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A Computational Investigation Into The Catalytic Activity Of A Diselenolene Sulfite Oxidase Biomimetic Complex

*Eric A. C. Bushnell**

Department of Chemistry, Brandon University, 270-18th Street, Brandon, Manitoba R7A 6A9,
Canada.

Author to whom correspondence should be addressed:

Email: bushnelle@brandonu.ca

Phone: 204 571 7899

Abstract

Molybdenum is the only 4d-metal found in almost all life. One such molybdenum-containing enzyme is sulfite oxidase which also contains the dithiolene-molybdopterin ligand. Sulfite oxidase is essential in the degradation of sulfur containing compounds such as cysteine and methionine. Past work has shown parallels in the chemistry of dithiolene- and diselenolene-metal complexes. Thus, in this present work the O-atom transfer mechanism for a diselenolene sulfite oxidase biomimetic complex was investigated using computational tools. The results of which were compared to the analogous dithiolene biomimetic complex.

From the results obtained the molybdenum-diselenolene sulfite oxidase biomimetic complex is able to catalyse the O-atom transfer and does so with a marginally lower value of $\Delta_r G^\ddagger$ than that for the analogous dithiolene complex. In particular, it was found that on average the diselenolene complex had an activation energy 1.2 kJ mol^{-1} lower in energy than the analogous dithiolene complex. However, the calculated value of $\Delta_r G$ suggests that the oxidation of sulfite is more favourable for the dithiolene complex where the average difference in reaction aqueous Gibbs reaction energy was -9.4 kJ mol^{-1} relative to the diselenolene complex.

It is noted that the use of D3 and D3BJ corrections in combination with the B3LYP functional the barrier for O-atom transfer is lowered by more than 30.0 kJ mol^{-1} for both the diselenolene and dithiolene complexes. Such results suggest that to study such oxo-transfer reactions the proper treatment of dispersion interaction is necessary.

Keywords: Diselenolene, Density Functional Theory, Computational, Dithiolene, Sulfite Oxidase Biomimetic Complex

Introduction

Molybdenum (Mo) is the only 4d-metal found in almost all life. In biological systems Mo most often exists in the active site of an enzyme ligated by the molybdopterin (MPT) ligand; notably, such enzymes are critical in carbon, nitrogen and sulfur metabolism.¹⁻⁴ The mononuclear Mo-containing enzymes are divided into three main families; Dimethyl sulfide reductase (DMSOr), xanthine oxidase and sulfite oxidase (SO) which are defined on the sequence and structure of the oxidized active sites of the enzyme.⁴

In general the mononuclear Mo-containing enzymes catalyse oxo-transfer reactions to or from substrates. It is noted that an oxo-transfer reaction is defined such that: (i) an O-atom is transferred and not O^{2-} , (ii) the change in oxidation state of the metal is due solely to transfer of the O-atom and (iii) the transferred O-atom is oxidic and is directly bound in a terminal or bridging mode to the metal.⁵ Previous DFT investigations have studied the oxo-transfer mechanism for DMSOr biomimetic complexes.⁶⁻⁷ One such study looked at two possible mechanisms for the oxo-transfer between various mononuclear Mo complexes and various oxo-atom acceptors/donors. Of the two possible pathways the preferred mechanism involves the lone pair of electrons of the substrate *attacking* an oxo-ligand on the Mo via a 6-coordinate transition state (TS). The alternative mechanism involves the formation of 7-coordinate intermediate whereby the substrate first binds to the Mo center followed by an oxo-transfer to form product. Importantly, the direct oxo-transfer (i.e., 6-coordinate TS) mechanism has a considerably lower rate-determining barrier and is therefore the kinetically preferred pathway.⁶ In another study the oxo-transfer mechanisms between a biomimetic catalyst of DMSOr and several O-atom accepting substrates were investigated.⁷ In all cases a direct O-atom transfer occurs (i.e., 6-coordinate TS).⁷ It is noted that in both of the above-mentioned studies the rate-limiting step is the O-atom transfer step.⁷⁻⁸

