Rieske Iron-Sulfur Cluster Proteins from an Anaerobic Ammonium Oxidizer Suggest Unusual Energetics in their Parent Rieske/cytochrome *b* complexes

Running title: Rieske proteins from anaerobic ammonium oxidizers

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Abstract: Anaerobic ammonium-oxidizing (anammox) bacteria employ a unique, hydrazine-based pathway to obtain energy from nitrite and ammonium. These organisms express distinct Rieske/ cytochrome *b* complexes of which the exact function in anammox metabolism is unclear, but which has been proposed to include the generation of NAD(P)H. This would require energetics and structural features unusual for such complexes. Here we present crystal structures and electrochemical investigations of the Rieske subunits of two of these complexes from the anammox organism *Kuenenia stuttgartiensis*, Kuste4569 and Kustd1480. Both proteins display high redox potentials (>+300 mV), which can be in part explained by their crystal structures and which fit perfectly in the energetic scheme of the proposed NAD(P)H generation mechanism. Moreover, AlphaFold3 models of the parent complexes trace out a path for the electrons required for NAD(P) production, which includes a proposed, novel *b*-type heme in the membrane-bound part of the complex.

Introduction

Anaerobic ammonium oxidation or "anammox" is a bacterial pathway in which ammonium is condensed with nitrite to yield nitrogen gas and water, supplying energy for the cell. The anammox process, which was only discovered in the 1990s, is of global importance: it is responsible for up to 10% of the global nitrogen cycle, and in some ecosystems contributes up to 50% to the total yearly N_2 production. Anammox metabolism consists of a set of redox reactions taking place in a dedicated compartment, the anammoxosome (Figure 1a). First, nitrite (NO_2^-) is converted to nitric oxide (NO), which is then condensed with ammonia (NH_3) to yield the extremely unusual, highly reactive compound hydrazine (N_2H_4). The hydrazine is oxidized to nitrogen (N_2), yielding four electrons of extremely low redox potential. In our current understanding of the anammox process [1,2], these are believed to be passed on to an as yet unidentified membrane protein, which uses them to pump protons into the anammoxosome. The proton gradient thus produced is used by one or more ATPases to synthesize ATP. Moreover, this complex has been hypothesized to also reduce lipoquinone, which was proposed to then be used by one or more Rieske/cytochrome *b* complexes to pump even more protons over the anammoxosome's membrane.

Rieske/cytochrome *b* complexes are found in most organisms that use chemiosmosis to produce a proton gradient to drive ATP synthesis. In general, there are two major classes of these complexes. The first is made up by the bc_1 complexes found in many prokaryotes and in mitochondria, where they are also known as "Complex III". The second class are the b_6f complexes found in organisms performing oxygenic photosynthesis, where they are mediating electron transfer between PSII and PSI [3]. Both types of complexes contain a membrane-bound cytochrome and a "Rieske iron-sulfur protein", which consists of a small domain containing a [2Fe2S] cluster, typically connected to a single transmembrane helix. Importantly, Rieske/cytochrome *b* complexes make use of *electron bifurcation* to harvest the energy released by the two-electron oxidation of a lipoquinone as efficiently as possible, while coupling it to the reduction of a soluble one-electron transfer protein with a considerably higher potential. In this process, a quinone molecule is reduced at a site close to the positive side of the membrane (the Qp site). The two electrons resulting from this oxidation then follow different paths. One electron follows an energetically favorable route, being first transferred to the high-potential iron-sulfur cluster in the Rieske protein. The Rieske protein then reorients and transfers the electron to the *c*-type cytochrome part of the complex, from where it is transferred to a soluble redox partner. This "downhill", energetically favorable transfer enables the other electron to take an "uphill", energetically unfavorable route, in which it is transferred to a low-potential heme of the cytochrome *b* component, from where it can be transferred to another quinone binding site close to the negative side of the membrane (the Qn site). There it is used to perform a one-electron reduction of a quinone to a semiquinone radical. This is followed by another cycle of quinone oxidation and electron bifurcation, with the resulting electrons again follow different paths, one going favorably *via* the Rieske protein to the *c*-type cytochrome and from there to another molecule of the soluble redox partner, and the other electron again undergoing the unfavorable transfer to the low potential heme in the *b* component. From there, it is used to further reduce the semiquinone to quinol. In the entire process, two quinone molecules are thus oxidized in the Qp site, releasing four protons at to the positive side of the membrane, whereas one quinone molecule is reduced at the Qn site,

resulting in two protons being taken up at the negative side of the membrane. This couples the two electron transfer cycles to proton translocation.

Most organisms require only a single Rieske/cytochrome *b* complex for their energy metabolism. Strikingly however, the anammox model organism *Kuenenia stuttgartiensis* encodes a total of three such complexes on its genome (Figure 1b). Some other species have been found that also contain more than one copy of Rieske/cytochrome *b* complexes, although generally little is known about their energy metabolisms [4]. In proteomics studies, all three of the complexes of *K. stuttgartiensis* have been found to be expressed [5]. The simplest of the *K. stuttgartiensis* Rieske/cytochrome *b* complexes in terms of gene structure, Kuste3096-3097 (the proteins are named after their gene loci), appears to be the most similar to a canonical bc_1 complex, with two differences: first, the equivalent of cytochrome c_1 contains two hemes and second, this domain is fused with the cytochrome *b* into a single polypeptide. The other two complexes, Kustd1480-1485 and Kuste4569-4574, of which the latter is the most highly expressed of the three, have more peculiarities, and seem to be more closely related to b_6f rather than to bc_1 complexes. Indeed, these latter complexes both feature cytochrome b_6-like as well as "subunit IV(SUIV)"-like transmembrane proteins[2]. However, instead of cytochrome *f*, these complexes contain a hexa- or octaheme cytochrome *c* is and in the case of Kuste4569-4574, an additional HAO-like octaheme cytochrome *c* (OCC) is found. Most strikingly however, both complexes contain a putative NAD(P) oxidoreductase, likely placed on the riboplasmic side of the membrane[2].

Given the presence of these unexpected NAD(P) oxidoreductases in two of the three bc_1 complexes in *Kuenenia*, a novel function and mechanism for both these complexes has been proposed [2], in which the electron bifurcation process could be used for the production of NAD(P)H. In this proposal, one of the two electrons from quinol oxidation would not be used for the reduction of another quinone, but for the energetically unfavorable reduction of NAD(P)+ to NAD(P)H (E_0'= -320 mV), whereas the second electron is used for another, energetically favorable reaction. In the case of the Kuste4569-4574 complex, the presence of the HAO-like OCC suggests that this latter could be the reduction of nitrite to NO (E_0'= +380 mV)[2]. Overall, this coupling of NAD(P)+ reduction to nitrite reduction should be feasible thermodynamically, since the most abundant quinone species in *K. stuttgartiensis* has been shown to be menaquinone-7 (MK-7) [5] which has an E_0' of about -70 mV [6]. In the Kustd1480-1485 complex the situation is similar, but no proposal has been made as to what other redox reaction could be coupled to NAD(P) reduction.

In this study, we focus on the Rieske iron-sulfur cluster proteins of the two NAD(P) reductase-containing Rieske/cytochrome *b* complexes from *Kuenenia stuttgartiensis*. We study their crystal structures and redox potentials, and discuss these in the context of the thermodynamic constraints of the proposed reactions and AlphaFold3 models of the respective complexes as a whole.

