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The efficient and selective biocatalytic oxidation of norisoprenoid and aromatic substrates by CYP101B1 from *Novosphingobium aromaticivorans* DSM12444

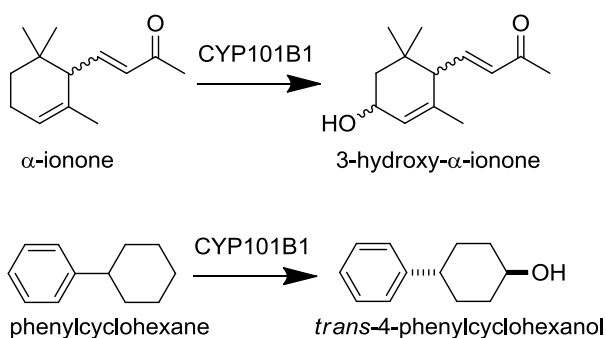
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TOC



CYP101B1 from *Novosphingobium aromaticivorans* oxidises ionone derivatives and phenylcyclohexane with high activity and regioselectivity.

Abstract

CYP101B1 from *Novosphingobium aromaticivorans* DSM12444 is a homologue of CYP101A1 (P450cam) from *Pseudomonas putida* and the CYP101D1, CYP101D2 and CYP101C1 enzymes from the same bacterium. CYP101B1 binds β -ionone more tightly than camphor and efficiently hydroxylates this norisoprenoid to 3-hydroxy- β -ionone, 90 %, and 4-hydroxy- β -ionone, 10 %. This reaction is supported by a ferredoxin reductase, ArR, and ferredoxin, Arx, electron transfer partners from *N. aromaticivorans*. The related norisoprenoids, α -ionone and β -damascone are both oxidised by CYP101B1 with high product formation activity, $> 500 \text{ min}^{-1}$. α -Ionone oxidation occurred regioselectively at the allylic C3 position while β -damascone was hydroxylated predominantly at C3 with the main competing minor product arising from oxidation at the allylic C4 position. When incorporated into a whole cell oxidation system, with ArR and Arx, CYP101B1 is also capable of oxidising indole to indigo indicating that aromatic molecules may be viable substrates. Phenylcyclohexane and *p*-cymene were tested and both were hydroxylated by CYP101B1. Phenylcyclohexane was selectively oxidised to *trans*-4-phenylcyclohexanol while *p*-cymene was hydroxylated at the benzylic carbons to yield a mixture of isopropylbenzyl alcohol and *p*- α,α -trimethylbenzylalcohol. *trans*-4-Phenylcyclohexanol was formed with a product formation rate of 141 min^{-1} and was five times more active than the oxidation of *p*-cymene.

Introduction

Cytochrome P450 (CYP) enzymes constitute a superfamily of heme-containing monooxygenases which, among other activities, are able to insert one oxygen atom from dioxygen into chemically inert carbon-hydrogen bonds with high regio- and stereoselectivity.^{1, 2} They are of great interest due to their myriad of physiological roles and potential application in the biocatalytic synthesis of fine chemicals under mild conditions.³⁻⁵ Dioxygen activation requires two electrons that are usually derived from NAD(P)H and delivered to the CYP enzymes by electron transfer proteins.⁶ Numerous CYP enzymes with potentially interesting and desirable activities have been discovered but many of these are orphaned, with no electron transfer partners located nearby in the genome, and their activities are often compromised in hybrid electron transfer systems.⁷⁻⁹ Therefore, the identification and characterisation of CYP enzymes with functional and highly active electron transfer chains is imperative in order to optimise the catalytic activity of this class of enzymes across a broad range of substrates and reaction types.

We have reported the heterologous production and purification of the majority of the sixteen P450 enzymes from *Novosphingobium aromaticivorans* DSM12444.^{5, 10} Potential substrates for many of these enzymes have been identified and these span a broad range of organic molecules including terpenoids, linear alkanes and polyaromatic hydrocarbons.^{5, 11, 12} The CYP enzymes of this bacterium are presumably involved in metabolic processes which enable it to survive in the oligotrophic environments where it lives.^{13, 14} A class I electron transfer system, consisting of a flavin-dependent ferredoxin reductase, ArR, and a [2Fe-2S] ferredoxin, Arx, has been identified which is able to reconstitute the monooxygenase activity of at least five of these enzymes (CYP101B1, CYP101C1, CYP101D1, CYP101D2 and CYP111A2).^{5, 9, 10} Whole-cell systems capable of product formation on the gram-per-litre scale in shake flasks have also been constructed.¹⁰ Like P450cam (CYP101A1), CYP101D1 and CYP101D2 both bind and oxidise camphor (yielding ≥ 98 % 5-*exo*-hydroxycamphor). While CYP101B1 catalyses the unselective

oxidation of camphor generating four products, CYP101C1 does not. CYP101C1 and CYP101B1 are able to bind and oxidise β -ionone. Crystal structures of CYP101D1, CYP101D2 and CYP101C1 and the ArR and Arx electron transfer partners reveal striking similarities between these CYP101 family enzymes and P450cam (CYP101A1).^{9, 15-18} The enzymes also provide templates in order to understand how variations in the amino acid sequence of closely related P450 enzymes can lead to different substrate binding preferences, altered product selectivity and a preference for specific electron transfer partners.^{9, 15-17}

CYP101B1 when combined with ArR and Arx in a whole-cell oxidation system was found to turn the culture medium blue indicating that it is able to hydroxylate indole to 3-hydroxyindole which can then dimerise to form indigo.¹⁹ *Novosphingobium* species are able to degrade a wide variety of aromatic hydrocarbons and therefore CYP101B1 has the potential to be a biocatalyst for the oxidation of these hydrophobic substrates.^{10, 13, 14} Here we report our investigations into the substrate range of CYP101B1 and show it is a highly active and regioselective biocatalyst for the oxidation of α -ionone and β -damascone as well as β -ionone. We also investigate the ability of CYP101B1 to oxidise hydrophobic aromatic ring containing substrates such as phenylcyclohexane and *p*-cymene.

Results

Phylogenetic analysis of CYP101B1

CYP101B1 shares 46 % sequence identity with CYP101D2 and 44 % with CYP101A1, and CYP101D1 (Fig. 1 and Table S1). A BLAST search revealed only one CYP enzyme in the NCBI database, from *Novosphingobium tardaugens* NBRC 1675, with a greater than 50 % identity to CYP101B1 (59 %). Other CYP enzymes identified in the 45-50 % range all have greater sequence homology with CYP101A1 or CYP101D2. As a result there are currently only two identified members of the CYP101B subfamily and both are found in species of *Novosphingobium* bacteria. CYP101B1 has little sequence similarity with its closest structurally characterised relative outside of the CYP101 family, CYP176A1 (P450cin) or other ionone binding P450 monooxygenases such as CYP109D1 and CYP264B1, or those from *Streptomyces* species which are known to oxidise norisoprenoids (Table S1, *vide infra*).²⁰⁻²³

Despite the relatively low sequence similarity with CYP101B2 from *N. tardaugens* a comparison of the residues that are likely to make up the active site and substrate access channel revealed the almost complete conservation of amino acids (Fig. 1 and Table S2). The only difference was the conservative replacement of Ile236 in CYP101B1 with Val244 in CYP101B2. This is the equivalent position to Val247 in P450cam a residue located in the active site which is important for substrate binding.²⁴ This comparison also revealed important differences in the active sites of the two CYP101B subfamily enzymes when compared to the other members of the CYP101 family. For example sequence alignment reveals that, Val91 aligns with Phe and Trp residues (Phe87; CYP101A1 numbering given) and His100 with Tyr residues (Tyr96). However there are similarities with Thr173 aligning with Thr residues (Thr185) and Val284 and Val385 with Val residues (Val295 and Val396; Table S2).²⁵⁻²⁹ Additionally residues such as Thr85 and Ile384 (Thr101 and Ile395) align with other Thr and Ile residues in all the CYP101 family members except CYP101C1.¹⁶

In CYP101B1 there are also changes to the residues that comprise the potassium binding site and salt bridge network of P450cam. Glu84 and Tyr96 of the P450cam potassium binding site are replaced with Arg72 and His80, respectively in CYP101B1. In the salt bridge network most of the residues are conserved but there are modifications with Asp97 being replaced by Gly81 and Lys178 by Arg166. These differences when taken together with those in active site are likely to account for lower affinity for camphor and the altered substrate profile and C-H bond oxidation selectivity of CYP101B1.⁵ It is of note that the number of different active site residues in CYP101B1 compared to CYP101A1 is greater than in both CYP101D enzymes but fewer when compared to CYP101C1 (Table S2 and Fig. 1 and 2).¹⁶