Due to the presence of one or more oxo-ligands highly oxidized metal centers are required. In particular, the chosen metal cannot be in an oxidation state less than +4, with no more than 4 d-electrons.⁵ However, even with the highly oxidized metal center additional means are required to stabilize this metal-oxo group. Such stabilization occurs through the folding of the MPT ligand.⁹⁻¹⁰ Importantly, the MPT ligand contains a dithiolene functional group which ligates the metal center has been suggested to help tune different possible charges at the metal center.¹¹ In particular, it is the ability of the dithiolene ligand(s) to fold that provides a mechanism for the electronic buffering of the high positive charge on the metal center when it cycles between +4 to +6 oxidation states.^{4, 11-14}

As mentioned above one enzyme that contains a MPT ligand is SO. This enzyme is essential in the degradation of sulfur containing compounds such as cysteine and methionine.¹³ Deficiencies in the enzyme activity often lead to premature death.¹⁵⁻¹⁷ In particular it contains a single MPT ligand that ligates the Mo center along with two oxide-oxygen (O^{2-}) atoms and active site cysteine residue.¹⁷ It is noted that recent work has shown the parallels in the chemistry of dithiolene- and diselenolene-metal complexes.¹⁸⁻¹⁹ Thus, in this present work the O-atom transfer mechanism is investigated to determine the aqueous Gibbs activation energy and the aqueous Gibbs reaction energy for oxo-transfer by the diselenolene sulfite oxidase biomimetic complex. In addition, the O-atom transfer mechanism is investigated for dithiolene sulfite oxidase biomimetic complex to determine the effect of substituting the S with Se on the aqueous Gibbs activation energies as well as the thermodynamics of the reaction.

Computational Methods

The Gaussian 09 software suite was used to obtain optimized geometries and aqueous Gibbs reaction energies.²⁰ In the present investigation the SO biomimetic diselenolene complex (L'MoO₂) investigated herein is shown in **Figure 1**.

It is noted that in past experimental work the reduced mononuclear Mo-containing [Mo(OSer)(S₂pd)₂]¹⁻ complex has a water that ligates the metal center following the transfer of the O-atom.²¹⁻²² Thus, in the present model a water molecule was included (**Figure 1**) that was found to later bind to the product complex after the oxo-transfer step in agreement with experimental evidence.

Previous theoretical work has shown that both B3LYP and BP86 correctly describe the electronic structures and geometries of dithiolene-metal complexes.²³⁻²⁵ Thus, the geometries discussed herein were obtained at the BP86/BS1 level of theory.²⁶⁻²⁷ Single point energies were obtained at the IEFPCM-B3LYP/BS2 level of theory.²⁸⁻³³ BS1 is defined as the DEF2SVP + ECPs on Mo whereas BS2 is the DEF2TZP + ECPs on Mo.³⁴ It is noted that past work has shown the accuracy of the M06 functional when calculating reduction potentials of diselenolene complexes.^{18, 35-36} Thus, the IEFPCM-M06/BS2//BP86/BS1 level of theory was also used to compute single point energies.³⁷⁻³⁸ M06 is a hybrid functional for general-purpose applications, and is very suitable for applications in transition metal chemistry giving better performance than B3LYP for main-group thermochemistry, barrier heights, and non-covalent interactions.³⁷⁻³⁸ Single point energies were also calculated at the IEFPCM-B3LYP-D3/BS2//BP86/BS1 and IEFPCM-B3LYP-DBJ3/BS2//BP86/BS1 levels of theory.³⁹⁻⁴⁰ The addition of the D3 and D3BJ corrections were used to investigate the effect of dispersion interactions on the oxo-transfer reaction energies. The D3 corrections represent the D3 version of Grimme's dispersion corrections. D3BJ combines the D3 version of Grimme's dispersion with Becke-Johnson

damping. It is noted that for all levels of theory used to calculate single point energies the IEFPCM approach was used to model the presence of solvent on the reaction where water was chosen as the solvent.⁴¹⁻⁴⁵