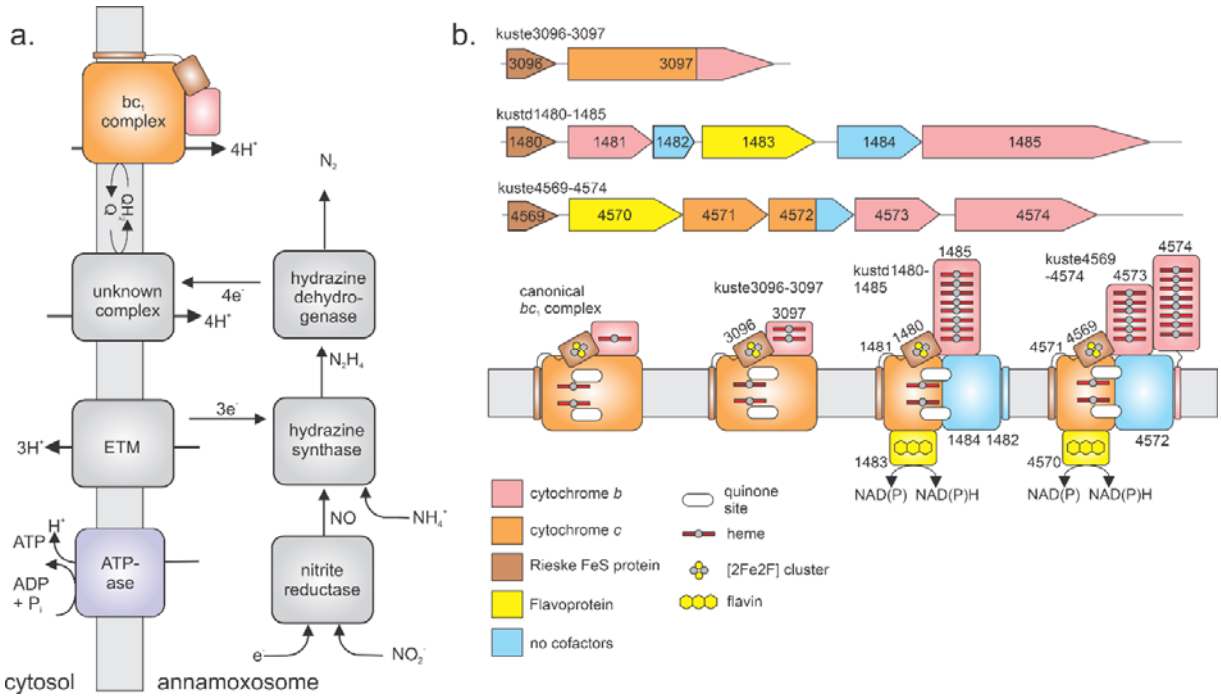

Figure 1.a. The anammox process consists of a series of redox reactions driving an electron transfer chain used to pump protons into the anammoxosome. The resulting proton gradient is then used to fuel ATP synthesis. **b.** Gene- and proposed domain organization of Rieske/cytochrome *b* complexes in *K. stuttgartiensis* as was presented by Kartal *et al.*[2].

Materials and Methods

Protein production

Vectors based on pET24d(+) were designed for expression of the soluble domains (without the linkers between the transmembrane helices and the soluble parts) of Kustd4569 and Kustd1480 guided by AlphaFold3 [7] and ordered from GenScript (Netherlands) B.V. (Rijswijk, the Netherlands). Proteins were expressed in *E. coli* BL21 suf++. Cells were cultured in 2 L LB medium supplemented with 50 µg/mL kanamycin sulfate main in 5L flasks with baffles were inoculated with 20 mL of preculture and grown at 37°C, 120 rpm until the OD_{600} reached 0.4-0.6. Temperature and shaker speed were then reduced to 18°C and 90 rpm, respectively, and IPTG, L-cysteine and ammonium iron (III) citrate were added to final concentrations of 1 mM each.

The cultures were harvested after 20 h by centrifugation with a Sorvall Lynx 6000 centrifuge, using an F9-6x1000 LEX rotor (ThermoFisher Scientific, Bremen, Germany) at 4°C, 6000 rpm, 15 min. Cell pellets were resuspended in wash buffer (300

mM sodium chloride, 50 mM Tris/Cl pH 8.0, 10 mM imidazole), frozen in liquid nitrogen and stored at -20°C. For purification, thawed cell suspensions were supplemented with *Complete™ EDTA-free* protease inhibitor cocktail and incubated for up to 30 minutes on ice. Cells were then lysed by sonication using a W-450 D Branson Digital Sonifier at 30% amplitude and 1 s cycles for 8 min, and the lysate centrifuged using a Sorvall Lynx 6000, in an F20-12x50 LEX rotor (ThermoFisher Scientific, Bremen, Germany) at 20,000 rpm, 4°C, for 1 h. The cleared lysate was filtered through 0.45 µm syringe filter and loaded onto a column with 4 mL Ni-NTA beads (Qiagen, Hilden, Germany) equilibrated in wash buffer. The column was washed with 3x 15 mL wash buffer, after which bound proteins were eluted with ~5 mL of wash buffer with 250 mM imidazole. The eluted protein was dialyzed against wash buffer without imidazole overnight using 3.5 kDa RC Tubing (Spectrumlabs, Piraeus, Greece). The proteins were then concentrated to a volume of 1 mL and loaded onto a Superdex S75 16/600 GL (GE Healthcare, Uppsala, Sweden) column, equilibrated in gel filtration buffer (150 mM sodium chloride, 50 mM Tris pH 8). Flow rates of 0.5-1.5 mL/min were used and 1 mL fractions collected. Colored fractions were investigated by SDS-PAGE and sufficiently pure fractions combined. After concentrating to 0.5-1 mL, 50 µL aliquots were prepared frozen in liquid nitrogen and stored at -80°C. All proteins were stored in gel filtration buffer.

UV/Vis spectroscopy

Proteins were diluted in gel filtration buffer and UV/Vis spectra measured between 250 and 800 nm (0.5 nm bandwidth, scan speed 400 nm/min) in quartz cuvettes with a 1.0 cm path length (Hellma GmbH, Müllheim, Germany) using a JASCO V-650 spectrophotometer (Jasco GmbH, Gross-Umstadt, Germany) at room temperature. To collect spectra of oxidized proteins, samples were diluted in 1 mM potassium ferricyanide in gel filtration buffer, and the spectrometer blanked against the same solution without protein prior to data collection. Spectra of protein thus diluted in ferricyanide-containing buffer were collected after 1- and 90 minutes intervals and compared; no differences were observed.

Spectroelectrochemistry

Spectroelectrochemical experiments were carried out in a custom-built optically transparent thin-layer electrochemical (OTTLE) cell [8] with a gold mesh electrode freshly modified with a 4,4'-dithiopyridine solution (20 mM in 160 mM Tris-Cl, 20% ethanol (v/v)) for at least 1 hour at room temperature. The cell was connected to a Keithley model 2450 source measure unit (Tektronix Inc., Beaverton, OR, USA) running as a potentiostat to perform chronoamperometry and initiate the measurement of spectra. Every sample was pre-poised at the first potential for 10 min. UV/Vis spectra were recorded in 20-50 mV potential steps using a Jasco V-760 Spectrophotometer (Jasco GmbH, Gross-Umstadt, Germany). The sample was allowed to equilibrate for 2 min at every potential before collecting a spectrum. The current range of the source measure unit was limited to 1 mA.

All spectra were baseline-corrected using the absorbance averaged between 700 nm and 650 nm to increase the signal to noise ratio. The baseline-corrected absorbance at wavelengths of maximal change (465-485 nm for both Kuste4569 and Kustd1480) was then extracted, averaged over the wavelength range and normalized. However, due to the nature of the cell,

the path length is not completely fixed and can decrease during the measurement due to capillary forces in the parafilm sealing the cell and/or evaporation. For this reason, a linear correction was applied based on the absorbance difference of the first and the last spectrum that were taken at the same potential, which, importantly, has little influence on the fit results but improves plot visuals. The corrected absorbance was then plotted against the potential and fitted to a single-transition Nernstian function using a custom-written Python script calling NumPy [9], Pandas [10], Scipy [11] and Matplotlib [12]:

$$Y = A - A_{red} = \frac{a}{e^{\left(\frac{zF}{RT}(E-E_m)+1\right)}} + c \#(5)$$

where A is the averaged and normalized absorbance, A_{red} the absorbance of the assumed fully reduced reference spectrum taken at the lowest potential, a the amplitude of the transition, z the number of electrons (set to 1 in this case), E the potential set by the SMU, E_m the midpoint potential and c an offset. The Faraday constant F was taken to be 96,485.34 J mol^{-1} V^{-1}, the ideal gas constant R 8.3145 J mol^{-1} K^{-1} and the temperature T was 293 K. The offset of the Ag/AgCl reference electrode (a thin patch of Ag/AgCl ink) at 100 mM KCl was taken to be +280 mV against the standard hydrogen electrode (SHE) based on comparison with a commercial Ag/AgCl electrode (Pine Research, Durham, USA).