The acid alcohol pair of the I-helix which is involved in proton delivery and oxygen activation and the glutamate and arginine pair (EXXR), which is proposed to be involved in heme incorporation, are conserved in CYP101B1.^{30, 31} The normally conserved phenylalanine amino acid seven residues towards the N-terminus from the proximal iron ligating cysteine, Cys346, is also present (Fig. 1).³² One potentially interesting point of difference in the CYP101B1 sequence is the presence of a proline residue, Pro347, one residue to the the C-terminal side of the proximal cysteine. Proline occurs naturally at this position in chloroperoxidase and P450s such as CYP7A1, and CYP121A1.^{30, 33, 34} The introduction of proline residues at this position is known to have distinctive effects in other CYP enzymes, with the Leu358Pro mutant of CYP101A1 exhibiting the same spectral perturbations induced by putidaredoxin binding.^{35, 36} The Ile401Pro mutant of CYP102A1 (P450Bm-3) displays enhanced oxidation rates with non-natural substrates and exhibits unusual electronic properties and structural changes.^{37, 38}

The substrate range of CYP101B1

β -Ionone induces a large type I spin state shift ($\geq 95\%$) on substrate binding (K_d , $0.23 \pm 4\ \mu\text{M}$) to CYP101B1.^{5, 9, 10} The activity of CYP101B1 can be reconstituted using Arx, which is genomically associated with CYP101D2, in conjunction with ArR.⁹ Under standard assay conditions ($0.5\ \mu\text{M}$

CYP: 5 μ M Arx) CYP101B1 oxidised β -ionone with high NADH consumption (1600 ± 100 nmol-nmol P450⁻¹-min⁻¹, henceforth abbreviated to min⁻¹) and product formation rates (1010 ± 60 min⁻¹). This indicates that β -ionone may be, or is a close structural analogue of, the physiological substrate of CYP101B1.^{5,9,10} Similar spin state shifts and dissociation constants are observed with the closely related substrate α -ionone, ≥ 95 % and 0.26 ± 0.04 μ M (Fig. 3 and 4). The norisoprenoid β -damascone, which switches the position of the ketone and alkene moieties on the butenone side chain, displayed a lower spin state shift and weaker binding, 80 % and 8.3 ± 0.9 μ M (Fig. 3 and 4). Both substrates yielded fast NADH turnover frequencies with CYP101B1, α -ionone (1380 ± 140 min⁻¹) and β -damascone (931 ± 13 min⁻¹), though both are slower than β -ionone (Table 1).

The oxidation of β -damascone generated one major product (~86 %) and two minor products (Scheme 1 and Fig. 5). GC analysis revealed two major products from α -ionone oxidation in 63:37 % ratio (Fig. 5). The product formation rate of α -ionone and β -damascone were similar, 663 ± 56 min⁻¹ and 562 ± 12 min⁻¹, with the coupling of NADH to product formation for β -damascone (60 %) compensating for its lower NADH turnover frequency when compared to α -ionone (Table 1).

Using a whole-cell oxidation system which produced CYP101B1, Arx and ArR in *E. coli* we were able to generate 100 – 200 mg of a mixture of the products formed from each norisoprenoid. The whole cell biotransformation of α -ionone generates three products all in roughly equal amounts (30:37:33 % ratio, Fig. 5). The first two of these correspond to the two products observed *in vitro* and have masses indicating they are hydroxylated monooxygenase products (Mass 208.2). The third product, which was not observed in the *in vitro* turnovers, has a mass indicating it arises from further oxidation of an alcohol product to a ketone (Mass 206.1). The whole-cell oxidation of β -damascone and β -ionone yielded predominantly one main product (Fig. 5) which corresponded to the products of the *in vitro* turnover systems. β -Damascone oxidation produced two minor products in low yields. Purification and isolation of the individual products was carried out using silica gel

chromatography with only the fractions containing predominantly a single compound being taken forward for characterisation. We isolated ~2 - 10 mg of each product from β -ionone, α -ionone and β -damascone after chromatography, with the remaining product being found in mixed fractions. These pure samples were used to identify the products using NMR and mass spectrometry (Experimental and ESI). The products of α -ionone oxidation were identified as *cis*- and *trans*-3-hydroxy- α -ionone and 3-oxo- α -ionone (Scheme 1). The lack of significant quantities of the further oxidation product 3-oxo- α -ionone in the *in vitro* enzyme assays suggests it is only produced when the amount of α -ionone substrate is limited relative to the two hydroxylated products or that the increased solubility of the alcohols allow them to enter the cells more readily than the less soluble substrate. Furthermore the proportion of the *cis*- and *trans* isomers were different in the whole-cell oxidation turnover suggesting that the *trans* isomer is more readily converted to 3-oxo- α -ionone. The regioselective oxidation of α -ionone at C3 and the absence of any evidence of the epoxidation of the double bond suggests that the substrate must be held in the active site with the C3 pseudoequatorial and pseudoaxial C–H bonds held close to the heme iron.

The major product from β -ionone was confirmed as 3-hydroxy- β -ionone and the minor product co-eluted with 4-hydroxy- β -ionone produced by CYP101C1 and P450Bm3.^{10, 16, 39} β -Damascone oxidation by CYP101B1 yielded 86 % of the majority product, 3-hydroxy- β -damascone, and 11 % of the more abundant minor product, 4-hydroxy- β -damascone. (Scheme 1). The other minor product that was produced ($\leq 3\%$ of an *in vitro* reaction) was not generated in a sufficiently pure enough form in high enough yields for NMR characterisation. GC-MS analysis indicated that it is likely to be a further oxidation product of one of the alcohols (mass, 206.2). The ratio of 3-hydroxy- to 4-hydroxy- β -damascone is similar to that observed for the equivalent products of β -ionone suggesting these two substrates are bound in a similar orientation in the active site with the C3 carbon being closest to the heme iron followed by C4.

When using the CYP101B1 whole-cell oxidation system we observed the formation of a

blue coloured pigment in cells after induction, which can be the result of indigo formation from indole oxidation.^{10, 19} The addition of indole to this system resulted in increased levels of blue pigment (Fig. S1). This indicates that indole and related aromatic molecules may be viable substrates for oxidation by CYP101B1. Therefore we tested a small selection of aromatic substrates for their ability to bind to and be oxidised by CYP101B1 (*p*-cymene and phenylcyclohexane). *p*-Cymene resulted in virtually no shift to the high spin form compared to indole which induced a small spin state shift (15 %). Phenylcyclohexane induced a slightly larger shift of 20 % but bound to CYP101B1 with comparable affinity to β -damascone (Table 1, Fig. 3 and 4).

Both substrates induced moderate activity with CYP101B1 as measured by the NADH turnover frequency, but both are lower when compared to the norisoprenoids. Phenylcyclohexane was more active, $293 \pm 9.0 \text{ min}^{-1}$, than *p*-cymene, $197 \pm 6.0 \text{ min}^{-1}$. Indole did not induce any enzyme activity above that of the leak rate. HPLC and GC analysis of phenylcyclohexane turnover indicated that a single product was formed (Fig. 6). This was isolated using the whole-cell oxidation system, purified (~10 mg) and characterised using NMR as *trans*-4-phenylcyclohexanol. Coupling of the NADH consumption to product formation was calculated to be 48 % resulting in a product formation rate of $141 \pm 17 \text{ min}^{-1}$. Two products were observed in small quantities in the turnover of *p*-cymene. These were identified via GC and HPLC co-elution experiments as *p*- α,α -trimethylbenzyl alcohol (25 %) and isopropylbenzyl alcohol (75 %). The coupling of NADH to product formation and the product formation rates are low (13 % and $25.3 \pm 6.0 \text{ min}^{-1}$).

Overall the data suggests certain aromatic substrates such as phenylcyclohexane are good substrates for CYP101B1 resulting in moderate activity and regioselective hydroxylations. However the norisoprenoid type substrates, ionone and damascone, show high affinities and activities for CYP101B1 and are efficiently oxidised with high regioselectivity and rates of product formation. α -Ionone is solely oxidised at the allylic C3 C–H compared to β -ionone and β -damascone where C3 oxidation dominates but with a contribution from allylic C4 hydroxylation.

Discussion

To date the CYP101B1 enzyme from *N. aromaticivorans* is one of only two members of this subfamily of P450 enzymes known with the other member only having 59 % sequence identity. The low number of CYP101B subfamily members and the presence of both in *Novosphingobium* species hint at a potentially unique functional role. It is of note that CYP101B1 is located on a plasmid, whereas the electron transfer partners, ArR and Arx are located on the chromosomal genomic DNA with CYP101D1, CYP101D2 and CYP101C1.^{5, 10} The active site residues of CYP101B1 vary when compared to those of the camphor oxidising CYP101A1, CYP101D1 and CYP101D2 and these differences will modify the substrate selectivity away from camphor towards alternative substrates such as norisoprenoids. The most significant change is the absence of an equivalent residue to tyrosine 96 of CYP101A1 which in CYP101B1 is replaced with a histidine residue.

