |
| Non-catalytic | Transcription factor | DmxR14 | _ | _ | GedR | 31.2 | AgnL10 | 29.4 | ClaE | 17.1 | 05433 | 32.8 | 09243 | 27.0 | AacuR | 28. |
| | Coactivator | _ | MdpA | _ | GedD ^c | _ | AgnL9 | | ClaA | _ | 05432 | _ | 09244 | _ | AacuS | |
| | Transcription factor | _ | MdpE | _ | _ | _ | _ | _ | _ | _ | 05421 | _ | _ | _ | _ | _ |
| | MFS transporter | DmxL4 | _ | _ | _ | _ | AgnL12 | 21.1 | _ | _ | 05422 | 47.9 | 09228 | 52.1 | _ | _ |
| | Transcription factor | _ | _ | - | _ | - | AgnL11 | | - | _ | | _ | _ | | _ | _ |
| | Transcription factor | _ | _ | _ | _ | _ | | _ | _ | _ | _ | _ | 09227 | _ | АасиВ | _ |
| | ABC transporter | | | | | | | | | | | | | | AacuA | |

Disruptions of *dmxL2* and *dmxL1* both abolished production of cryptosprioptide B **18** and C **19**, to give exclusively cryptosporioptide A **16** (Fig. 9B and C). Knockout of *dmxR13* gave a similar result, abolishing cryptosporioptide C **18** and D **19** production but retaining cryptosporioptide A **16** in smaller

quantities than previously (Fig. 9D). A number of new metabolites were produced in small quantities that precluded structure elucidation although mass spectrometry indicated molecular

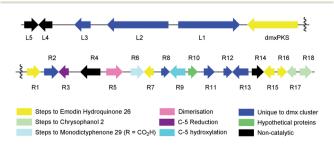


Fig. 5 Map of the cryptosporioptide dimeric xanthone (*dmx*) BGC coloured by proposed function (see Table 1). Not to scale.

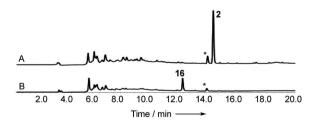


Fig. 6 Knockout of dmxR6 (BVMO). (A) LCMS analysis (DAD) of organic extract of Cryptosporiopsis sp. 8999 $\Delta dmxR6$ fermented on brown rice; (B) LCMS analysis (DAD) of organic extract of wild type Cryptosporiopsis sp. 8999 fermented on brown rice. LCMS method 50–90% $CH_3CN:H_2O$ gradient, 20 min. * = unrelated compound.

A 22 16 *

B 18*19

0.0 2.0 4.0 6.0 8.0 10.0 12.0 14.0 Time / min — 10.0 12.0 14.0

Fig. 7 Knockout of dmxR5 (P450). (A) LCMS analysis (DAD) of organic extract of Cryptosporiopsis sp. 8999 $\Delta dmxR5$ fermented on brown rice; (B) LCMS analysis (DAD) of organic extract of wild type Cryptosporiopsis sp. 8999 fermented on brown rice. LCMS method 50–90% $CH_3CN:H_2O$ gradient, 15 min. * = unrelated compound.

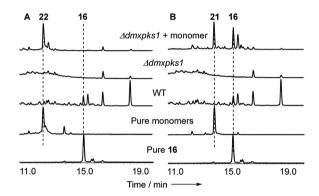


Fig. 8 Experiments showing that 21 is a precursor of 16: (A) feeding experiments using purified monomer 22; (B) feeding experiments using purified monomer 21. Fermentations were performed in liquid PDB media. LCMS method 10-90% CH₃CN:H₂O gradient, 20 min. DAD scans shown.

weights consistent with monomeric xanthones, in particular non-malonylated monomeric xanthone 35 (Scheme 1).

Discussion

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From these results, a biosynthetic sequence for cryptosporioptides can be proposed (Scheme 1) and more general conclusions

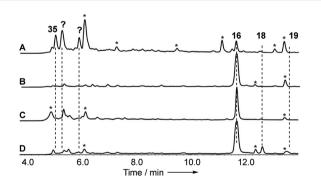


Fig. 9 Analysis of knockout experiments: (A) LCMS analysis (DAD) of organic extracts from $\Delta dmxR13$ (O-acetyl transferase); (B) LCMS analysis (DAD) of organic extracts from $\Delta dmxL1$ (acyl CoA carboxylase); (C) LCMS analysis (DAD) of organic extracts from $\Delta dmxL2$ (hrPKS); (D) LCMS analysis (DAD) of organic extracts from WT (Cryptosporiopsis sp. 8999). All strains were grown on brown rice. LCMS method 10–90% CH₃-CN:H₂O gradient, 15 min. * = unrelated metabolite.

for the formation of dimeric xanthones made. The BGCs encoding the biosynthesis of shamixanthone 3 (*mdp*),^{5,6} geodin 5 (*ged*),⁷ agnestin 6 (*agn*)⁸ and cladofulvin 7° (*cla*) are all known. Tudzynski and coworkers recently revealed a putative secalonic acid (*sec*) BGC in *Claviceps purpurea*.²⁷ In their analysis fifteen genes were described, but here, by comparison to the other known BGCs we extend this analysis to include six more genes in the *sec* cluster and two additional gene clusters from *Penicillium oxalicum* and *Aspergillus aculeatus* (Table 1 and see ESI†).