The error of the fitted midpoint potential was determined using parametric bootstrapping assuming a Gaussian distribution. Using a custom-written Python script, 1000 data sets were generated based on the experimentally determined means and Gaussian noise added to the data using the experimental standard deviations. The standard deviations were scaled by a factor of 3 before generating noise. Nernstian fits were applied to every bootstrapped dataset and the standard deviation of the resulting distribution of midpoint potentials taken as the estimate for the variation in the midpoint potential of the 3 experimental replicates.

Protein Crystallization and Structure Determination

To find initial crystallization conditions, the commercial screens of the JCSG Core Suite and Ammonium Sulfate Suite from NeXtal Biotechnologies (Holland, OH, USA) were used. Using a Mosquito robot (SPT Labtech Ltd., Melbourn, UK), 100 nL of concentrated protein solution were mixed with 100 nL of reservoir solution in 96-well sitting-drop plates (Greiner XTL low-profile, Greiner Bio One, Frickenhausen, Germany). Conditions were optimized to obtain larger crystals using sitting drops of 1 µL protein mixed with 1 µL of reservoir solution with glass slides placed on 24-well plates (Crystalgen SuperClear CPL-132, Jena Bioscience GmbH, Jena, Germany) filled with 700 µL of reservoir solution per well.

Raw x-ray diffraction data were processed using XDS [13]. Both structures were solved by molecular replacement using PHASER [14] with AlphaFold 3 models [7]. The initial models went through iterative rounds of refinement in PHENIX [15] and manual correction in COOT [16]. A lattice translocation defect in the Kuste4569 dataset was corrected for using the method of Wang and coworkers[17] using the programs 'SFTOOLS' and 'FFT' of the CCP4 suite [18] to edit the reflection data in the mtz file and to calculate difference Patterson maps [18]. Further details are given in the Supplemental Information. Ensemble refinement for Kustd1480 was performed with PHENIX. A three-dimensional grid search was set up, scanning different values for p_{TLS}, T_{bath} and t_x. The individual refinements were carried out in parallel on 36 cores of a cluster of Intel® Xeon®

CPU X7560 processors running at 2.3 GHz. The structure with the lowest difference between R_{free} and R_{work} was selected as the final ensemble model. Structural analysis was performed using COOT/PyMOL [19] and custom-written python scripts calling NumPy and Matplotlib. Figures were prepared using PyMOL.

Modeling of complexes

Models of the full Kustd1480-1485 and Kuste4569-4574 complexes were prepared using AlphaFold3, running on the AlphaFold server. Expected, as well as one novel heme (*b* and *c*) groups were included by the server, as were NADP and FAD. The only difference between a *b*- and *c*-type heme is that the latter is covalently attached to least one cysteine *via* one or both vinyl group(s). We observed that while AlphaFold3 places heme groups in their expected positions given the locations of heme binding domains, and predicts the covalent attachments in the case of *c*-type heme, it often labels these as *b*-type hemes and *vice versa* regardless of binding mode. Assignment of heme types were therefore done manually. The [2Fe2S] clusters from the Rieske proteins were added manually, guided by alignments of the crystal structures of these proteins to the AF3 models. Further iron-sulfur clusters were placed in the putative NAD(P) reductases Kustd1483 and Kustd4570 as follows: the predicted fold of Kustd4570 was submitted to a search for structural homologs using the DALI server [20]. This identified domains of the Bfu family member NfnABC from *Caldicellulosiruptor saccharolyticus* (pdb entry 9bp5 [21]) and of the tungsten-containing formylmethanofuran dehydrogenase from *Methanothermobacter wolfeii* (pdb entry 5t5i [22]) as having strong structural homology (RMSD 2.7 Å for 483 amino acids and 4.2 Å for 335 amino acids, respectively). These experimental structures contain multiple [4Fe4S] iron-sulfur clusters which aligned excellently with groupings of cysteine residues in Kustd1483 and Kustd4570, and these clusters from the aligned homologs were therefore used to complete the AF3 model. Due to the strong structural homology of Kuste4570 to Kustd1483, these clusters could also be used to complete the model of the latter protein. In both proteins, however, the iron-sulfur cluster closest to the FAD lacks a fourth coordinating cysteine, and a buried lysine closely approaches the cluster. This cluster was therefore modeled as an [3Fe4S] cluster. Inital, partial models also included one chlorophyll molecule per monomer, as seen in b_6f complexes, but these cofactors were omitted in the final models to save computational expenses and because no chlorophyll synthetic machinery seems to be present in *Kuenenia*..

Results

Crystal structure determination of Kustd1480 and Kuste4569

Expression constructs for the soluble domains of the Rieske iron-sulfur cluster proteins Kustd1480 and Kuste4569, *i.e.*, without their respective transmembrane helices and linkers, were prepared and the proteins expressed heterologously. Both proteins were purified using metal ion affinity- and size exclusion chromatography. Kustd1480 was concentrated to A_{280}^{1cm}=7.0, and crystallized in 1+1 µl hanging drops equilibrated with 0.1 M CHES pH 9.5, 17% PEG 8000 as the reservoir solution. Reddish brown, lozenge-shaped plates grew within one day and were cryocooled in liquid nitrogen after cryoprotection in mother liquor supplemented with 20% (v/v) glycerol. Data were collected to 1.8 Å resolution but showed severe anisotropy. These data were phased successfully using an AlphaFold3 model as the search model (TFZ=12.8 without

cofactors in the model), but upon refinement, the R-factors did not decrease as expected. Inspection of the data and the molecular replacement solution revealed strong noncrystallographic translation symmetry, which often hampers refinement as it causes correlations in the intensities that are not accounted for in the model[23,24]. Moreover, it can artificially increase the R-factors, particularly at high resolution, as a considerable fraction of the reflections will be very weak. We therefore cut the resolution to 2.5 Å, but while this improved the R-factors considerably, they never reached values below 30%. Inspection of the density revealed severe smearing out of the data in various distinct directions in several parts of the structure, such as around the iron sulfur clusters. After testing various possible explanations, such as incorrect space group assignment with or without various forms of twinning, it was found that the most parsimonious explanation was structural disorder in the protein. Indeed, the regions affected are the same in both molecules in the asymmetric unit, with the relative direction of the apparent disorder being the same in both molecules for each region, which is consistent with it being a property of the protein rather than a crystallographic artefact. To account for this disorder, we performed ensemble refinement, which resulted in an ensemble model of good R-factors and acceptable geometry.

Kuste4569 was concentrated to an A_{280}^{1cm} of 12 and crystallized in 1+1 µl hanging drops using 4% (v/v) 2,2,2-trifluoroethanol, 2 M ammonium sulfate as the reservoir solution. Brown, lozenge shaped crystals grew within one week, which were cryoprotected in mother liquor with 20% (v/v) glycerol before cryocooling in liquid nitrogen and data collection. Phasing was done by molecular replacement using an AlphaFold3 model as the search structure (TFZ=22), however, upon refinement the R-factors failed to converge for this structure as well. As described in detail in the Supplemental Information, this was found to be due to a lattice translocation defect, which was corrected at the intensity level using the method of Wang *et al.* [17]. This allowed the structure to be refined to good geometry and R-factors, as reported in Table 1.

