CytP450 has a cysteine-bound heme cofactor which, in its as-isolated resting (oxidized) form, can be conclusively described as a ferric thiolate species. Unlike the native enzyme, most synthetic thiolate-bound ferric porphyrins are unstable in air unless the axial thiolate ligand is sterically protected. Spectroscopic investigations on a series of synthetic mimics of cytP450 indicate that a thiolate-bound ferric porphyrin coexists in organic solutions at room temperatures (RT) with a thiyl-radical bound ferrous porphyrin i.e. its valence tautomer. The ferric thiolate state is favored by greater enthalpy and is air stable. The ferrous thiyl state is favored by entropy, populates at RT and degrades in air. These ground states can be reversibly interchanged at RT by the addition or removal of water to the apolar medium. It is concluded that hydrogen bonding and local electrostatics protect the resting oxidized cytP450 active site from degradation in air by stabilizing the ferric thiolate ground state in contrast to its synthetic analogues.
6.1. Introduction

Heme bound to a cysteine ligand is found at the active sites of several key enzymes in biology, including cytochrome P450 (cytP450) and nitric oxide synthase (NOS), which broadly comprise the cytP450 superfamily. Members of the cytP450 family of enzymes mediate key transformations in the synthesis of hormones and play an important role in the catabolism of metabolites and drugs. This subclass of heme enzymes distinguishes themselves by their ability to oxidize substrates using molecular O₂. The resting forms of their active sites are best described as an oxidized ferric heme bound to a thiolate ligand (the coordinating functional group of cysteine). The active sites in their resting ferric state are stable and only react with O₂ when they are reduced to the ferrous state. This is in sharp contrast to the behaviour of synthetic thiolate-bound ferric porphyrin complexes. Unless the thiolate is sterically protected, these synthetic ferric porphyrin complexes degrade in O₂. This phenomenon has remained an enigma ever since the initial reports of synthetic thiolate-bound ferric porphyrin complexes by Holm and Collman four decades ago. Similar sensitivity to O₂ by a formally oxidized metal center is exhibited by the active sites of ammine oxidase and intradioldeoxygenases. The sensitivity to O₂ is significantly reduced in thiolate-bound ferric porphyrins in aqueous environments which can catalytically hydroxylate inert C-H bonds using molecular O₂ with >200 turnovers i.e. bio-inspired functional mimics of CytP450. In addition, CytP450 enzymes form stable diamagnetic Fe₃⁺NO adducts. In contrast, attempts to form stable Fe₃⁺NO adducts of thiolate-bound iron porphyrin model systems inevitably resulted in the NO attacking the thiolate sulfur and not the iron. This is in spite of the fact that theoretical calculations predict these thiolate-bound porphyrin Fe₃⁺-NO species to be stable entities. Curiously, similar sensitivity to O₂ is also exhibited by most non-heme ferric thiolate and many nickel thiolate complexes which necessitates their handling in an inert atmosphere. This is particularly well established in the non-heme iron enzyme Nitrile Hydratase and its related synthetic models. While the active site, when isolated in the absence of air, bears three cysteine thiolates and is inactive, its reaction with O₂ leads to the active form which bears a cysteine sulfenate and a cysteine sulfinate as its ligands. Similar transformations have been reproduced in synthetic model complexes.
The existing paradox of O₂ sensitivity of synthetic thiolate-bound ferric heme complexes thus requires an unusual electronic structure to be present in its genesis. Resonance Raman (rR), electron paramagnetic resonance (EPR), and ¹H NMR are useful tools to investigate the electronic structures of ferric heme complexes.⁴⁵-⁴⁷ In particular, the oxidation and spin state marker modes in the rR spectra of iron porphyrin complexes find abundant use in inorganic/bio-inorganic spectroscopy.²², ³⁴, ⁴⁸ Synthetic iron porphyrin complexes show characteristic sets of ν₄ (1340-1375 cm⁻¹) and ν₂ (1540-1575 cm⁻¹) vibrations with very high fidelity (Table 6.1).⁴⁵ A series of iron porphyrin complexes with thiolate axial ligands (Figure 6.1) are investigated here using a combination of rR, EPR, and ¹H NMR spectroscopy. These complexes are previously characterized and vary in the nature of the thiolate ligand; the aliphatic complex (Figure 6.1A) is unstable in air and has an alkyl thiolate ligand, the bulky-aliphatic complex (Figure 6.1B) has a sterically protected alkyl thiolate and is stable in air, the benzylic complex (Figure 6.1C) is stable in air and the aromatic thiolate (Figure 6.1D) is unstable in air.⁴⁹-⁵¹ Excitingly, the data presented here show that these complexes exist as a mixture of two valence tautomers, namely ferric thiolate and ferrous thiyl species, in the solid state and in solution.