Potassium ions have been shown to increase the strength of camphor binding to CYP101A1. The behaviour of CYP101 family enzyme from *N. aromaticivorans* is different due to changes in the residues that comprise the camphor binding site between the CYP101 family members. The K⁺-binding site in CYP101A1 is octahedral, with the backbone carbonyl oxygens of Glu84, Gly93, Glu94 and Tyr96, and two water molecules, as ligands.⁴⁰ These residues are conserved in CYP101D2, but not in CYP101D1, CYP101C1 and CYP101B1. As well as the change at Tyr96, Glu84, is replaced with Arg residues in CYP101B1 and CYP101D1 and Gln in CYP101C1 which significantly reduces the effect of potassium on substrate binding.⁴¹ We have previously reported that, in common with these other CYP101 enzymes, CYP101B1 shows decreased activity at higher ionic strength predominantly due to an increasing K_M .⁴¹ The proximal face of CYP101B1 is likely to consist of more positively charged than negatively charged residues, similar to CYP101C1, CYP101D1 and CYP101D2, allowing for strong interactions with the negatively charged surface potential of Arx in the vicinity of the [2Fe-2S] cluster.⁴¹

The side-chains of Lys178, Asp182, Thr185, Arg186, Asp251, and Asn255 are involved in the extensive salt bridge interactions in camphor-bound CYP101A1.⁴²⁻⁴⁴ In addition the Asp97 (B' helix) and Lys197 (G helix) interaction has been proposed to play a role in camphor entry and product exit. Structural analysis of CYP101D1, CYP101D2 and CYP101C1 revealed that this salt bridge network was less extensive in these CYP101 family members. In CYP101B1 the changes of Lys178 to an arginine and the more dramatic alteration of Asp97 to a glycine would also be expected to alter this salt bridge network. The modifications in these regions along with those in the active site will alter the substrate range and C-H bond oxidation selectively of CYP101B1, relative to the other CYP101 subfamily members. Overall these changes in CYP101B1, when compared with CYP101A1, are fewer than those of CYP101C1 which agrees with the observation that CYP101B1 retains some binding affinity for camphor while binding of this substrate is virtually abolished in CYP101C1.^{5, 10}

CYP101B1 is able to bind norisoprenoids and camphor as well as selected substituted aromatics. It is tempting to speculate that the proline residue one position to the C-terminus of the proximal iron binding cysteinate residue contributes to the seemingly broader substrate range of this enzyme, though this remains to be confirmed. This would agree with data from the Ile401Pro variant of P450Bm3 but the CYP121A1 enzyme from *Mycobacterium tuberculosis* which has a proline in the same position has been reported to have a very specific substrate and reaction type, the C–C coupling of a cyclodipeptide.⁴⁵

The physiological substrate of CYP101B1 is yet to be confirmed. However, the norisoprenoid class of compounds such as β - and α -ionone and β -damascone are efficiently oxidised, the binding affinity for these substrates is relatively strong and they induce large type I spin state shifts. Norisoprenoids can be derived from the breakdown of carotenoids and *N. aromaticivorans* contains a carotenoid dioxygenase, though this is a 13,14-dioxygenase.⁴⁶ The relative location of the ketone and alkene functionalities in the butenone side chain has more of an

effect on the binding affinity than the location of the alkene double bond in the cyclohexyl ring with α - and β -ionone being better substrates than β -damascone. The location of the double bond in the cyclohexyl ring does have an effect on the selectivity of the hydroxylation. The allylic C3 C–H bonds of α -ionone being exclusively oxidised but for β -ionone and β -damascone allylic C4 hydroxylation is observed alongside C3 oxidation. The C–H bonds of the C3 in the norisoprenoid substrates, which are oxidised in the major products, are presumably held closer to the heme iron than any other C–H bond. The lower regioselectivity of β -ionone and β -damascone is presumably due to the more reactive hydrogens on the allylic C4 being in close enough proximity to the heme iron enabling them to compete with oxidation at C3. In α -ionone the C4 hydrogen is vinylic and the reactive alkene double bond must be too far away from the heme-iron for epoxidation to occur.

Microbial oxidative biotransformations of α - and β -ionones have been reported using different bacteria including *Streptomyces*.²¹ P450 enzymes from *S. griseolus* and *S. griseus* were shown to oxidise α - and β -ionone at the allylic C3 and C4 positions, respectively.⁴⁷ Variants of the self-sufficient cytochrome P450, P450Bm3, are able to selectively oxidise β -ionone at the allylic C4 position.³⁹ Others have reported the stereoselective oxidation of the different enantiomers of α -ionone at the C3 position.⁴⁸ The best reported product formation rates and coupling of these variants of the highly efficient and self-sufficient P450Bm3 enzyme with norisoprenoids are 280 min⁻¹ and 35 % for β -ionone, 152 min⁻¹ and 39 % for (*R*)- α -ionone and 98 and 44 % for (*S*)- α -ionone, which are lower than those observed with the CYP101B1/ArR/Arx system.⁴⁸

Other researchers have reported the binding and oxidation of ionones by the CYP264B1, CYP109B1 and CYP109D1 bacterial enzymes.^{20, 23, 49} The CYP109 enzymes were regioselective for oxidation at the allylic position while CYP264B1 oxidised both α - and β -ionones solely at C3.^{20, 23, 49} Non-physiological electron transfer partners were used for all three of these cytochrome P450 enzymes and the catalytic rates were slow compared to those reported for P450Bm3 and CYP101B1

($< 5 \text{ min}^{-1}$).

CYP101C1 from the same *Novosphingobium* bacterium is interesting in that it can rapidly oxidise β -ionone (PFR $\sim 2000 \text{ min}^{-1}$) to a mixture of 4-hydroxy- (75 %) and 3-hydroxy- β -ionone (25 %) but the turnover with α -ionone is much slower (PFR $\sim 220 \text{ min}^{-1}$). CYP101C1 oxidation of α -ionone is also regioselective for allylic C3 oxidation. It can also oxidise β -damascone to a mixture of 3- and 4-hydroxy products as well as further oxidation products. CYP101B1 is more active than all the other P450s tested so far for α -ionone oxidation. Whether this reaction is stereoselective with enantiomerically pure α -ionones remains to be determined. With β -ionone and β -damascone CYP101B1 is less active than CYP101C1 but alters the selectivity to favour oxidation predominantly at the C3 rather than the allylic C4 position. Of the other enzymes utilised to oxidise ionones P450Bm3 mutants and the CYP109 enzymes family are less active but are more selective for allylic hydroxylation at C4 while CYP264B1 is very selective for oxidation at C3 but has very low activity.

The selective oxidation of the unrelated and more hydrophobic aromatic substrate phenylcyclohexane to *trans*-4-phenylcyclohexanol by CYP101B1 at moderate activity on the aliphatic ring is interesting. Tyrosine variants of CYP101A1 have been used to oxidise phenylcyclohexane at predominantly the 4-position though the activities were lower. Other mutations in the active site were also shown to alter the selectivity though none were completely regioselective.⁵⁰⁻⁵² CYP108D1, also from *N. aromaticivorans*, has also been reported to tightly bind phenylcyclohexane and oxidise it to *trans*-4-phenylcyclohexanol, though the activity using non-physiological electron transfer partners is very low.⁵³ The oxidation of *p*-cymene was significantly slower than phenylcyclohexane suggesting the smaller size of this substrates is detrimental to binding and productive and selective turnover. *p*-Cymene can bind with either methyl or isopropyl substituent closest to the heme-iron. The combination of selective oxidations, high monooxygenase activities and the large total number of turnovers obtained using the whole-cell

oxidation system make CYP101B1 ideally suited to the biocatalytic generation of hydroxylated products.