	Kustd1480 **pdb entry 9rk3**	**Kustd4579** **pdb entry 9rk4**
Data collection		
Space group	$P2_12_12_1$	$P2_12_12_1$
a, b, c (Å)	46.2, 76.2, 79.6	104.0, 120.7, 209.2
α, β, γ (°)	90, 90, 90	90, 90, 90
Wavelength (Å)	0.88560	0.88560
Resolution range (Å)	40-1.80 (1.85-1.80)	104.6 – 2.8 (2.9 – 2.8)
Total no. of reflections	86,269 (6,681)	879,981 (83,186)
No. of unique reflections	25,291 (1,871)	65,436 (6,430)
Completeness (%)	94.4 (95.3)	99.9 (100.0)
Redundancy	3.4 (3.6)	13.4 (12.9)
$\langle I/\sigma(I)\rangle$	8.2 (1.9)	13.0 (1.9)
R_{merge}	0.065 (0.729)	0.136 (1.622)
$CC_{1/2}$	0.998 (0.909)	0.999 (0.803)
Wilson B-factor (Å^2)	33.8	64.9
Refinement		
Resolution range (Å)	40-2.5	73.7 – 2.8
Completeness (%)	93.6	99.5
No. of reflections	9,570	65,248
Final R_{cryst}	0.2205	0.2645
Final R_{free}	0.2761	0.2972
No. of non-H atoms		
Protein	14,848: 8 models, 2 monomers/AU	10,260: 12 monomers/AU
Ligands	64 [2Fe2S], 8 models	48 [2Fe2S], 60 SO_4^{2-}
Water	185, 8 models	n.a.
R.m.s. deviations		
Bonds (Å)	0.019	0.002
Angles (°)	1.71	0.515
Average *B* factors (Å^2)		
Protein	47.4	72.5
Ligands	47.7	72.4
Water	45.7	n.a.
Ramachandran plot		
Most favoured (%)	86.3*	96.5
Allowed (%)	10.5*	3.4
Outliers	3.3*	0.2
Rotamer outliers (%)	12.8*	1.8

* A large number of unfavorable (φ, ψ) combinations and rotamers is expected, as ensemble refinement samples high-energy conformers[25]

Table 1. Data collection and refinement statistics.

The soluble domains of both Kustd1480 and Kuste4569 display the expected fold of a Rieske iron-sulfur protein, consisting of a cofactor binding domain with an incomplete β-barrel topology that is an insertion on a larger, "basal" domain as shown in Figure 2. Indeed, the structures of Kuste4569 and Kustd1480 are very similar (Figure 2, Supplemental Figure S4) even when considering the generally low structural variation between Rieske proteins. Both proteins coordinate their iron-sulfur cluster with the usual motif of two conserved histidines and two cysteines (Figure 3, Figure 4). The structures can also be aligned well with Rieske proteins from other species. A search for homologous structures of Kuste4569 using the DALI server [20,26] showed it to be most similar to the Rieske protein from the *Thermosynechococcus elongatus* BP-1 b_6f complex (pdb entry 3azc) [27]. Other hits with high structural similarity were Rieske proteins from other b_6f complexes, as well as Rieske-type proteins from arsenite oxidases. Small differences are found in the cluster binding domains and the other two β-sheets, while the loops frequently show insertions of various sizes, as has been noted before [28,29]. However, the C-termini of Kuste4569 and particularly Kustd1480 appear to be longer than in many other Rieske proteins; few examples, such as the *Spinacia oleracea* protein feature a tail of similar length (Figure 4). The C-terminus of the *S. oleracea* protein appears to be typical for Rieske proteins in b_6f complexes [27]. However, unlike those of the b_6f complex Rieske proteins, the ends of the C-terminal tails of Kuste4569 and Kustd1480 are hydrogen-bonded to β-strand 4 for a short stretch in a β-sheet pattern at the very end. The C-terminal part of Kustd1480, which is the longest of the two, forms a loop on the surface of the protein (Figure 2, Supplemental Figure S4). The flexibility observed in the Kustd1480 structure mostly concerns this C-terminal loop, as well as the loop between β3 and β4 (which link the basal- and cofactor binding domains) and part of the "proline loop" (which covers one side of the cofactor, and whose C-terminal part forms the second link between the basal- and cofactor binding domains) (Supplemental Figure S5), but also the relative position of the cofactor-binding domain, which appears to be moving as a rigid body with respect to the basal domain. The amplitude of this domain's flexibility is largest at its outermost tip, which appears to move from side to side by as much as 2 Å (Figure 2).

The high redox potential of Rieske proteins in comparison to other [2Fe2S]-type iron-sulfur cluster proteins is not only due to their clusters being coordinated by two histidines and two cysteines instead of four cysteines, but also due to residues in the second coordination sphere, in particular the hydrogen bonding network around the cluster [30]. Here, two positions in the sequence at the end of strand β7 appear to be of particular importance (Figure 4); presence of a tyrosine and a serine in these positions increases the redox potential by hydrogen bonding to a cofactor-coordinating cysteine- and a cluster sulfur, respectively[6,31,32]. In Kuste4569, both these residues (Tyr129/Ser127) are present and engage in the expected interactions, but Kustd1480 has a phenylalanine (Phe116) in the position of the tyrosine, although the serine (Ser114) is present and interacts with the cluster (Figure 3).

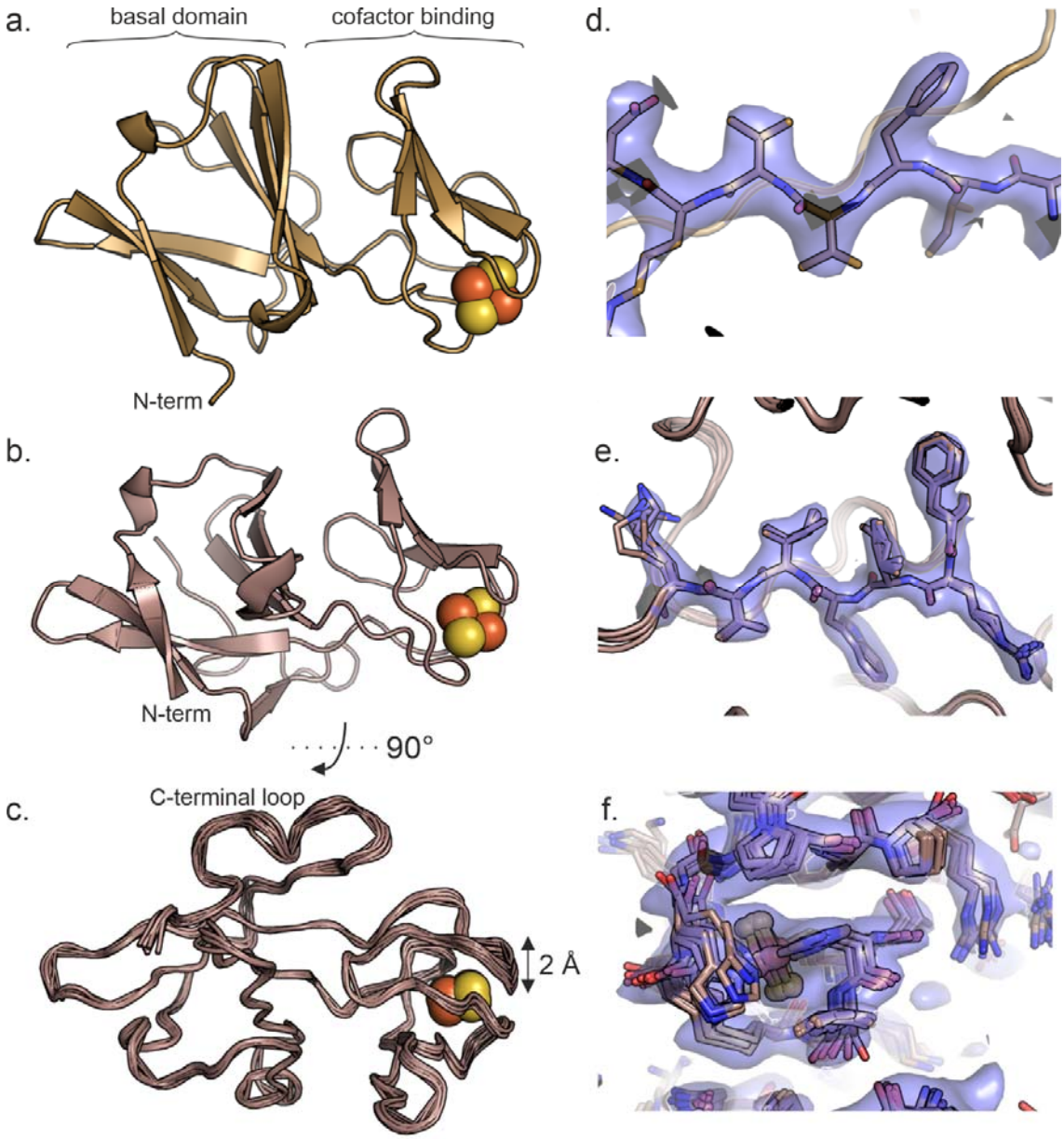

Figure 2. Crystal structures of the soluble part of **a.** Kuste4569 and **b.** Kustd1480. The cofactor is shown as yellow and orange spheres. **c.** Ensemble structure of Kustd1480. The largest degree of flexibility is seen around the cofactor and in the C-terminal loop. **d.** Close up of a portion of the 2*m*Fo-*D*Fc electron density map for Kuste4569. **e.** Close-up view of part of the 2*m*Fo-*D*Fc electron density map for Kustd1480 in a well-ordered part of the structure, and **f.** in the cofactor binding domain. The latter shows considerable disorder in one direction. All maps were contoured at 1 σ and shown together with the final, refined structure (the ensemble structure in the case of Kustd1480).