Figure 6.1: Iron porphyrin complexes bearing thiolate ligands
6.2. EXPERIMENTAL section

6.2.1. Materials and Methods

The organic solvents used are purified by distilling them in the presence of the appropriate drying agent. The solvents were degassed by three to five freeze-pump-thaw cycles and stored in an MBraun argon glove-box to prepare the solutions. All reactions were performed under inert conditions using Schlenk techniques. The aliphatic, bulky aliphatic and benzylic complexes were synthesized as previously described in the chapter 1. The synthesis of the [Fe(TPP)(SPh)] (aromatic) complex was carried out using solvents that were dried over CaH₂ and distilled under argon. The resonance Raman experiments were performed using a Coherent Sabre Kr ion laser and a Princeton Instruments Trivista 555 triple monochromator spectrograph fitted with a PixisExcelion CCD camera for all complexes. The EPR data were collected on a
Jeol instrument at the IACS EPR facility. The $^1$H NMR spectra were obtained on a Bruker DPX-300 or a DPX-500 instrument at room temperature (25°C) as well as low temperature (-60°C) in CDCl$_3$ solvent. The absorption data were collected on an Agilent technology 8453 spectrophotometer.

The data were collected using 413.1 nm laser excitation by irradiating the sample with <10 mW power. Normally the data are collected using a 45° back scattering configuration. The stray light is rejected using the first two stages of the Trivista monochromator as a tunable band pass. The variable temperature data are collected using a home built set-up where the temperature of a sample is maintained by controlling the flow of N$_2$ gas cooled by passing it through a Cu tube immersed in liq. N$_2$. The temperature is adjusted by controlling the flow of the cold N$_2$ gas and measured in-situ using an alcohol thermometer. The typical sample concentration is 1 mM.

6.3. Results and Discussion

6.3.1. Resonance Raman (rR)

rR data of the aliphatic complex (excitation wavelength 413.1 nm) with axial alkyl-thiolate ligation show the $\nu_4$ and $\nu_2$ modes at 1361 cm$^{-1}$ and 1554 cm$^{-1}$, respectively, at 77 K (LT) in a weakly coordinating solvent, indicating the presence of a high-spin Fe$^{III}$ center (Figure 6.2A and B). Similarly, the rR data of the aromatic complex shows the $\nu_4$ and $\nu_2$ vibrations at 1361 cm$^{-1}$ and 1553 cm$^{-1}$ (Figure 6.2D). In a coordinating solvent like MeOH, the $\nu_4$ and $\nu_2$ modes of the aliphatic-MeOH complex shift to 1369 cm$^{-1}$ and 1567 cm$^{-1}$, respectively, indicating the presence of a six coordinate low-spin Fe$^{III}$ center with methanol bound to the iron center (Figure 6.2A). The rR data of the benzylic complex at LT in a weakly coordinating solvent like THF show the presence of $\nu_2$ modes at 1552 cm$^{-1}$ and 1565 cm$^{-1}$ originating from a high-spin and low-spin Fe$^{III}$ species, respectively (Figure 6.2C). In MeOH solution this complex shows only one set of $\nu_4$ and $\nu_2$ modes at 1365 cm$^{-1}$ and 1565 cm$^{-1}$, respectively, suggesting the presence of a low-spin Fe$^{III}$ species in a coordinating solvent (Figure 6.2C). Importantly, rR data of this series of thiolate-bound ferric porphyrin complexes, collected at RT, show that there is a mixture of two species. One of them is the parent ferric thiolate species and the other is characterized by the $\nu_4$ and the $\nu_2$ bands at 1343-1346 cm$^{-1}$ and 1540-1543 cm$^{-1}$, respectively (Figure 6.2A, B, C and D).
Importantly, these values are characteristic of high-spin ferrous species. Although rR intensities are not quantitative, the relative intensities of the ferrous and ferric species at RT are comparable for all of these complexes. Furthermore, the change from a mixture of ferric and ferrous species at RT to a purely ferric species at LT is completely reversible as the same mixture is obtained when the frozen solution is warmed up to RT and vice versa (S6.1).