The contribution of the transferring O-atom and Mo atom to the LUMO of the diselenolene complex and the contributions of the sulfur atoms to the HOMO of the sulfite was calculated at the BP86/TZ2P level of theory using the ADF program suite.⁴⁶

Given that the aqueous Gibbs reaction energies we calculated in a dilute aqueous environment SO_3^{2-} was modeled as protonated given the generally accepted pK_a value of 7.21. Thus, the reaction was modeled as a direct O-atom transfer from the diselenolene Mo-complex to HSO_3^- . The aqueous Gibbs reaction energies were determined based on the following general chemical equation,

The reactants are the oxidized Mo-complex, L'LMoO_2 , and HSO_3^- and the products are the reduced Mo-complex, $\text{L'LMoO(H}_2\text{O)}$, and HSO_4^- . L' represents the diselenolene ligands whereas L represents the methyl thiolate ligand. As noted in the **Introduction** the favoured pathway for oxo-transfer involving DMSO or biomimetic complexes involves the direct O-atom transfer. Moreover, this step represents the rate-determining step. Thus, in this study of the diselenolene SO biomimetic catalyst only the oxo-transfer barrier was examined where the reactants and products on the PES are the infinitely separated species defined in equation 1.

Results and Discussion

The reaction occurs via the interaction of a lone pair of electrons localized in the HOMO of the sulfite anion with the LUMO π^* -orbital of the diselenolene Mo-complex. As seen in **Figure 2** the LUMO π^* -orbital of the diselenolene complex is primarily an antibonding interaction between the equatorial O-atom and the metal center. At the BP86/TZ2P level of theory using the ADF program suite the equatorial O-atom contributes 17.8 % whereas the Mo-atom contributes 52.1 % to the LUMO. For the dithiolene analogue marginal differences are calculated where the equatorial O-atom contributes 22.0 % to the LUMO whereas the Mo-atom contributes 51.8 % to the LUMO. Given that only O_e and not O_a contributes to the LUMO for both complexes it is expected then that the transferring oxygen is the equatorial O_e -atom of both the diselenolene and dithiolene complexes. The HOMO of HSO_3^- is given in **Figure 2** and is largely localized on the S-atom. In particular, at the BP86/TZ2P level of theory using the ADF program suite the sulfur atom contributes approximately 28 % to the HOMO. Given the very similar contribution and shape of the LUMO of the diselenolene and dithiolene Mo-complexes the direction of attack by the HSO_3^- is expected to be essentially identical. Regarding dithiolene complexes it has been suggested that the dithiolene ligand trans to O_e promotes the transfer of this oxygen rather than O_a .^{3, 47} Thus, given the contribution of O_e to the LUMO and the likely trans effect of the diselenolene ligand only the transfer of O_e -atom was examined.

While the sulfite anion was modeled as HSO_3^- (see **Computational Methods**) the likely protonation state of the diselenolene complex was explored. In particular, the possibility of the non-transferring O_a -atom being protonated was examined. Given the choice of water as solvent the chemical potential of a proton in a dilute aqueous environment was chosen to be $-1124.2 \text{ kJ mol}^{-1}$ as per the work by Llano and Eriksson.⁴⁸ At the IEFPPCM-B3LYP/BS2//BP86/BS1 level of theory the aqueous Gibbs energy for protonation was calculated to be 55.3 kJ mol^{-1} . For the dithiolene complex the aqueous Gibbs reaction energy of protonation was calculated to be 55.6 kJ

mol⁻¹. Thus, in a dilute aqueous environment it is unlikely the O_a-atom is protonated and in aqueous conditions the reactive Mo-complex is most likely the di-oxo complex. As a side it is noted that the other levels of theory (see **Computational Methods**) used in the present study also support the notion that the O_a-atom is not likely protonated in an aqueous environment.