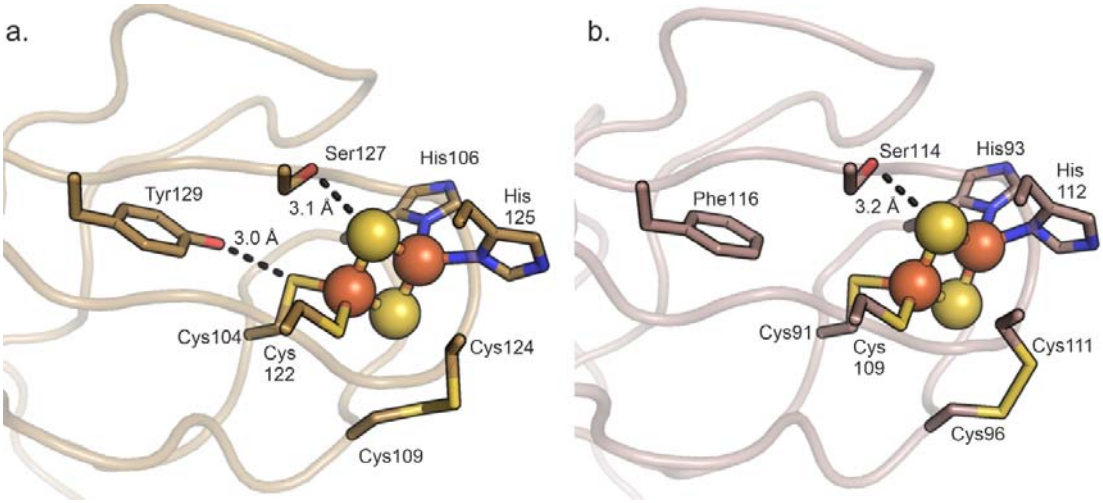

Figure 3. Coordination and surroundings of the [2Fe2S]-cofactors in **a.** Kuste4569 and **b.** Kustd1480. The [2Fe2S] clusters are shown as balls and sticks. The iron-coordinating histidines and -cysteines are shown as sticks, as are the disulfide bridge and the Tyr129/Ser127-pair (Phe116/Ser114 for Kustd1480) implicated in redox potential tuning[6,31,32]. Interaction distances are indicated in Å.

Spectropotentiometry

In their as-isolated states, both proteins show similar UV/Vis spectra (Figure 5a,b), apart from a large difference in absorption around 280 nm, which is much higher in the case of Kustd1480 than for Kuste4569. This is easily explained by the absence of tryptophan residues in the latter protein. Moreover, in its oxidated form Kustd1480 has an absorption peak at 430 nm, whereas Kuste4569 has no peak there in the as-isolated state, which may contribute to the somewhat more reddish hue of Kustd1480 in solution. Upon oxidation, both proteins show increases in absorption over a broad range of absorptions, particularly between 320 and 380 nm and between 420 and 580 nm. These changes were used for spectropotentiometric redox potential determination.

Using an optically transparent thin-layer electrochemical (OTTLE) cell kept at fixed potentials with respect to an Ag/AgCl reference electrode, we measured spectra at potentials between -50 and +550 mV vs. Standard Hydrogen Electrode (SHE). For both proteins, these showed a single, clear transition in the averaged absorption between 465 and 485 nm which could be explained excellently with a single-electron redox transition (Figure 5c,d). Experiments were carried out in triplicates to obtain error bars on the individual absorption changes, which in turn were used to estimate the error in the observed midpoint potentials using bootstrap resampling. In this way, midpoint potentials of 303 ± 5 mV and 335 ± 14 mV could be determined for Kuste4569 and Kustd1480, respectively.

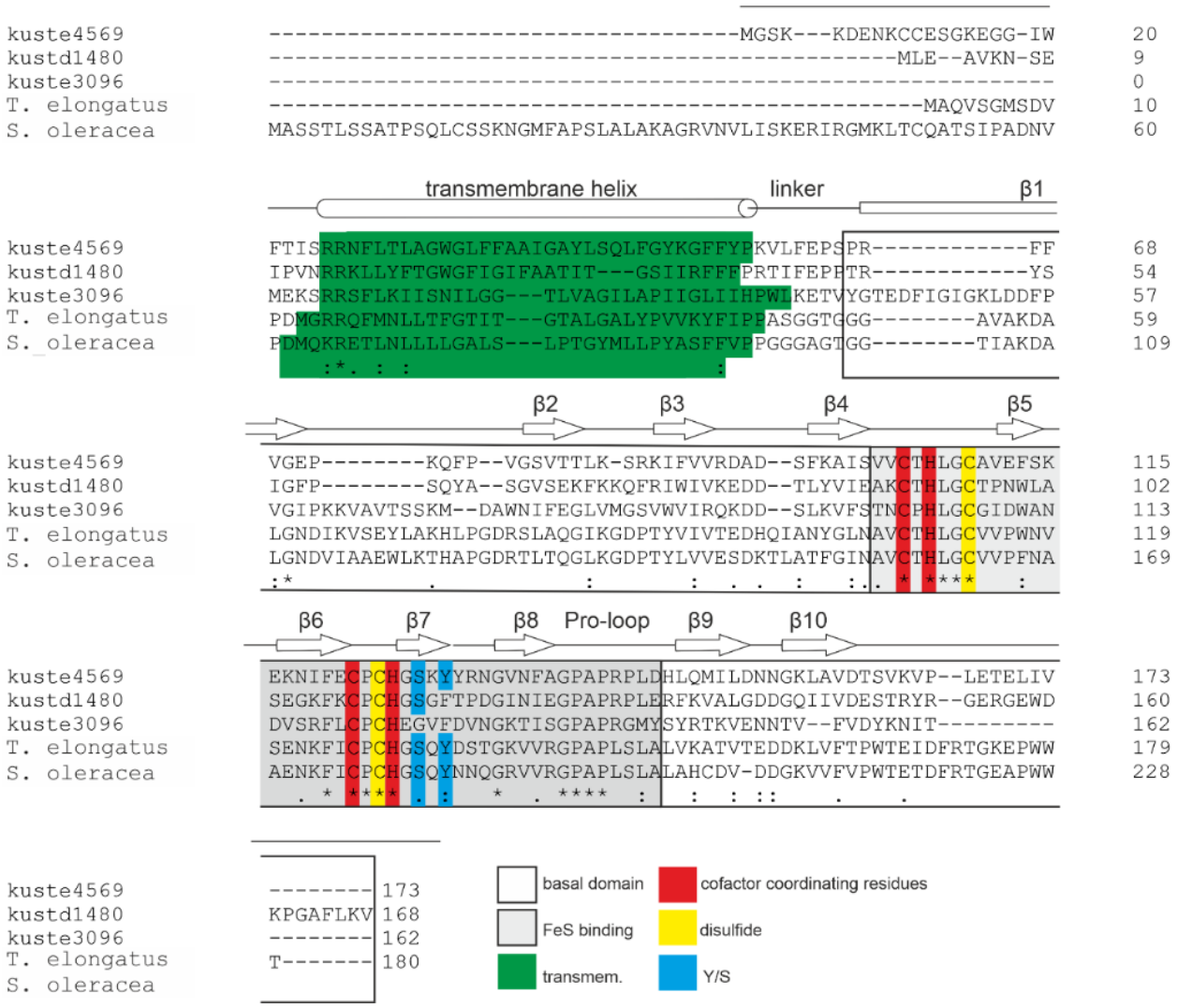

Figure 4. Multiple sequence alignment of Rieske proteins from *Kuenenia stuttgartiensis* (kuste4569, kustd1480, kustd3096) and the closest structural homologs of kuste4569, the Rieske proteins from *Thermosynechococcus elongatus* (WP_011056803.1) and *Spinacia oleracea* (NP_001413377.1). Secondary structure elements are indicated for the soluble part of Kuste4569 according to its crystal structure; the positions of the transmembrane helices were predicted using AlphaFold3 [7]. The basal- and cofactor-binding domains are indicated as are the positions of the binding domain's disulfide bridge, the cofactor coordinating residues and the Tyr/Ser pair ("Y/S") implicated in tuning the redox potential[6,31,32].