Experimental Section

General

General reagents and organics were from Sigma-Aldrich or VWR, Australia. Buffer components, NADH, and isopropyl- β -D-thiogalactopyranoside (IPTG) were from Anachem (Astral Scientific, Australia) or Biovectra, (Scimar, Australia). UV/Vis spectroscopy was performed on Varian Cary 5000 or Agilent Cary 60 spectrophotometers. Gas chromatography (GC) analyses were carried out on a Shimadzu GC-17A instrument coupled to a QP5050A MS detector using a DB-5 MS fused silica column (30 m x 0.25 mm, 0.25 μ m) and helium as the carrier gas. Analytical liquid chromatography was performed using an Agilent 1260 Infinity pump equipped with an Agilent Eclipse Plus C18 column (250 mm x 4.6 mm, 5 μ m), an autoinjector and UV detector. A gradient, 20 - 95 %, of acetonitrile (with trifluoroacetic acid, 0.1 %) in water (TFA, 0.1 %) was used. NMR spectra were recorded using a Varian Inova-600 spectrometer

Phylogenetic Analysis

BLAST searches were performed using the databases at the National Center for Biotechnology Information. Sequence alignments were performed using ClustalW.⁵⁴ The evolutionary history was inferred by using the Maximum Likelihood method based on the Jones Taylor Thornton (JTT) matrix-based model.⁵⁵ The tree with the highest log likelihood is shown. Initial tree(s) for the heuristic search were obtained automatically by applying Neighbor-Join and BioNJ algorithms to a matrix of pairwise distances estimated using a JTT model, and then selecting the topology with superior log likelihood value. The tree is drawn to scale, with branch lengths measured in the number of substitutions per site. All positions containing gaps and missing data were eliminated. There were a total of 386 positions in the final dataset. Evolutionary analyses were conducted in MEGA6.⁵⁶

Protein production and purification

General DNA manipulations and microbiological experiments and the expression, purification and

quantitation of the electron transfer proteins ArR and Arx from *N. aromaticivorans* were performed as described elsewhere.^{5, 10} The CYP101B1 gene has been cloned into the pET26 vector and the encoded CYP101B1 protein was produced in *E. coli* BL21(DE3).^{5, 9, 10} A single colony was inoculated into 20 mL Luria-Bertani broth (LB) containing kanamycin (25 mg L⁻¹; LB_{kan}) and grown at 37 °C for 6 hours. This culture was then inoculated into LB_{kan} (1 ml per 500 ml) medium and grown at 37 °C for 6 h to an OD₆₀₀ of ~1. Protein production was induced by the addition of IPTG (0.1 mM, from a 0.5 M stock in water). The incubator temperature was lowered to 25 °C, and the culture was grown for a further 16 h. The red cell pellet, harvested from the culture by centrifugation (9000 g), was resuspended in 200 ml of buffer T (50 mM Tris, pH 7.4). The cells were lysed by sonication (30 x 20 s pulses with 40 s gap in between each pulse) and the cell debris was removed by centrifugation 27,000 g for 30 min at 4 °C. The supernatant was loaded onto a DEAE Fastflow Sepharose column (200 mm × 50 mm; GE Healthcare) and the protein eluted using a linear salt gradient of KCl (80 – 350 mM) in buffer T developed over eight column bed-volumes at a flow rate of 8 mL min⁻¹. The red protein-containing fractions were collected and concentrated by ultrafiltration. The protein was desalted using a gel filtration step on a G25 Sephadex column (600 mm × 10 mm) using Buffer T. The final purification step was anion-exchange chromatography using a Source-15Q column (120 mm × 26 mm; GE Healthcare) and eluting with a linear gradient of 50 – 250 mM KCl in buffer T developed over 20 column bed-volumes at a flow rate of 6 mL min⁻¹. Purified fractions ($A_{418}/A_{280} \geq 1.2$) were combined and concentrated by ultrafiltration. An equal volume of glycerol was added, the solution filtered through a 0.22-μm sterile syringe filter and stored at -20 °C. CYP101B1 was quantitated using $\epsilon_{417} = 113 \text{ mM}^{-1} \text{ cm}^{-1}$.¹⁰

Substrate binding and kinetic analysis

For substrate binding the P450 enzymes were diluted to ~2.0 μM using 50 mM Tris, pH 7.4. The high spin heme content was estimated, to approximately ±5 %, by comparison with a set of spectra generated from the sum of the appropriate percentages of the spectra of the substrate-free form (>95

% low spin, Soret maximum at 418 nm) and camphor-bound form (>95 % high spin, Soret maximum at 392 nm) of wild-type CYP101A1.

To determine the dissociation constant the CYP101B1 enzyme was prepared as above in a total volume 2.5 mL and used to baseline the spectrophotometer. Aliquots of substrate (0.5–2 μL) were added using a Hamilton syringe from a 1, 10 or 100 mM stock solution in ethanol. The solution was mixed and the peak-to-trough difference in absorbance recorded between 700 nm and 250 nm. Further aliquots of substrate were added until the peak-to-trough difference did not shift further. The apparent dissociation constants, K_d , were obtained by fitting the peak-to-trough difference against substrate concentration to a hyperbolic function (Eqn. 1):

$$\Delta A = \frac{\Delta A_{\max} \times [S]}{K_d + [S]} \quad \text{Eqn. 1}$$

Where ΔA is the peak-to-trough absorbance difference, ΔA_{\max} is the maximum absorbance difference and $[S]$ is the substrate concentration.

Both ionone substrates exhibited tight binding, with $K_d < 5[E]$, and in these instances the data were fitted to the tight binding quadratic equation (Eqn. 2):

$$\frac{\Delta A}{\Delta A_{\max}} = \frac{([E] + [S] + K_d) - \sqrt{([E] + [S] + K_d)^2 - 4[E][S]}}{2[E]} \quad \text{Eqn. 2}$$

where ΔA is the peak-to-trough absorbance difference, ΔA_{\max} is the maximum absorbance difference, $[S]$ is the substrate concentration and $[E]$ is the enzyme concentration.

NADH turnover assays were performed with mixtures (1.2 mL) containing 50 mM Tris, pH 7.4, 0.5 μM CYP101B1, 5 μM Arx, 1 μM ArR and 100 $\mu\text{g mL}^{-1}$ bovine liver catalase. The mixtures were oxygenated and then equilibrated at 30 $^{\circ}\text{C}$ for 2 min. Substrates were added as 100 mM stock solutions in ethanol to a final concentration of 1 mM. NADH was added to $\sim 320 \mu\text{M}$, final $A_{340} = 2.00$, and the absorbance at 340 nm was monitored. The rate of NADH turnover was calculated using $\epsilon_{340} = 6.22 \text{ mM}^{-1} \text{ cm}^{-1}$ (Table 1).

Product formation and isolation

Where authentic product standards were available they were utilised for identification purposes via HPLC and GC co-elution experiments. Extraction of the products from activity assays and product analysis by GC were performed as before.¹⁰ The *p*-cymene turnover products isopropylbenzyl alcohol and thymol eluted together on the GC-MS and HPLC. The alcohol products were derivitised using BSTFA/TMCS and analysed via GC-MS to identify the product as isopropyl benzyl alcohol rather than thymol. The product concentration in incubation mixtures was calculated by calibrating the total ion count response of the GC detector to products when available (or the substrate if the product was not available). Where more than one product was produced the detector response was assumed to be equal, e.g. 4-hydroxy- β -damascone and 3-hydroxy- β -damascone were assumed to have equal detector responses. The coupling efficiency was the percentage of NADH consumed that led to product formation.

GC-MS analyses were carried out with the injector held at 250 °C and the interface at 280 °C. The oven temperature was varied as follows: for norisoprenoids and phenylcyclohexane, 120 °C for 3 minutes followed by a gradient of 10 °C min⁻¹ for 10 min and held at 220 °C for a further 7 minutes; *p*-cymene 80 °C for 3 minutes followed by a gradient of 10 °C min⁻¹ for 14 min and held at 220 °C for a further 3 minutes. The GC retention times were as follows: β -ionone, 7.5 min; 4-hydroxy- β -ionone, 9.9 min; 3-hydroxy- β -ionone, 10.3 min; α -ionone, 6.7 min; *trans*-3-hydroxy- α -ionone, 9.4 min; *cis*-3-hydroxy- α -ionone, 9.5 min; 3-oxo- α -ionone, 9.8 min; β -damascone, 6.5 min; 4-hydroxy- β -damascone, 9.1 min; 3-hydroxy- β -damascone, 9.3 min; phenylcyclohexane, 5.1 min; *trans*-4-hydroxyphenylcyclohexane, 7.7 min; *p*-cymene 4.4 min; isopropylbenzyl alcohol, 8.9 min (14.0 after derivitisation); *p*- α,α -trimethylbenzylalcohol, 7.2 min; thymol, 8.9 min (11.9 after derivatisation); carvacrol, 9.1 min.