As seen in **Figure 3** for the oxidized diselenolene Mo-complex (L'LMoO₂) the Mo–O_e bond is essentially equal in length (rounded to three decimal places) to the Mo–O_a bond. In particular, the Mo–O_e bond length was calculated to be 1.731 Å whereas the Mo–O_a is 1.731 Å. Regarding the dithiolene complex the Mo–O_e bond length was calculated to be 1.733 Å whereas the Mo–O_a is 1.731 Å. This, slight difference is likely due to the trans-effect of the ligating sulfur atom of the dithiolene ligand where a S–Mo–O_e angle of 133.3° was measured. As noted in **Computational Methods** a water molecule was included in the model. In the present model following the geometry optimization it was found that this water acts as a hydrogen bond donor to the two oxide atoms (**Figure 3**). However, the water forms medium to weak hydrogen bonds where the average H-bond distance is 2.108 Å (**Figure 3**). For the dithiolene complex similar bond lengths are measured (**Figure 3**). In addition to the possible trans effect of the dithiolene/diselenolene ligand it has previously been suggested that the thiolate ligand plays a role in selecting the equatorial oxo-group for transfer in SO biomimetic complexes.^{3, 47} However, it has also been stated that the thiolate ligand instead plays a role in modulating the reduction potential of the Mo and perhaps provides a super-exchange pathway for regeneration of the active site after oxo-transfer has occurred.^{3, 49}

Upon closer examination of the oxidized diselenolene complex it was found that diselenolene ligand is folded upwards towards the Mo=O_a bond. As discussed in the **Introduction** such folding has been previously seen in various dithiolene complexes and has been suggested to stabilize the high oxidation state of the metal center as well as modulate the redox potential of the

metal center.⁹⁻¹⁰ In particular, such folding results in the filled *p*-orbitals on sulfur atoms of the dithiolene ligand overlapping with the empty *d*-orbitals of the metal.⁹⁻¹⁰ It is noted that the degree of folding is related to the oxidation state of metal where the more oxidized the metal becomes the more the folding occurs as a result of the greater need to stabilize the empty *d*-orbitals of the metal.¹¹ It has been stated that the ability of the ligands to fold provides a mechanism for the electronic buffering of the high positive charge on the metal center as it cycles between +4 to +6 oxidation states.^{4, 11-14} In the present work the diselenolene ligand is folded upwards toward the Mo=O_a bond by 12.1° whereas the dithiolene ligand is folded upwards by 15.2° (**Figure 3**). Thus, it appears that the degree by which the diselenolene π -orbital helps to stabilize the high valent Mo center is similar to that of the dithiolene ligand and suggests a similar tendency to buffer the high positive charges on the Mo center.

In the reaction between HSO₃⁻ and the Mo-diselenolene complex, L'MoO₂, **Figure 4** shows the TS structure with key bond lengths. From **Figure 4** it can be seen that the Mo...O_e bond length has lengthened considerably by 0.182 Å where $r(\text{Mo}\cdots\text{O}_e)$ is now 1.913 Å. The Mo...O_a bond on the other hand has shortened marginally by 0.016 Å where $r(\text{Mo}\cdots\text{O}_a)$ is now 1.715 Å. Regarding the forming S...O_e bond the calculated distance $r(\text{S}\cdots\text{O}_e)$ is calculated to be 1.945 Å. In the case of the dithiolene complex the TS for oxo-transfer has very similar bond lengths (**Figure 4**). Like the case for the oxidized complex the water is found to act as a H-bonding donor, however, in the TS the water now forms a medium strength hydrogen bond to one of the oxygens of HSO₃⁻ with a H-bond distance of 1.961 Å (**Figure 3**). Moreover, the sulfite molecule forms a weak hydrogen bond to the methylthiolate ligating the Mo-center with a H-bond length of 2.124 Å. Such interactions likely help to stabilize the TS.