![Raman spectra](image)

Figure 6.2: rR data (413.1 nm, 10 mW) of the A) aliphatic, B) bulky aliphatic, C) benzylic, and D) aromatic complexes in THF (black) and MeOH (gray) at RT (bold line) and LT (dashed line). The (*) represent plasma lines from the laser.

### 6.3.2. EPR

EPR data of the same series of thiolate-bound complexes at LT show that the iron centers in the complexes exist in its high-spin (S=5/2) or low-spin (S=1/2) ferric state in non-coordinating or coordinating solvents, respectively (Figure 6.3). The iron center in the aliphatic complex is high-spin in THF and low-spin in MeOH. Thus, both the rR and EPR data collected
at LT indicate that these thiolate bound iron porphyrins can be described as ferric thiolate complexes consistent with previous reports. However, the rR data suggest that there is a significant decrease in the population of the ferric species and increase in population of a ferrous species in solution at RT relative to LT. The corresponding EPR data at RT show the increase in population of a radical species characterized by a sharp signal at $g=2$ (Figure 6.3) relative to the data obtained at LT. Although expectedly, the EPR data at RT do not show significant intensity of the $g=6$ signal from the high-spin ferric species present in solution, the solution rR data under the same conditions clearly demonstrate the presence of both ferric and ferrous porphyrin species. These data suggest that apart from the ferric thiolate species, a ferrous ligand radical species exists at RT. Note that the ferrous ligand radical species is a valence tautomer of the ferric thiolate complex. Spin quantification of this radical signal at RT indicate that the population of this species for the aliphatic, bulky aliphatic, benzylic and aromatic thiolate complexes are 52%, 50%, 46% and 45%, respectively.

![Figure 6.3](image)

Figure 6.3: EPR data of the A) aliphatic, B) benzylic and C) aromatic complexes in toluene at RT (black) and LT (dashed line). Note that the LT spectrum in C is taken at 10 K.

### 6.3.3 Variable-Temperature and Radical Trapping Experiments

The conversion of the mixture of ferrous and ferric porphyrins at RT to the ferric porphyrin at LT is continuous as reflected in the variable temperature (VT) rR data. The VT rR data of the aliphatic complex in THF show that the $\nu_4$ and $\nu_2$ bands at 1344 cm$^{-1}$ and 1536 cm$^{-1}$, corresponding to the high-spin ferrous porphyrin, lose intensity as the temperature is gradually lowered and those for the high-spin ferric species (1361 cm$^{-1}$ and 1554 cm$^{-1}$) increase (Figure 6.4A, left). Similarly, the $\nu_2$ and the $\nu_4$ bands of the benzylic and aromatic complexes
corresponding to the high-spin ferrous component lose intensity with decreasing temperature and those of the ferric porphyrin gain intensity (S6.2). This appearance of the radical signal at RT and its reversibility is further indicated from variable temperature EPR data (Figure 6.4B, right). The radical signal at $g=2$ observed at RT reduces in intensity at the temperature is gradually reduced. The radical signal regains intensity when the temperature of the sample is gradually increased to RT. Similar transitions between ferric and radical signals are observed for the benzylic and aromatic thiolate-bound complexes as well (S6.3A & B).

![Figure 6.4](image)

Figure 6.4: (left) VT rR of the aliphatic complex in THF and (right) VT EPR of aliphatic complex in toluene. Temperatures are indicated in the legend in °C.

![Figure 6.5](image)

Figure 6.5: A) VT absorption data of the aliphatic complex in THF and B) Eyring plot for the corresponding data.
Variable temperature absorption data on the aliphatic thiolate bound complexes is obtained in THF solution. The data indicate that transitions at 670 nm, 522 nm, 419 nm and 320 nm gain intensity as the temperature is lowered with isosbestic points at 330 nm and 600 nm (Figure 6.5A). Analyses of these data indicate that the ferric thiolate state for the aliphatic complex is favored by $\Delta H$ of 5.6 Kcal/mol while the ferrous-thiyl state is favored by $\Delta S$ of 10.9 cal/mol.