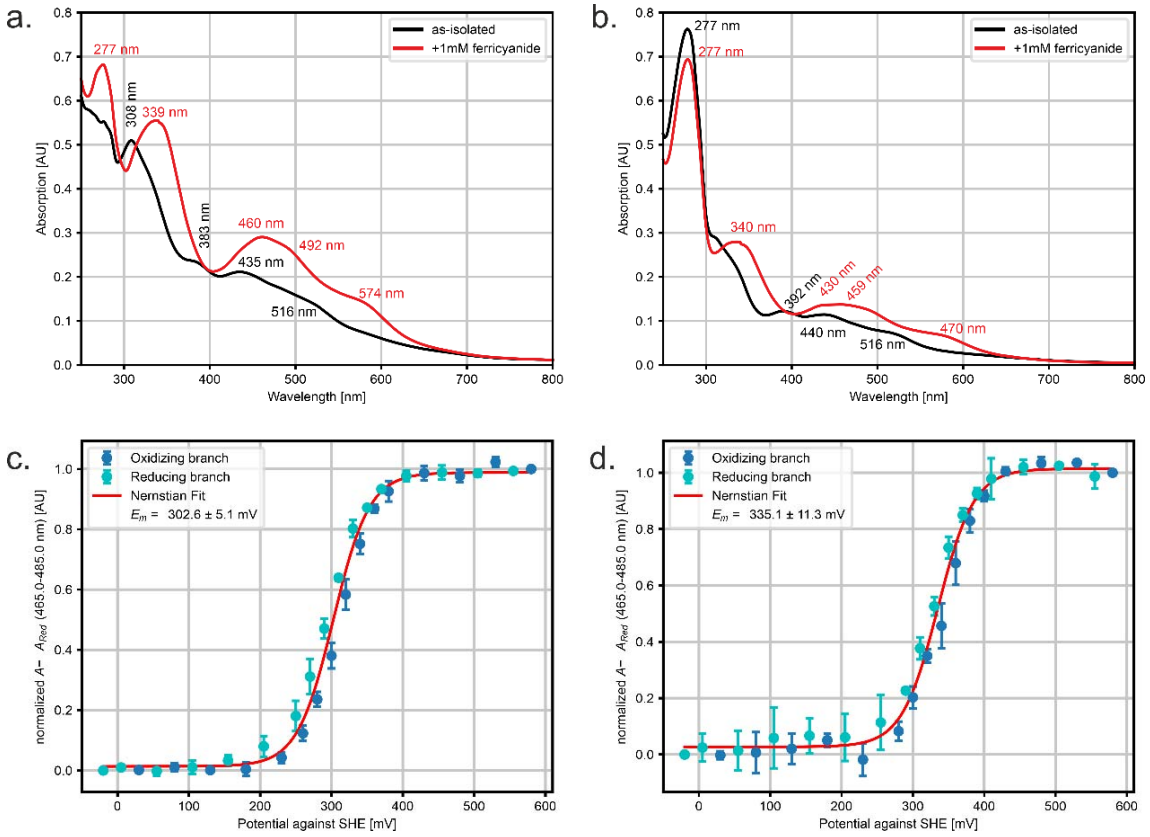

Figure 5. Top panels: UV/Vis spectra of Kuste4569 (**a.**) and Kustd1480 (**b.**) in the as-isolated state (black lines) and after oxidation with 1 mM potassium ferricyanide (red lines). Due to a lack of tryptophans in Kuste4569, the absorption peak at 277 nm is much lower than for Kustd1480. Peak wavelengths are indicated in nm. **Bottom panels:** spectroelectrochemical midpoint potential determination of Kuste4569 (**c.**) and Kustd1480 (**d.**). The oxidizing and reducing branches are shown in dark- and light blue, respectively, and the fit (which assumes a 1-electron transition) in red. Potentials are indicated *vs.* the Standard Hydrogen Electrode (SHE). Midpoint potentials of 303 ± 5 mV and 335 ± 14 mV were determined for Kuste4569 and Kustd1480, respectively.

Modeling of Rieske/cytochrome b complexes

Using AlphaFold3[7], we prepared models of the complete Kuste4569-4573 (i.e., without Kuste4574) and Kustd1480-1485 complexes, assuming a dimeric state for the membrane-bound parts (the cytochromes *b* , SUIV-like and Rieske proteins) as well as for the associated *c*-type cytochromes on the positive membrane side, and a monomeric state for the proposed NAD(P) reductase domains on the negative membrane side (Figure 6, Figure 7). These initial models contained all heme *c* and *b* cofactors, as well as the iron-sulfur clusters in the Rieske proteins and FAD and NADP in the NAD(P) reductases. In both complexes, these latter domains showed a number of cysteine clusters tracing out a path between the Rieske/cytochrome *b* part and the active site of the NAD(P) reductases, likely binding [4Fe4S] and/or [3Fe4S] iron-sulfur

clusters, which were placed in these positions using homologous experimental structures as described in the methods section. Both models show high confidence in the core regions, with lower confidence values in loops on the outside of the protein. The models suggest that the cytochrome *b* and subunit IV parts of both complexes are very similar to each other as well as to b_6f complexes, except that the SUIV part has five instead of three transmembrane helices in both complexes. In crystal structures of bc_1 complexes, the Rieske proteins can be observed in at least three conformations: '*b*', 'Int' or 'c_1', where the iron-sulfur cluster points either to the Q_p site in cytochrome *b*, to heme *c* of cytochrome c_1 or takes on an intermediate position that is similar to the '*b*' state [33]. In our AlphaFold models, the Rieske proteins appear to be modeled in the '*b*' or intermediate position in both complexes, with the [2Fe-2S] cluster pointing toward the quinone binding site.

As expected from their sequences, the multiheme *c*-type cytochromes share only little similarity between the two complexes, though their transmembrane helices are in the same position in the complex and the two *c*-type hemes closest to the membrane are positioned approximately in the same position. Kustd1485 is far larger than Kuste4573 and has long α-helices that wrap halfway around the complex including the Rieske protein Kustd1480.

The membrane hemes *b* and c_N (which are *c*-type hemes in the transmembrane part close to the negative side of the membrane) are positioned and coordinated the same as expected for canonical Rieske/cytochrome *b* complexes (Figure 7). In contrast, the *c*-type hemes of the large multi-heme cytochromes show very different arrangements with smallest edge-to-edge cofactor distances to the membrane-bound cofactors of just 26-28 Å compared to 38 Å in the *Spinacia oleracea* b_6f [34]. The remaining *c*-type hemes are positioned in groups of two (Kuste4573, Kustd1485) and three (Kustd1485). Strikingly, a new *b*-type heme binding site at the interface of the cytochrome *b* dimer was predicted by AlphaFold3 for both complexes. In the Kuste4569-4573 complex model, this unexpected *b*-type heme is bound by the His43 residues of the two Kuste4571 monomers as the two iron-coordinating residues (Supplemental Figure S3), whereas its propionate groups are positioned in the vicinity of the Kuste4571 Arg247 side chains and the Kuste4570 Arg511 side chain. The iron-coordinating residues in the Kustd1480-1485 complex model are the His62 (one from each Kustd1481 monomer), with the side chains of Arg266 and Lys267 from Kustd1481 and Arg550 from Kustd1483 positioned well to compensate the negative charge of the heme propionates.