With the O-atom transfer complete, optimization of the reduced complex (L'LMoO) resulted in the water to ligate the Mo center (**Figure 5**). Thus, the product complex is better represented as L'LMoO(OH₂). This was the case for both the diselenolene and dithiolene-mononuclear Mo-containing complexes. Like the oxidized complex the aqueous Gibbs reaction energy for protonation of O_a of the reduced diselenolene (L'LMoO(OH₂)) complex was calculated. It was found that the aqueous Gibbs reaction energy for protonation is -8.9 kJ mol⁻¹. Similarly, the aqueous Gibbs reaction energy for protonation of the reduced dithiolene complex was calculated to be -10.0 kJ mol⁻¹. Thus, in a dilute aqueous environment both the diselenolene and dithiolene complexes most likely exist with a protonated O_a oxo-group. Hence at the present level of theory the best formulation of the product complex is L'LMoOH(OH₂) and its structure is shown in **Figure 5**.

With the ligation of the water $r(\text{Mo}-\text{OH}_2)$ is measured to be 2.265 Å in the product complex (**Figure 5**). With the loss of O_e the diselenolene ligand forms a stronger interaction with the Mo center where the average change in Se-Mo bond length is -0.204 Å, whereas the ligating methyl thiolate forms a weaker interaction with the Mo center where the Mo-SCH₃ distance increases by 0.100 Å. However, it is noted that with binding of the water the methyl thiolate now takes up the coordination site of the O_e oxo-group that transferred to sulfite. While such a change in geometry is possible for the present biomimetic complex in the active site of SO, however, such a change would not likely occur given that the ligating cysteine would be attached to the backbone of the protein. If we consider the changes in the C=C bond length between the oxidized and reduced Mo-diselenolene complexes it is clear the ligand is not redox active. In particular, the oxidized complex has a C=C length of 1.355 Å (**Figure 3**) whereas the product complex has a bond length of 1.347 Å (**Figure 5**). It is noted that this has already been established for the dithiolene biomimetic complexes where the dithiolene ligands behave as ene-dithiolate, i.e., the ligands are

not redox active.⁸ Like the oxidized complex we find that the diselenolene ligand is folded upwards toward Mo–OH bond. However, given that the degree of oxidation of the metal has been reduced from +6 to +4 it is expected that the folding will be less severe. Indeed, from **Figure 5** the calculated fold angle for the diselenolene complex is 10.5°. A similar angle is measured for the dithiolene complex.

Regarding the energetics for the reaction, at the IEFPCM-B3LYP/BS2//BP86/BS1 it was found that the O-atom transfer occurs with an aqueous Gibbs energy of activation ($\Delta_r G^\ddagger$) of 141.4 kJ mol⁻¹. This activation energy is marginally less than that seen for the dithiolene complex where $\Delta_r G^\ddagger = 142.3$ kJ mol⁻¹. For both complexes the oxo-transfer is an endergonic process. Specifically, for the diselenolene complex the products lie 47.8 kJ mol⁻¹ higher in energy than the reactants whereas for the dithiolene complex the products lie 39.6 kJ mol⁻¹ higher in energy than the reactants. Thus, at the present level of theory the choice of bidentate ligand has a marginal effect on the kinetics but a significant effect on the thermodynamics of the oxo-transfer process. As noted in the methods section M06 has been shown to be suitable in the investigation of the chemistry of diselenolene complexes.^{18, 35-36} As seen in **Table 1** the use of the IEFPCM-M06/BS2//BP86/BS1 level of theory results in a considerable reduction in the aqueous Gibbs energy of activation (i.e., $\Delta\Delta G^\ddagger = -22.3$ kJ mol⁻¹) relative to the activation energy obtained at the IEFPCM-B3LYP/BS2//BP86/BS1 level of theory. Moreover, a considerable reduction in the aqueous Gibbs reaction energy (i.e., $\Delta\Delta_r G = -29.4$ kJ mol⁻¹) is calculated with the use of the IEFPCM-M06/BS2//BP86/BS1 level of theory. For the dithiolene complex similar changes in $\Delta_r G^\ddagger$ and $\Delta_r G$ are observed. Because of the considerable differences between the energies obtained at the IEFPCM-B3LYP/BS2//BP86/BS1 and IEFPCM-M06/BS2//BP86/BS1 levels of theory dispersion interactions were modeled by adding the D3 and D3BJ corrections to the B3LYP functional. Such corrections were used since M06 was parameterized with training sets

that included non-covalent interactions to better treat dispersion interactions, which B3LYP completely ignores.³⁷⁻³⁸