The spectroscopic data are consistent with the presence of valence tautomerism in thiolate-bound iron porphyrin model complexes; irrespective of the nature of the thiolate ligand. The possibility of a $\text{Fe}^{\text{III}} + RS^- = \text{Fe}^{\text{II}} + \text{RSSR}$ process is eliminated by the fact that these changes are reversible with temperature and the resultant disulfide species is diamagnetic and hence, would not give rise to the significant population of the radical at RT. Porphyrin cation radicals are characterized by very weak bands in the rR spectrum, with $v_4$ and $v_2$ at 1351 cm$^{-1}$ and 1532 cm$^{-1}$, respectively. These are not consistent with our data which show clear rR signatures of high-spin ferrous porphyrins for the additional species observed at RT. This raises the possibility of a $\text{Fe}^{\text{III}}-\text{RS}^- \leftrightarrow \text{Fe}^{\text{II}}-\text{RS}^-$ valence tautomerism in these complexes. This would require the radical species, observed at RT, to be a thiyl radical. The $g$ values of the radical signal observed at room temperature in solution range from 2.05-2.02 typical for metal-bound thiyl radicals in solution. Further on incubation of the aliphatic complex with 5,5-Dimethyl-1-Pyrroline-N-Oxide (DMPO) the EPR data show a dominate radical signal, even at LT, indicating the formation of a thiyl adduct of DMPO, and only a very weak signal corresponding to $\text{Fe}^{\text{III}}$ is detected (Figure 6.6B). The corresponding rR data of this species show the $v_4$ and $v_2$ vibrations at 1344 cm$^{-1}$ and 1541 cm$^{-1}$ suggesting the presence of a high-spin Fe(II) center in this complex (Figure 6.6C). This implies that the formation of the thiyl radical adduct with DMPO has locked the complex in its Fe$^{\text{II}}$ state and does not allow its conversion to the ferric thiolate valence tautomer even at LT. To confirm that the radical is indeed a thiyl radical a deuterated version of the benzylic complex was prepared where the benzylic and the aromatic protons are replaced with deuterium. A vibration at 1260 cm$^{-1}$ is observed to shift to 914 cm$^{-1}$ upon deuteration of the thiolate ligand. This mode, which is only observed at RT and is thus unique to the radical state, likely, represents a benzylic CH$_2$ wagging mode, coupled to the C-S stretch. The observed isotope shift is consistent with that predicted by DFT calculations on a benzyl thiyl radical.
The rR data of this complex show that it exists exclusively as a ferrous species at RT and reversibly converts to a ferric species at low temperatures (Figure 6.6A). The entropic contribution leading to the change of ground state at RT seems to be derived from the population of low lying C-H vibrational modes of the thiolate ligand in the ferrous thyl state. The substitution of these C-H units by C-D lowers their energy, increasing their populations and leading to a greater entropic stabilization of the ferrous thyl radical state at RT. A similar gain in entropy is proposed to stabilize the entatic state of blue Cu proteins with axial methionine ligands which results in low frequency vibrational and rotational modes involving the methyl and methylene side chains of the methionine. Our data provide direct evidence for the presence of Fe$^{III}$-RS$^-$ ↔ Fe$^{II}$-RS$^-$ valence tautomerism in these model complexes similar to those of metal dithiolenes.\textsuperscript{53}

Figure 6.6. A) rR data of the benzylic thiolate (black) and the deuterated benzyl thiolate (gray) at RT in THF. B) EPR spectra of the CO bound bulky aliphatic complex in toluene at RT and C) rR data (413.1 nm, 10 mW) of the aliphatic complex (dashed line) and aliphatic + DMPO (black) in THF.

6.3.4. CO Complexes

Similarly, when CO is added to a solution of the bulky aliphatic complex in THF at RT, a sharp Soret band at 418 nm and a Q-band at 538 nm are observed, establishing the formation of a single Fe$^{II}$-CO species that dominates the absorption spectrum (S6.5A). These features are quite different from the ferrous CO complex which features a soret band at 445 nm and a Q-band at 567 nm.\textsuperscript{51} The rR data of this CO adduct show a major species with $v_4$ and $v_2$ bands at 1366 cm$^{-1}$.
1 and 1564 cm\(^{-1}\) and two new band at 522 cm\(^{-1}\), 1953 cm\(^{-1}\) (S6.5B, C & D). A minor high spin ferric species with a \(\nu_2\) at 1555 cm\(^{-1}\) is also present. The EPR data of this complex show a sharp radical signal at RT with a \(g\) value of 2.03 consistent with a thiyl radical (Figure 6.6B, gray). Spin quantification of this signal indicates 75% population at RT.