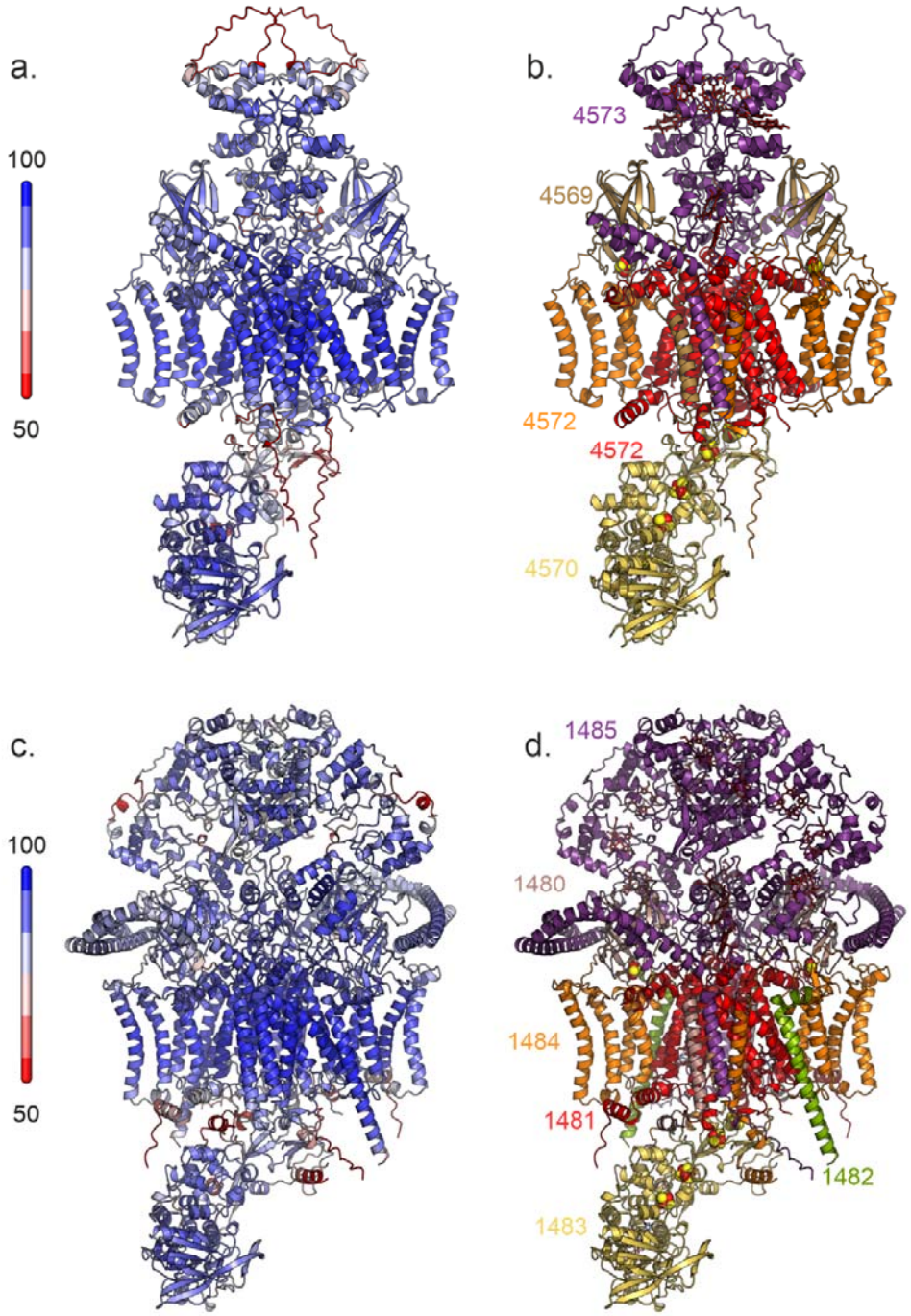

Figure 6. AlphaFold3[7] models of the Kuste4569-4573 (a.,b.) and Kustd1480-1485 (c., d.) complexes. Panels a. and c. are colored according to plDDT, with red indicating a low confidence (plDDT ≤50) and blue indicating high confidence. Panels b. and d. are colored according to polypeptide chain.

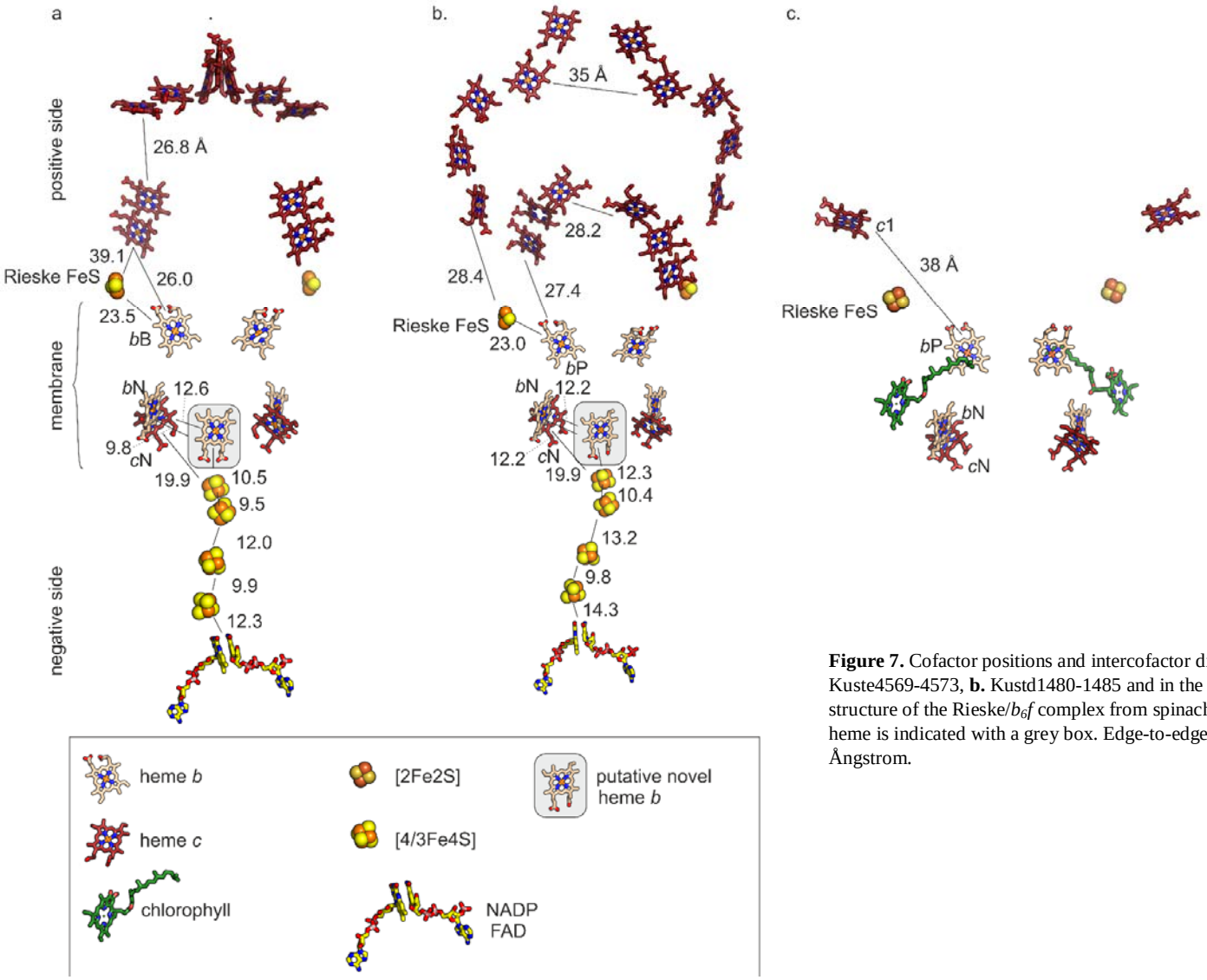

Figure 7. Cofactor positions and intercofactor distances in the models of **a.** Kuste4569-4573, **b.** Kustd1480-1485 and in the experimentally determined structure of the Rieske/b_6f complex from spinach. The proposed novel *b*-type heme is indicated with a grey box. Edge-to-edge distances are indicated in Ångstrom.