All analysed clusters encode proteins with high homologies (41-76% orf for orf) to proteins known to be involved in the biosynthesis of emodin hydroquinone 26, and all BGCs except that for geodin contain genes which advance the pathway to chrysophanol 2 (Table 1). Thus, the nrPKS (DmxPKS) produces an enzyme-bound octaketide 23 which is released (DmxR1, giving 24), decarboxylated (DmxR15, giving 25) and oxidised (DmxR16) to give emodin 1, followed by reduction (DmxR7) to emodin hydroquinone 26. These steps are fully consistent with previous experimental results.8 A-ring reduction (DmxR18 giving 27), dehydration (DmxR17) and probable spontaneous reoxidation, results in overall deoxygenation to chrysophanol 2, again consistent with previous results.8 Baeyer-Villiger oxidation (DmxR6) would then be expected to give monodictylactone 28 in equilibrium with monodictyphenone 29a ($R = CO_2H$) as we recently observed in the agnestin pathway.8 All pathways encode this BVMO except the cla cluster which does not form xanthones. We have previously8 demonstrated the existence of BVMO enzymes which have complementary regioselectivity, and such a BVMO is likely to be operating in the ascherxanthone 8 pathway in which C-12 (C-10 AQ numbering) becomes attached to the non-starter unit ring (Fig. 1).

At this stage we propose a branch-point in the pathway. Conversion of monodictyphenone 29a ($R = CO_2H$) to a methyl ester 29c would direct the intermediates towards the secalonic acids which feature a distinctive C-12 methyl ester. Recent results from Matsuda and coworkers support this conclusion by showing that a specific methyltransferase NsrG directs monodictyphenone 29a towards the biosynthesis of the heterodimeric xanthone neosartorin.37 This is consistent with the presence of methyltransferase-encoding genes (CPUR_05424, P_oxa-09242 and aacuQ) in the secalonic acid BGCs but not the others (Table 1). Alternatively, reduction at C-12 to form an aldehyde 29b would direct the pathway towards the shamixanthone group. In the case of the cryptosporioptides, however, reduction of C-12 to an alcohol 30 and hydroxylation at C-5 (likely DmxR9, see below) could give the electron-rich aromatic 31 which could eliminate H2O to form the ortho-quinonemethide 32, followed by tautomerisation to para-quinone 33 and complete the formal reduction to produce the 10-methyl group.

C-5 hydroxylation is required in the cryptosporioptide **16**, shamixanthone **3** and secalonic acid **10**, **11** pathways. In shamixanthone **3**, this is proposed to be carried out by the monoxygenase MdpD, which shows 68% homology to DmxR9, while CPUR_05423 encodes a homolog in the *sec* cluster. Homologs of DmxR9 are also encoded in the *P. oxalicum* and *A. aculeatus*

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Scheme 1 Proposed cryptosporioptide biosynthesis and relationships among monomeric and dimeric xanthone metabolites. Secalonic acid numbering used throughout.²⁰ Red bond indicates polyketide starter unit. Green atom derived from C-10 of chrysophanol (=C-12 secalonic acid numbering).

clusters. Notably homologs of *dmxR9* are missing from the *ged*, *agn* and *cla* clusters where this chemistry is not required.

In an early application of doubly ¹³C-labelled acetate feeding experiments, Vining and coworkers showed³⁸ that during secalonic acid biosynthesis in *Pyrenochaeta terrestris*, the initial product of anthraquinone ring cleavage must have a symmetrical 1,3-dihydroxyphenyl ring as in **29–33**. Our suggested pathway is in agreement with this observation.

We propose that conjugate addition of C-4a-OH to the resulting *para*-quinone 33 then gives cyclohexadienone 34, which is then reduced at C-5 to give the dihydroxanthone 35. The ring closing reaction may be performed by DmxR10. This protein has no close BLAST hits with proteins of known

function, but structural analysis using Phyre-2 (ref. 39) (see ESI†) shows that it contains a SnoAL domain⁴⁰ and is related to proteins such as PhzB⁴¹ and Trt14 (ref. 42) known to be involved in secondary metabolite ring-forming reactions.

In this step the stereochemistry at C-10a is set, and it is known that both epimers at this position can be formed in the cases of the secalonic acids (*e.g.* see Fig. 10). It is interesting to note that the three secalonic acid clusters examined here (Table 1) appear to encode multiple copies of this protein, conceivably explaining the presence of both 10a-epimers in these systems. However further experimental work will be required to confirm this hypothesis.