To isolate and identify products where standards were not available a whole-cell oxidation system utilising the plasmids pETDuetArx/ArR and pRSFDuetArx/CYP101B1 was used to oxidise β -ionone, α -ionone, β -damascone and phenylcyclohexane, as described previously.¹⁰ The

supernatant (200 mL) was extracted in ethylacetate (3 x 100 mL), washed with brine (100 mL) and dried with magnesium sulphate and the organic extracts were pooled and the solvent was removed by vacuum distillation and then under a stream of nitrogen. The products were purified using silica gel chromatography using a hexane/ethyl acetate stepwise gradient ranging from 80:20 to 50:50 hexane to ethyl acetate using 2.5 % increases every 100 mL. The composition of the fractions was assessed by TLC and GC-MS and those containing single products (≥ 95 %) were combined for characterisation. The solvent was removed under reduced pressure. The purified product was dissolved in CDCl_3 and the organics characterised by NMR spectroscopy and GC-MS. NMR spectra were acquired on a Varian Inova-600 and spectrometer operating at 600 MHz for ^1H and 150 MHz for ^{13}C .

A combination of ^1H , ^{13}C , COSY, HSQC and HMBC experiments was used to determine the structures of the products. The *cis/trans* configuration of 3-hydroxy- α -ionone diastereomers was assigned from the assignments of Yamazaki⁵⁷ and the selective nOe difference measurements in ROESY experiments. The diagnostic nOe was between the H3 and H6 protons in the *cis* diastereomer with the C11 methyl 3H signal.

NMR and GC MS data

Data for **3-hydroxy- β -ionone**: $m/z = 208.2$, ^1H NMR (600 MHz, CDCl_3) δ 7.21 (d, $J = 16.4$ Hz, 1H, H8), 6.11 (d, $J = 16.4$ Hz, 1H, H7), 3.99 (s, 1H, H3), 2.43 (d, $J = 17.5$ Hz, 1H, H4), 2.29 (s, 3H, H10), 2.09 (dd, $J = 17.3, 9.7$ Hz, 1H, H4), 1.83 – 1.78 (m, 1H, H2), 1.77 (s, 3H, H13), 1.49 (t, $J = 12.0$ Hz, 1H, H2), 1.11 (s, 3H, H11), 1.10 (s, 3H, H12); ^{13}C NMR (151 MHz, CDCl_3) δ 198.68 (C9), 142.47 (C8), 135.52 (C6), 132.50 (C5), 132.19 (C7), 64.27 (C3), 48.31 (C2), 42.70 (C4), 36.82 (C1), 30.03 (C11), 28.51 (C12), 27.22 (C10), 21.54 (C13).

Data for ***trans*-3-hydroxy- α -ionone**: $m/z = 208.1$; ^1H NMR (500 MHz, CDCl_3) δ 6.54 (dd, $J = 15.8, 10.1$ Hz, 1H, H7), 6.10 (d, $J = 15.8$ Hz, 1H, H8), 5.65 – 5.61 (m, 1H, H4), 4.27 (s, 1H, H3), 2.50 (d, $J = 10.1$ Hz, 1H, H6), 2.26 (s, 3H, H10), 1.84 (dd, $J = 13.5, 5.9$ Hz, 1H, H2), 1.62 (d, $J = 0.6$ Hz,

3H, H13), 1.41 (dd, $J = 13.6, 6.2$ Hz, 1H, H2), 1.03 (s, 3H, H11), 0.89 (s, 3H, H12); ^{13}C NMR (126 MHz, CDCl_3) δ 198.03 (C9), 147.09 (C7), 135.43 (C5), 133.61 (C8), 125.83 (C4), 65.47 (C3), 54.30 (C6), 43.83 (C2), 33.86 (C1), 29.31 (C11), 27.20 (C10), 24.70 (C12), 22.66 (C13).

Data for **cis-3-hydroxy- α -ionone**: $m/z = 208.1$; ^1H NMR (600 MHz, CDCl_3) δ 6.64 (dd, $J = 15.8, 9.6$ Hz, 1H, H7), 6.08 (d, $J = 15.8$ Hz, 1H, H8), 5.59 (s, 1H, H4), 4.25 (t, $J = 7.6$ Hz, 1H, H3), 2.29 – 2.25 (m, 4H, H6 & H10), 1.69 (dd, $J = 12.9, 6.5$ Hz, 1H, H2), 1.63 (s, 3H, H13), 1.40 (dd, $J = 12.8, 9.9$ Hz, 1H, H2), 0.98 (s, 3H, H11), 0.89 (s, 3H, H12); ^{13}C NMR (151 MHz, CDCl_3) δ 198.46 (C9), 147.83 (C7), 135.30 (C5), 132.68 (C8), 126.47 (C4), 66.37 (C3), 54.32 (C6), 40.65 (C2), 34.97 (C1), 29.10 (C11), 27.61 (C10), 26.41 (C12), 22.41 (C13).

Data for **3-oxo- α -ionone**: $m/z = 206.1$; ^1H NMR (600 MHz, CDCl_3) δ 6.69 (dd, $J = 15.8, 9.5$ Hz, 1H, H7), 6.20 (d, $J = 15.8$ Hz, 1H, H8), 5.98 (s, 1H, C4H), 2.73 (d, $J = 9.6$ Hz, 1H, H6), 2.37 (d, $J = 16.9$ Hz, 1H, H2), 2.29 (s, 3H, H10), 2.15 (d, $J = 17.0$ Hz, 1H, H2), 1.91 (s, 3H, H13), 1.09 (s, 3H, H11), 1.02 (s, 3H, H12); ^{13}C NMR (151 MHz, CDCl_3) δ 198.20 (C3), 197.49 (C9), 159.12 (C5), 143.57 (C7), 133.74 (C8), 126.88 (C4), 55.40 (C6), 47.33 (C2), 36.67 (C1), 27.89 (C10), 27.55 (C11), 27.31 (C12), 23.48 (C13).

Data for **3-hydroxy- β -damascone**: $m/z = 208.2$; ^1H NMR (600 MHz, CDCl_3) δ 6.74 (dq, $J = 13.8, 6.9$ Hz, 1H, H9), 6.16 (dd, $J = 15.7, 1.3$ Hz, 1H, H8), 4.11 – 4.04 (m, 1H, H3), 2.36 (dd, $J = 16.8, 5.8$ Hz, 1H, H4), 2.04 (dd, $J = 17.1, 9.3$ Hz, 1H, H4), 1.93 (dd, $J = 6.9, 1.4$ Hz, 3H, H10), 1.79 – 1.73 (m, 1H, H2), 1.54 (s, 3H, H13), 1.51 (t, $J = 12.0$ Hz, 1H, H2), 1.15 (s, 3H, H11), 0.99 (s, 3H, H12); ^{13}C NMR (151 MHz, CDCl_3) δ 201.85 (C7), 146.41 (C9), 139.87 (C6), 134.40 (C8), 128.23 (C5), 64.65 (C3), 47.78 (C2), 40.87 (C4), 36.31 (C1), 29.70 (C12), 29.08 (C11), 21.04 (C13), 18.41 (C10).

Data for **4-hydroxy- β -damascone**: $m/z = 208.2$; ^1H NMR (600 MHz, CDCl_3) δ 6.77 (dq, $J = 15.6, 6.9$ Hz, 1H, H9), 6.15 (dd, $J = 15.7, 1.5$ Hz, 1H, H8), 4.00 (t, $J = 5.0$ Hz, 1H, C4H), 2.03 – 1.96 (m, 1H, H3), 1.93 (dd, $J = 6.9, 1.5$ Hz, 3H, H10), 1.80 – 1.74 (m, 1H, H3), 1.69 – 1.65 (m, 1H, H2), 1.65 (s, 3H, H13), 1.45 (ddd, $J = 13.4, 7.7, 3.1$ Hz, 1H, H2), 1.04 (s, 6H, H11 & H12); ^{13}C NMR (151

MHz, CDCl₃) δ 200.89 (C7), 146.46 (C9), 143.59 (C6), 133.92 (C8), 130.98 (C5), 69.01 (C4) 34.64 (C2), 33.98 (C1), 28.82 (C11), 28.64 (C3), 27.64 (C12), 18.46 (C10), 17.96 (C13).

Data for ***trans*-4-phenylcyclohexanol**: $m^+/z = 176.1$

¹H NMR (600 MHz, CDCl₃) δ 7.31 – 7.16 (m, 5H, H 8-12), 3.70 (tt, $J = 10.7, 4.3$ Hz, H1_{ax}), 2.50 (tt, $J = 12.1, 3.4$ Hz, 1H, H4_{ax}), 2.13 – 2.07 (m, 2H, H3_{eq} & H5_{eq}), 1.96 – 1.90 (m, 2H, H2_{eq} & H6_{eq}), 1.50 – 1.58 (m, 2H, H3_{ax} & H5_{ax}), 1.48 – 1.40 (m, 2H, H2_{ax} & H6_{ax}).