Note that the EPR data of these complexes in the solid state show the presence of the same radical signal at RT as well as at LT (S6.6). The inability of these complexes to exhibit reversible temperature dependent valence tautomerism in the solid state implies that the process entails a change in geometry of these complexes which is only possible in solution. Thermal population of an excited state does not require a change in geometry and would occur in the solid state as well. Similarly, spin quantification of the radical signal at RT indicated more than 50% population at RT. Thus, it seems most likely that the valence tautomers are in equilibrium with each other in solution (change in ground state, Figure6.7).

![Schematic representation of the valence tautomerism equilibrium.](image)

**6.3.5. The Role of Hydrogen Bonding**

rR data of the bulky aliphatic and benzylic complexes when attached to self-assembled monolayers of thiols on Ag surfaces (S6.7A &B, blue) and dipped in aqueous solution show the presence of only ferric thiolate species. In contrary to the data observed in organic solution (S6.7A &B, red) the \(\nu_4\) and \(\nu_2\) modes at 1343 cm\(^{-1}\) and 1542 cm\(^{-1}\) corresponding to ferrous species are not observed in these cases. This implies that water may play a role in tuning the equilibrium. The equilibrium of ferrous thiyl and ferric thiolate species in solution is completely shifted to a ferric thiolate state when hydrated with only 0.5% H\(_2\)O (by volume) in THF at RT (Figure6.8A, black to dashed line). The equilibrium could be reinstated (Figure6.8A black to
gray) by dehydrating the THF solution using a moisture adsorbent (MgSO₄). Thus the aqueous environment stabilizes the ferric thiolate state only.²⁷ In these heterogeneous systems the thermodynamic reduction potentials (E⁰ Fe³⁺/²⁺ = 0.0 V vs. NHE) are shifted towards positive potentials relative to analogous synthetic complexes in organic medium (-0.3 V vs NHE) consistent with the presence of hydrogen bonding to the axial thiolate ligand.⁵⁹-⁵¹, ⁵⁷, ⁵⁸ The conversion to the ferric thiolate state indeed imparts tolerance to O₂ in these systems as indicated by the fact that while the aliphatic thiolate complex readily degrades in O₂ in THF resulting in sulfur oxidation (S-O vibration at 1080 and 918 cm⁻¹, Figure 6.8B, dashed line), this complex is quite stable in the presence of 0.5% H₂O (Figure 6.8B, black line). In parallel, the Fe-S and C-S vibrations in the rR spectrum of this complex dissolved in THF are lost when exposed to O₂ but retained in the presence of 0.5% H₂O (Figure 6.8C).

Figure 6.8. rR data of the air stable A) bulky aliphatic complex in THF (black), in the presence of 0.5% H₂O (dashed line) and after dehydration with activated MgSO₄ (gray). B) IR data of the aliphatic complex.

6.4. Conclusions

In summary, our data, collected at LT, indicate that thiolate-bound model complexes are best described as high-spin ferric porphyrins, consistent with previous literature reports. Synthetic models fit the description of the cytP450 active site. However, the VT data show the presence of a temperature-dependent valence tautomerism between the ferric thiolate and a ferrous thiyl species, with significant amounts of ferrous thiyl species present in solution at RT. The thiyl radical of the latter species could be trapped as a DMPO adduct, and formation of this species was further driven by CO coordination to the heme. The presence of the ferrous-thiyl
state helps explain the mysteriously high sensitivity of synthetic thiolate-bound ferric porphyrin mimics of cytP450 towards O$_2$, which is not exhibited by ferric porphyrins having any other innocent axial ligand, as well as their instability towards a free radical like nitric oxide. O$_2$ sensitivity exhibited by thiolate bound non-heme iron systems (e.g. Nitrile hydratase) and in synthetic complexes may have very similar origins.$^{40}$ This situation is comparable to O$_2$ activation by the cupric active site of ammine oxidase and the ferric site of intradioldioxygenase, where a valence tautomer of the resting oxidized state involving an oxidized ligand radical and the reduced metal center is heralded as the active form.$^{25, 26, 59}$ The enzyme active sites bearing cysteine-bound hemes, on the contrary, are established to exist in their ferric thiolate forms and hence are stable in O$_2$.