The 6,7-epoxide in the cryptosporioptides could be introduced by the cytochrome P450 monooxygenase encoded by

Fig. 10 Stereochemical analysis of the known secalonic acids and correlation with producing organisms *Penicillium oxalicum, Aspergillus aculeatus* and *Claviceps purpurea*. Atom labelling according to Fig. 1.

dmxL3, which is unique to the dmx cluster, to give 36. Our results suggest that the hrPKS (DmxL2) manufactures butyrate. This is consistent with domain analysis of DmxL2 (NCBI CDD)⁴³ which shows it to consist of N-terminal KS and AT domains, followed by a DH domain. Highly-reducing PKS often feature a *C*-methyltransferase domain but this appears to be absent or inactive in DmxL2, consistent with the lack of methylation observed. Canonical C-terminal ER, KR and ACP domains make up the rest of the hrPKS. Butyrate is then carboxylated (DmxL1) to form ethylmalonate. It is not yet clear whether the carboxylation occurs while the butyrate is attached to the ACP of DmxL2, but this unusual fungal metabolite could then be esterified to *O*-5 by DmxR13.

In the absence of ethylmalonate or the acyl transferase DmxR13, malonyl CoA can be used, possibly transferred by DmxR2. Finally, dimerisation (DmxR5) gives the observed dimers 16, 18 and 19 as the final products of the pathway. A homolog of dmxR5 is found in the C. purpurea sec cluster (CPUR_05419, again previously unrecognised) and P. oxalicum and A. aculeatus clusters, and the cladofulvin cluster where claM has been already shown to direct oxidative dimerisation. However, dmxR5 is missing from the agn, mdp and ged clusters as expected. The lower relative homology of the cladofulvin dimerase may reflect the fact that cladofulvin is a dimeric anthraquinone rather than a dimeric xanthone, and that cladofulvin is an asymmetric dimer in contrast to the symmetric cryptosporioptide and secalonic acid dimers.

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A key step in the pathways to the dimeric xanthone metabolites is reduction at C-5. This could result in either 5S or 5R products depending on the selectivity of the reductase. Both types of xanthones are known44 (Fig. 10) and are, as shown above, likely to be direct precursors of the secalonic acids. Indeed, the ergochrome nomenclature explicitly recognises this, such that secalonic acid A 38 is also known as ergochrome AA showing that it is a dimer of two xanthone A 39 units. Xanthones A 39, B 40, C 41 and D 42 have C-5S stereochemistry, while xanthones E 43 and F 44 and blennolide B 45 have 5R stereochemistry. C. purpurea produces secalonic acids which are derived from xanthones A-D and it thus must reduce to give exclusively 5S stereochemistry. In contrast P. oxalicum produces secalonic acid D 11 which derives from xanthone E 43 which has 5R stereochemistry. Aspergillus aculeatus, however, produces both secalonic acids B 10 and D 11 which are made from xanthones B 40 and E 43 and it must therefore be able to reduce at C-5 to give both possible stereoisomers. In accord with this observation the sec cluster encodes a single SDR, which is homologous to DmxR3 (58%). The cryptosporioptides 16, 18 and 19 and secalonic acids A 38 and B 10 possess 5S stereochemistry, so we propose that DmxR3 is a 5S reductase. The P. oxalicum cluster possesses a different SDR encoded by P_oxa-09231 and we propose that this is a 5R selective reductase. In agreement with these ideas the A. aculeatus cluster encodes two SDRs, one of which (AacuD) is homologous to the 5S reductase DmxR3, while the other (AacuF) is homologous to the 5R selective P_oxc-09231. Homologous SDRs are not encoded by the agn, geo or cla clusters where the pathways do not require C-5 reduction, again consistent with this hypothesis.

Conclusions

Here we have shown that the originally reported monomeric structures of the cryptosporioptides must be reassigned to a series of dimeric xanthones featuring unusual malonate substituents and full reduction at C-10 (=C-12 in SA nomenclature). Isolation of the cryptosporioptide BGC and its verification by directed knockout experiments allowed the unusual biosynthesis and attachment of the ethylmalonyl substituents to be determined. Furthermore, comparison with known, but partially characterised fungal gene clusters, has allowed a fuller hypothesis regarding the biosynthesis of the dimeric xanthones in general, and the secalonic acids in particular, to be developed. Questions remain surrounding the proposed reduction of monodictylactone 28 in the cryptosporioptide and shamixanthone pathways where evidence for enzyme candidates is lacking. Similarly the catalyst for xanthone formation in the shamixanthone pathway is unknown, although the cryptosporioptide, agnestin and secalonic acid pathways appear to use homologs of DmxR10 for this step. Missing catalysts in the shamixanthone pathway may be related to the fact that the shamixanthone BGC is split, with outlying prenyltransferase genes and at least one redox-encoding gene located in a BGC distant from the core PKS-encoding BGC so the 'missing' genes may be elsewhere on the A. nidulans genome. However, the remaining very close genetic, and therefore chemical,

homologies of the pathways revealed here should allow further targeted engineering in known dimeric xanthone clusters to be designed and performed, and it should also allow clusters encoding new dimeric xanthones to be more rapidly recognised and discovered.

Conflicts of interest

There are no conflicts to declare.

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