Conclusion

CYP101B1 is a valuable addition to the field of monooxygenase biocatalysis. It is stable, produced in high yield and its electron transfer partners are known. It has product formation rates that approach, and in certain cases exceed, those of the self-sufficient P450Bm3. The coupling of reducing equivalents to product formation is also high. Using a whole-cell oxidation system we were able to generate significant quantities of hydroxylated metabolites. CYP101B1 was capable of oxidising a broad range of substrates including norisoprenoids, monoterpenes and hydrophobic aromatic compounds, which is distinct to the other members of the CYP101 family and therefore offers a specialised substrate binding profile. Taken together these factors, and the additional potential to engineer CYP101B1 for more efficient and selective turnovers, will enable the development of biocatalytic routes to as yet unobtainable fine chemicals.

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Table and Figures

Table 1. Substrate binding, steady state kinetic data and coupling for CYP101B1 with different substrates. Steady state turnover activities were measured using a ArR:Arx:CYP101B1 concentration ratio of 1:10:2 (0.5 μ M CYP enzyme, 50 mM Tris, pH 7.4). Coupling is the percentage efficiency of NADH utilisation for the formation of products. Rates are reported as mean \pm S.D. ($n \geq 3$) and given in nmol-nmol CYP⁻¹-min⁻¹.

CYP101B1/ substrate	%HS heme	K_d (μ M)	NADH consumption frequency (min ⁻¹)	Product formation rate (min ⁻¹)	Coupling %
β -ionone	≥ 95 %	0.23 ± 0.1	1600 ± 100	1010 ± 60	63
α -ionone	≥ 95 %	0.26 ± 0.04	1380 ± 140	663 ± 56	48
β -damascone	80 %	8.3 ± 0.9	931 ± 13	562 ± 12	60
phenylcyclohexane	20 %	7.8 ± 0.9	293 ± 9.0	141 ± 17	48
<i>p</i> -cymene	5 %	23.0 ± 3.0	197 ± 27	25.3 ± 6.0	13

Scheme 1. Substrate tested with CYP101B1 and the products isolated from the turnovers.

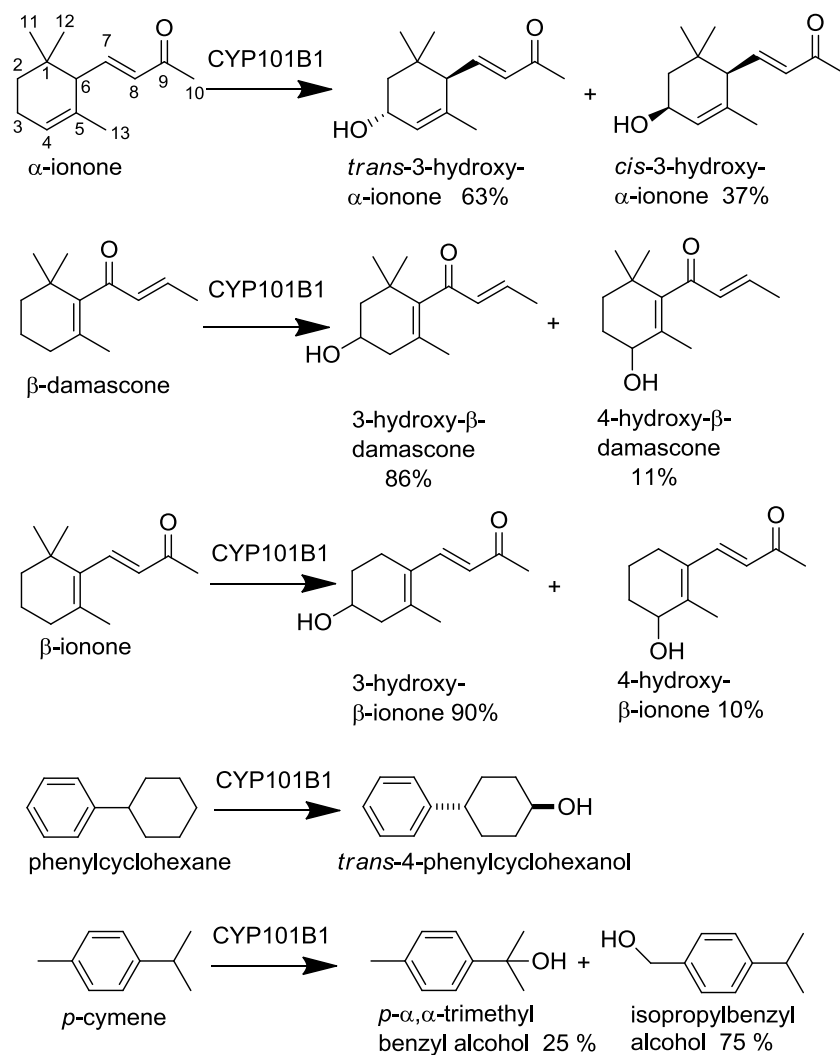


Figure 1 Protein sequence alignments of CYP101B1, CYP101D1, CYP101D2 and CYP101C1 from *N. aromaticivorans*, CYP101A1 (P450cam) from a *Pseudomonas putida* species and CYP101B2 from *Novosphingobium tardaugens* NBRC 16725

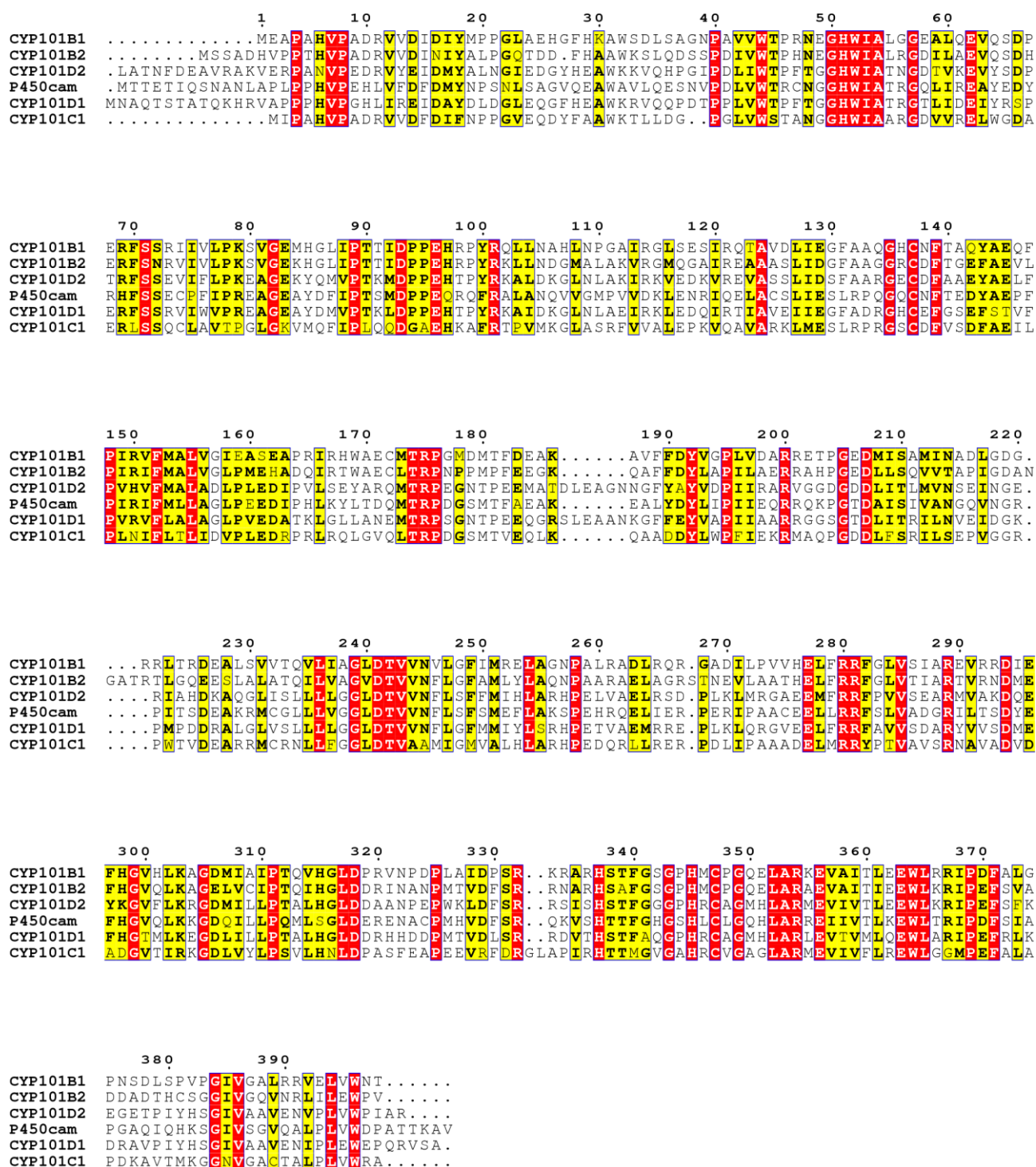


Figure 2. A phylogenetic tree (phenogram) of the CYP101 family of P450 enzymes from *N. aromaticivorans* DSM12444, CYP101B1, CYP101C1, CYP101D1 and CYP101D2, CYP101A1 (P450cam) from *Pseudomonas putida*, and CYP101B2 from *Novosphingobium tardaugens* NBRC 16725. Included for comparison are P450cin (CYP176A1) the closest structurally characterised homologue to CYP101B1 outside of the CYP101 family. Also included are CYP109D1 and CYP264B1 from *Sorangium cellulosum* and CYP105D1 from *Streptomyces griseus* all of which can bind and catalyse the oxidation of norisoprenoids.