Discussion

Both Kuste4569 and Kustd1480 show high redox potentials of +303 and +335 mV, respectively. Relatively high (>200 mV) redox potentials would be expected given the presence of the hydrogen-bond donating serine in the cofactor's second coordination sphere in both Rieske proteins (Ser127 in Kuste4569/Ser114 in Kustd1480) as well as Tyr129 in Kuste4569. Mutating these residues in the *S. cerevisiae* Rieske protein results in redox potential decreases of 130 mV for the serine mutant and 65 mV for the tyrosine mutant, with roughly an additive effect for the double mutant [6]. These effects were of similar magnitude in mutants of the Rieske proteins from *B. taurus* [35] and *R. sphaerodies* [31]. Accordingly, it is somewhat unexpected that Kustd1480 displays a potential even higher than that of Kuste4569, despite lacking one of these hydrogen-bonding residues. Possible reasons for this observation could include other differences in the second coordination sphere, surface electrostatics or pH dependence, but the discrepancy is not easily attributed to any single effect, and is likely a combination of several, more subtle influences.

More importantly, the potentials of both Rieske proteins are higher than would be expected for a canonical, menaquinol-oxidizing Rieske/cytochrome *b* complex. The energy expended for proton translocation during the Q-cycle is compensated for by the electron transfer from quinol to the Rieske protein, and corresponds to the potential difference between them. However, the number of protons that are translocated in this mechanism is fixed to exactly two per half-cycle, and the energy required depends mostly on the proton-motive force. Consistent with this, the redox potentials of Rieske proteins and quinone species tend to correlate well across different organisms and low-potential quinones are found together with Rieske proteins of lower potentials (<200 mV) [36]. Conversely, these higher potentials would fit nicely into the proposed alternative mechanism that couples NAD(P)H production to the reduction of a high potential electron acceptor such as nitrite in the case of Kuste4569-4574, since a larger potential difference would be needed to provide electrons with sufficiently low potential for $NAD(P)^+$ reduction in the electron bifurcation step. Specifically, if the other trends in redox potentials outlined by Bergdoll and coworkers [36] also apply to the two anammox complexes investigated here, potentials of -350 to -320 mV are calculated for heme b_N on the negative side of the membrane (based on the measured Rieske potentials). From this point, the electrons would only need a viable transfer pathway to the active site of the putative NAD(P) oxidoreductase.

The AlphaFold3 models of the complexes trace out just such a pathway (Figure 7), starting from the newly predicted, unexpected *b*-type heme at the center of the homodimer that could accept electrons from the hemes b_n or c_n from either monomer (Figure 7). The electrons could then be shuttled along the four [4/3Fe4S] clusters to the FAD cofactor with a maximum of 15 Å tunneling distance. This would enable efficient electron transfer rates [37] but even when not taking the novel *b*-type heme binding site into account, electron transfer from heme c_N to the first [4Fe4S] cluster could still be possible at 20 Å. The electron pathways on the other site of the membrane are less obvious but, as seen with canonical bc_1 and b_6f complexes, the soluble domain of the Rieske protein will likely rotate and reduce the closest *c*-type heme. As mentioned in the results, the distance between hemes b_P and the *c*-type hemes are surprisingly low, given that the energetically favorable short-circuit would be undesirable. Furthermore, the need for the large number of *c*-type hemes is not entirely clear, but for Kuste4569-Kuste4573, some of the hemes could be involved in further electron transfer to the likely nitrite-reducing

Kuste4574. Unfortunately, no reasonable models of the complex including Kuste4574 were predicted by AlphaFold3 despite the experimentally observed comigration of all subunits [5].

Clearly, considering only the Rieske redox potentials provides only limited new insight into the function of the unusual Rieske/cyt *b* complexes. Here, experimental data on the redox potentials of the other redox centers would be the most helpful in that matter but these are not available thus far. Nevertheless, some considerations in this matter can be discussed using the insights gained by AlphaFold modeling and comparison with the literature. What could not be inferred from sequence data alone is the novel heme *b* that was placed by AlphaFold at the center of the dimeric complexes. If this heme is truly present in the native complexes, it would enable very efficient electron transfer to the proposed NAD(P) reductase subunit, which would certainly make quinone reduction at the negative side of the membrane as in the Q-cycle less likely. The efficiency of this pathway would depend on the potential of hemes and iron-sulfur clusters, and while nothing can be said about the latter apart from theoretically covering the relevant potential range[38], at least for the hemes *b* there are examples of *Firmicutes* with very low potentials (-360/-220 mV) for hemes *b*p and *b*n [36].

In the case of heme *c*n (Figure 7) this is not as simple. In the chloroplast b_6f complex its redox potential is approximately +100 mV – the same as that of plastoquinone [39] [3]. That its potential matches that of the quinone appears not to be a coincidence, and is also observed in menaquinone-utilizing organisms (although determination is non-trivial and the values generally have low certainty) [36,40]. The major determinant of the heme *c*n's redox potential is the nature or absence of the second axial ligand. High-potential hemes *c*n are only coordinated by a water molecule while low-potential (-50 mV) hemes cn additionally have a glutamate as axial ligand [36,41]. Even though no structure is available for a *b6f* complex and heme *c*n with this coordination, there is direct spectroscopic (EPR) evidence for it [41]. That this is indeed the determining factor is supported by the observed drastic decrease in heme *c*n redox potential upon addition of the coordinating inhibitor NQNO [39] (directly observed in a crystal structure[42]) and mutational analysis of a Phe-Tyr mutant in the equivalent position to the ligating glutamate in low potential hemes *c*n [43].

Importantly, in the models of Kustd1480-1485 and Kuste4569-4574 heme cn is ligated by a glutamate suggesting, at the very least a potential around -50 mV. This would still be ~200 mV higher than the rest of the electron chain. However, a lower potential would make sense if the electrons were shuttled towards NAD(P)+ instead of menaquinone reduction. For the Phe-Tyr mutant, a potential of -200 mV was observed, showing that an even lower potential is at the very least possible [43]. However, given the low cofactor distances, electron transfer should still be possible in the case of a 'regular' heme *c*n potential, even for a possibly ~ 250 mV energetically uphill step.

A far larger issue would be how quinone reduction at the negative side of the membrane would be effectively prevented. Perhaps the lack of a favorable quinone binding site compared to true, canonical b_6f complexes would be sufficient, but at the same time, this electron transfer is expected to be highly favorable. The hemes *c*n certainly do not appear to be significantly less accessible than in regular b_6f complexes. Moreover, a histidine sidechain is modeled very close to heme and glutamate in both complexes. The presence of these residues would make far more sense with a proton-coupled electron transfer such as quinone reduction than for a simple heme-to-heme electron transfer. This could be conciliated with the

presence of the novel heme *b* if NAD(P)H would be used to refill the quinol pool via reduction at heme *c*n. However, this would also come at the cost of a significant energy loss and is therefore not the most appealing hypothesis, especially considering that *K. stuttgartiensis* also expresses NADH dehydrogenases that should couple this reaction with proton (or sodium) translocation more efficiently [5].

Returning to the Rieske proteins, the observed flexibility in the Kustd1480 cofactor binding domain and C-terminal loop appears puzzling. Typically, electron transfer proteins display little conformational flexibility to minimize reorganization energy upon redox state changes. Possibly, the observed flexibility is an artefact caused by removing the Rieske protein from its natural surroundings in the complex. However, it is also possible that it is part of an induced-fit-type mechanism that allows the Rieske protein to adapt to the various positions and orientations inside the complex it needs to assume.

In conclusion, the Rieske iron-sulfur cluster proteins investigated here display high redox potentials, which can at least in part be explained by their crystal structures. Moreover, these high redox potentials align very well with the proposed, novel function -NAD(P)H generation- of the parent complexes of these proteins. Finally, models of these complexes provide a basis for the explanation and further investigation of the mechanism of NAD(P)H generation by the unusual Rieske/cytochrome *b* complexes in anammox organisms.

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