Figure 6.9. (left) The conserved secondary structure near the coordinated cysteine and (right) the resulting electrostatic potential experienced by the cysteine sulphur are shown.

While the protein active sites of these enzymes are hydrophobic, quite like the organic solvents used here, there is at least one hydrogen bonding interaction present between the protein backbones to the cysteine thiolate sulfur (Figure 6.9 left, dashed line).$^{30, 60-64}$ In the past, much research has been devoted towards understanding the function and significance of these hydrogen bonds for P450 catalysis. Initially it had been speculated that their role is solely confined to the fine-tuning of the Fe(III)-S interaction, but curiously, more recent spectroscopic investigations have shown that the effect of these hydrogen bonds on the Fe-S bond strength may be small. Overlay of structures of several members of the cytP450 family shows that the secondary structure near the cysteine ligand is quite conserved (Figure 6.9 right, GXCY where X and Y are hydrophobic residues). The stereochemistry of this loop is as such that three amide dipoles present in this loop are pointed towards the cysteine S (the NH amide between GX
corresponds to the conserved hydrogen bond to the cysteine). This results in a positive electrostatic potential near the cysteine sulfur (Figure 6.9 right). It is conceivable that the hydrogen bond and the peptide electrostatics stabilize the ferric thiolate state relative to the ferrous thiyl state due to the presence of higher charge separation in the former.\textsuperscript{57, 65} Accordingly, we have observed that thiolate-bound iron porphyrin complexes dissolved in organic solvent containing 0.5% water and when immobilized on the surface of electrodes in an aqueous environment show the presence of a dominant ferric thiolate ground state at RT i.e. no significant population of the ferrous thiyl state is observed. It is possible that hydrogen bonding and the high dielectric of water in these systems mimic those present in the protein active sites resulting in the stabilization of the ferric thiolate state in an aqueous environment in contrast to exhibiting the ferric thiolate and ferrous thiyl radical equilibrium in non-polar organic solvents which are devoid of any hydrogen bonding interactions. The lack of significant ferrous thiyl state at RT avoids oxidation of thiolate sulfur. In systems where the thiolate sulfur is sterically protected (e.g. the bulky aliphatic thiolate complex) the ferrous center generates O\textsubscript{2}\textsuperscript{-} which degrade the propyrin macrocycle (S6.8). Our results, therefore, indicate that one of the most important functions of the hydrogen bond to the cysteine ligand could be the stabilization of the ferric-thiolate ground state of the heme, to prevent degradation of the CytP450 active site in its (oxidized) resting state by O\textsubscript{2}.

6.5. References

6.6. Supporting Information

S6.1: rR data of the A) aliphatic, B) benzylic and C) aromatic complexes in THF at RT (blue line), LT (red line) and reversibility at RT (dashed line). D) Power dependence of PPSR.

S6.2: VT rR of the benzylic complex in THF, showing a transition from high-spin to low-spin (inset, right).
S6.3: VT EPR of the benzylic and aromatic complex (A and B) in toluene. The temperatures are indicated in the legend in °C.

S6.4: rR of the deuterated complexes in the low frequency region. A vibration at 1260 cm$^{-1}$ shifts to 914 cm$^{-1}$ on deuteration of the benzyl thiolate complex. The calculated frequencies for the CH$_2$ and CD$_2$ wagging mode of a protonated and deuterated m-hydroxy benzyl thyl radical are 1271 cm$^{-1}$ and 914 cm$^{-1}$, respectively. The computed (Gaussian 03 Ver. C02, BP86/6-311g*) vibrational modes are depicted in the inset. It is likely that this mode, characteristic of thiyl radical, gets enhanced in the resonance Raman experiments.
S6.5. A) Absorption, B) and C) RR data of the bulky aliphatic complex (blue) and bulky aliphatic complex + CO (red) at RT, D) RR in the high frequency region.

S6.6. EPR data of the A) aliphatic, B) aromatic and C) benzylic complexes in the solid state at RT (blue) and LT (red).
S6.7. rR data of the air stable A) bulky aliphatic and B) benzylic complex in THF (red) and in an aqueous environment (blue) at RT.

S6.8. The Fe\textsuperscript{II} center generates O\textsubscript{2}\textsuperscript{−} which degrades porphyrin macrocycle.