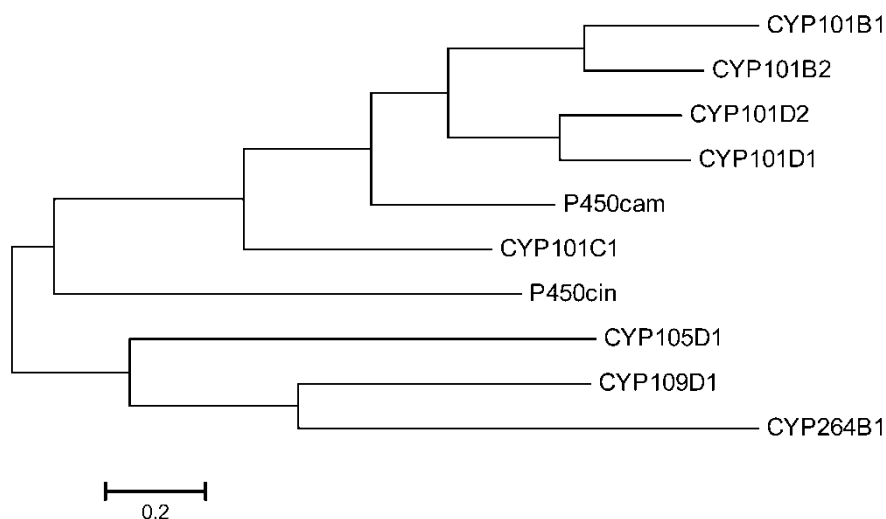


Figure 3. UV/Vis analysis of the CYP101B1 spin state shift with (a) α -ionone (b) β -damascone (c) phenylcyclohexane and (d) *p*-cymene.

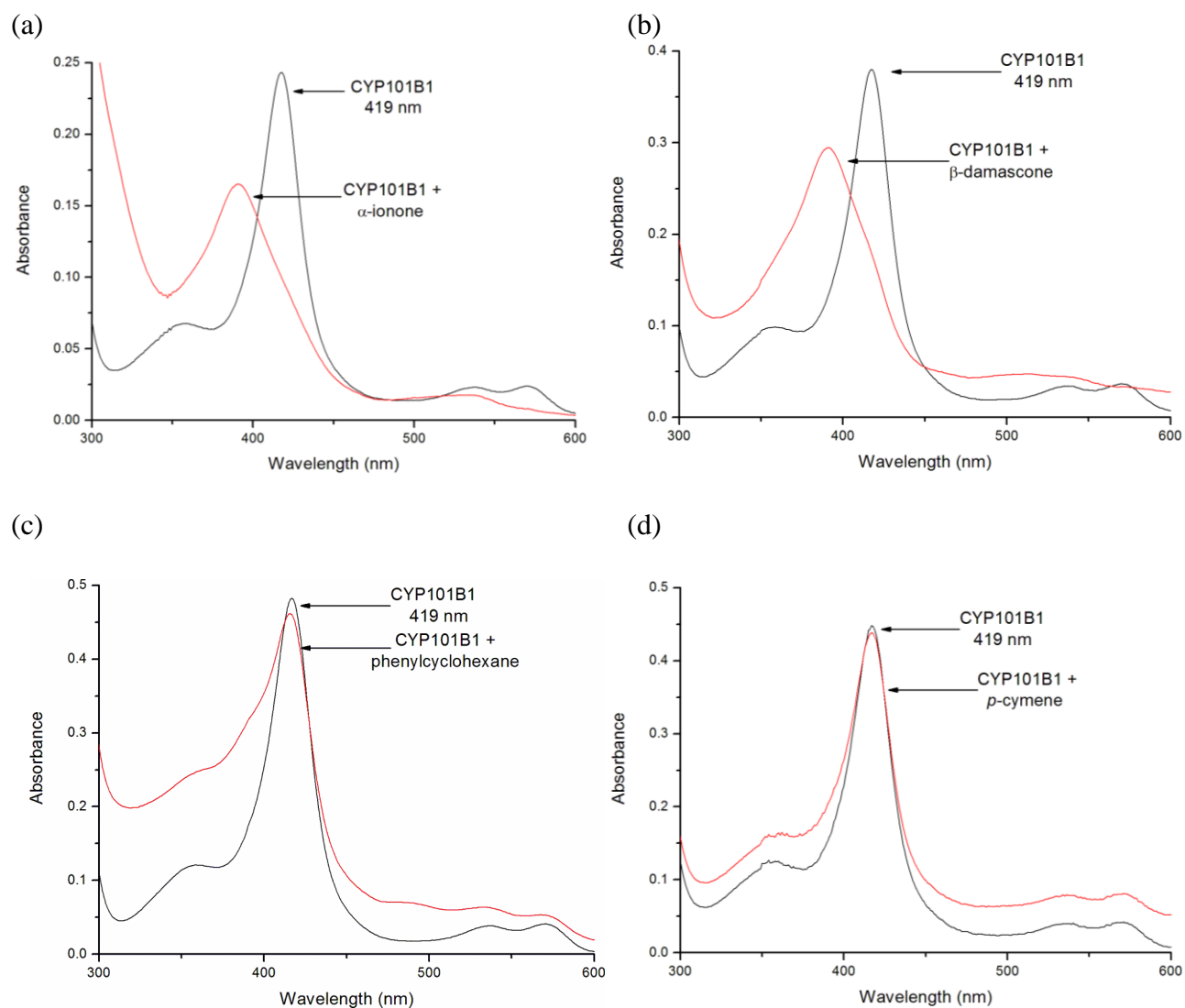


Figure 4. Substrate dissociation constant analysis of (a) α -ionone, (b) β -damascone, (c) phenylcyclohexane and (d) *p*-cymene with CYP101B1.

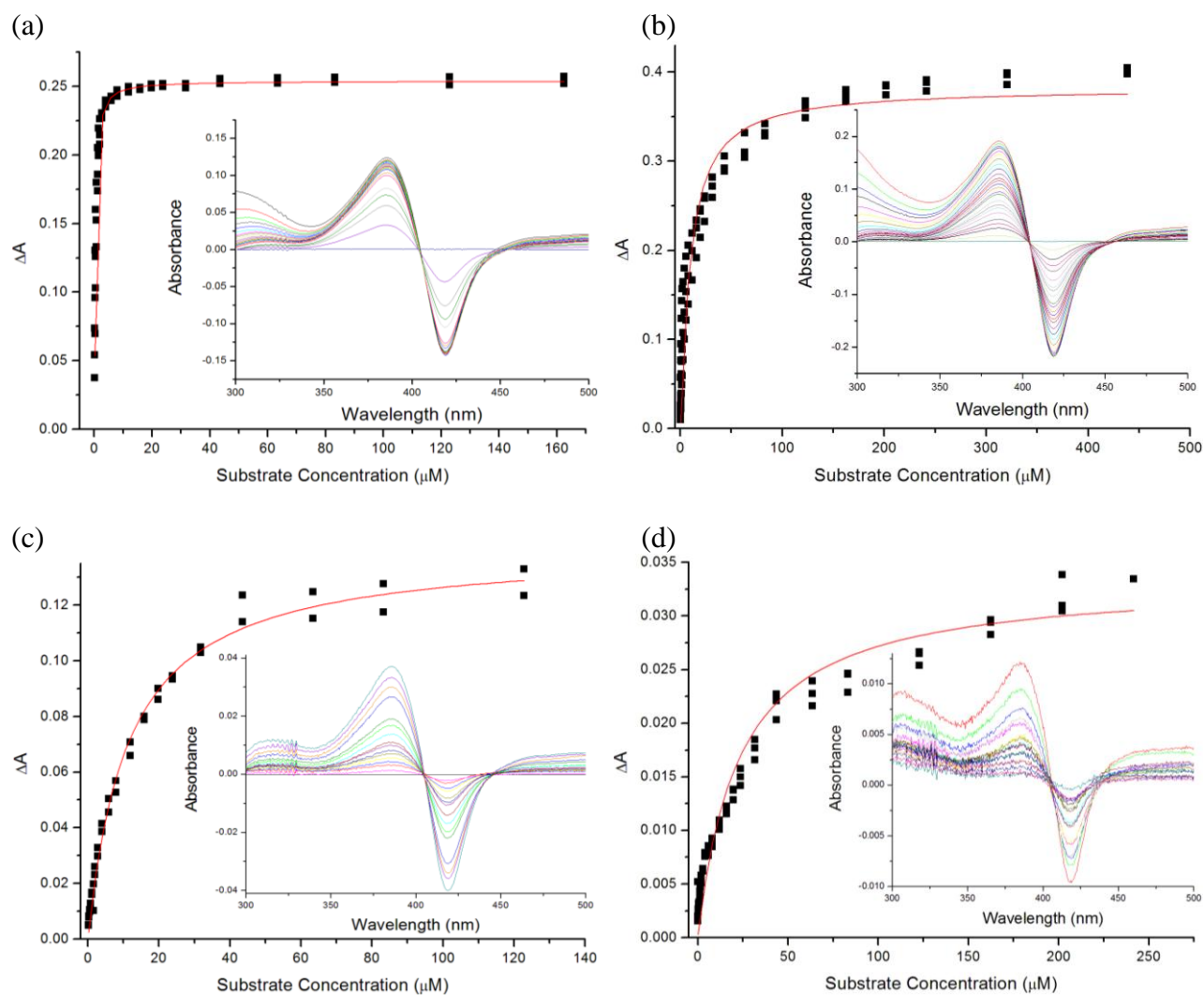
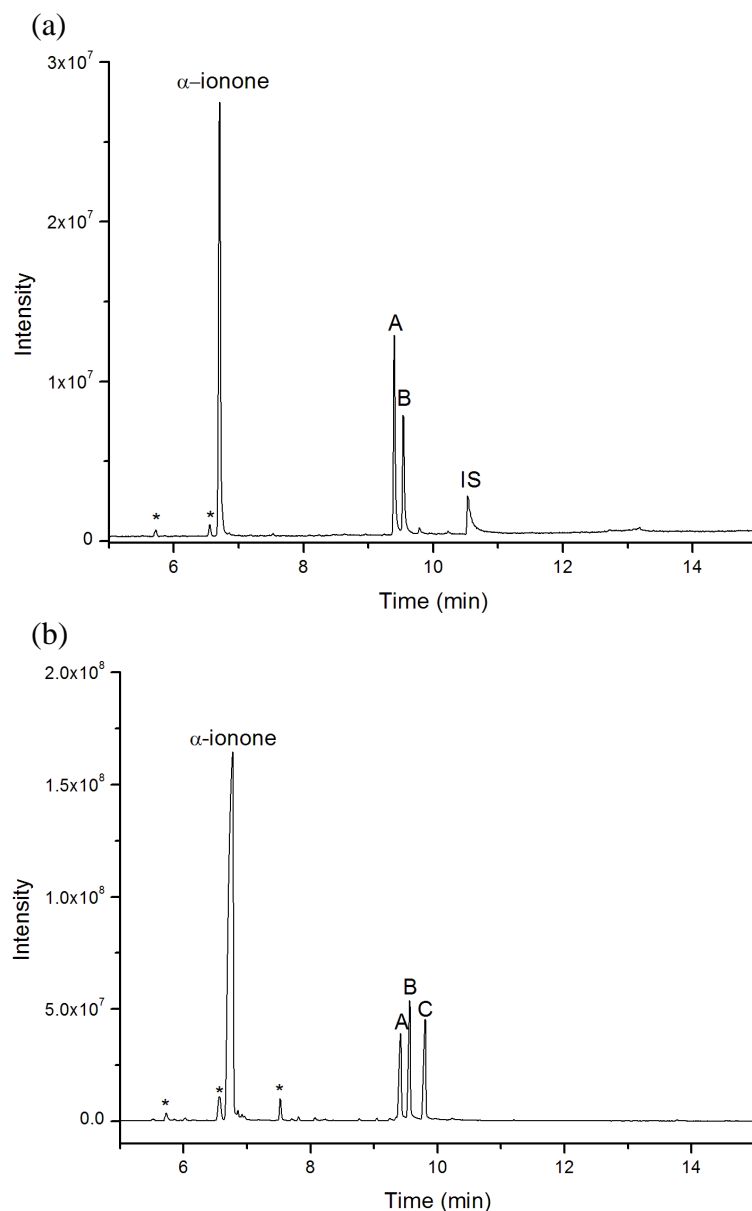
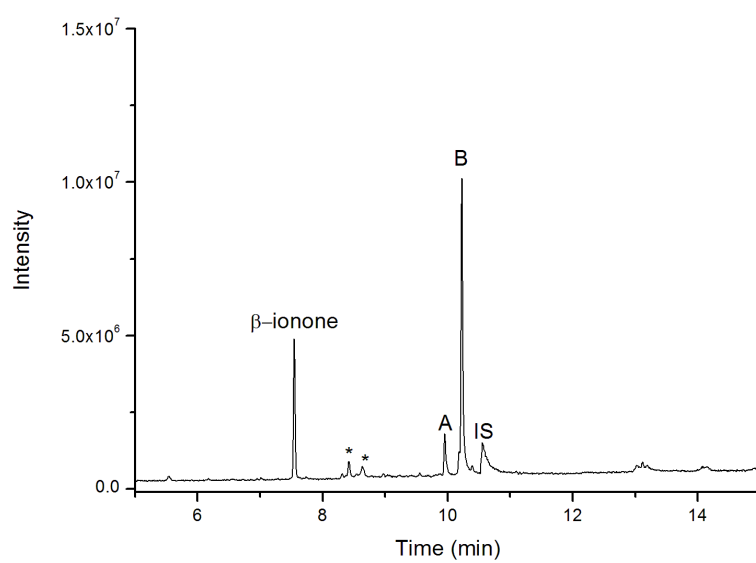


Figure 5 GC-MS analysis of CYP101B1 turnovers (Substrate, internal standard (IS) and impurities (*) are labeled); (a) *in vitro* turnover of α -ionone, (b) *in vivo* turnover of α -ionone (**A**, trans-3-hydroxy- α -ionone, **B**, cis-3-hydroxy- α -ionone and **C**, 3-oxo- α -ionone). (c) *in vitro* turnover of β -ionone (**A**, 4-hydroxy- β -ionone and **B** 3-hydroxy- β -ionone). (d) HPLC analysis of the *in vitro* turnover of CYP101B1 and β -damascone; **A**; 3-hydroxy- β -damascone, **B**; 4-hydroxy- β -ionone and **C**; a third minor oxidation product (likely a ketone).



(c)



(d)

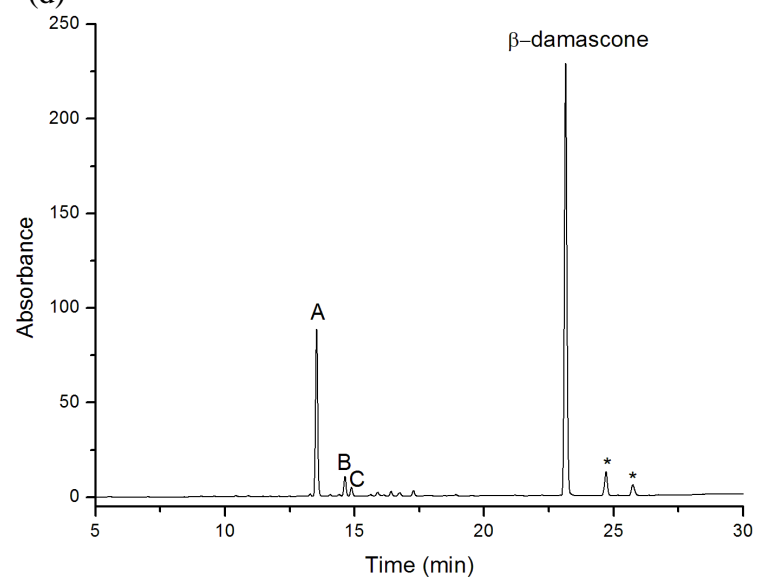


Figure 6 GC-MS analysis of CYP101B1 turnovers; (a) *in vitro* turnover of phenylcyclohexane (**A**, *trans*-4-phenylcyclohexanol) and (b) *in vitro* turnover of *p*-cymene (**A**, *p*- α,α -trimethylbenzylalcohol and **B**, isopropylbenzyl alcohol). Substrate, internal standard (IS) and impurities (*) are labeled.