From **Table 1** the calculated value of $\Delta_r G^\ddagger$ obtained at the B3LYP-D3/BS2//BP86/BS1 level of theory is in good agreement with that obtained at the M06/BS2//BP86/BS1 level of theory. In particular, $\Delta_r G^\ddagger$ is found to be 117.7 kJ mol⁻¹. However, like the aqueous Gibbs reaction energy obtained at the IEFPCM-B3LYP/BS2//BP86/BS1 the reaction is again considerably endergonic where $\Delta_r G = 46.1$ kJ mol⁻¹ and in comparison to $\Delta_r G$ obtained at the IEFPCM-B3LYP/BS2//BP86/BS1 level of theory is only 1.7 kJ mol⁻¹ less endergonic. With the combination of Becke-Johnson damping with the D3 version of Grimme's dispersion correction (i.e., IEFPCM-B3LYP-D3BJ/BS2//BP86/BS1 level of theory) further reduction in $\Delta_r G^\ddagger$ occurs (i.e., $\Delta_r G^\ddagger = 110.9$ kJ mol⁻¹). Regarding the aqueous Gibbs reaction energy it is found that the reaction remains considerably endergonic where $\Delta_r G = 50.6$ kJ mol⁻¹ (**Table 1**) and in comparison to $\Delta_r G$ obtained at the IEFPCM-B3LYP/BS2//BP86/BS1 level of theory is 2.8 kJ mol⁻¹ more endergonic. Thus, for the calculation of the aqueous Gibbs activation energy for oxo-atom transfer the treatment of dispersion interactions is critical. However, the reason why the M06 functional predicts the oxo-transfer to be considerable less endergonic whereas all other methods predict a considerable endergonic reaction is not exactly known.

Overall the diselenolene complex has a marginally lower aqueous Gibbs energy of activation for the oxo-transfer reaction. In particular, averaging the values of $\Delta\Delta_r G^\ddagger$ between the diselenolene and dithiolene reactions for the various levels of theory used the diselenolene complex catalyzes the O-atom transfer with an activation energy that is on average 1.2 kJ mol⁻¹ lower in energy. Given that the rate-limiting step has been proposed⁸ to be the oxo-transfer process it might be expected then that at the present levels of theory the diselenolene complex catalyses the oxo-transfer reaction to sulfite with a rate very similar, if not faster, to that of the

analogous dithiolene complex. However, at the present levels of theory the dithiolene complex has a less endergonic aqueous Gibbs reaction energy and on average is 9.4 kJ mol^{-1} less endergonic than the corresponding aqueous Gibbs reaction energies for the diselenolene complex and thus the products formed by the dithiolene complex are expected to be thermodynamically more favourable.

As noted above the addition of the water molecule likely aids in catalyzing the O-atom transfer, thus, to determine the effect of the added water the oxidized Mo-diselenolene and Mo-dithiolene complexes as well as the respective TS structures were optimized at the BP86/BS1 level of theory. Aqueous Gibbs reaction and activation energies were obtained at the IEFPCM-B3LYP-D3BJ/BS2//BP86/BS1 level of theory. The resulting complexes are shown in **Figure 6**. In general, the deletion of this water has a marginal effect on the key geometrical properties. However, regarding the energetics for the O-atom transfer it was found that aqueous Gibbs activation energy for O-atom transfer was found to be $124.6 \text{ kJ mol}^{-1}$, whereas for the analogous dithiolene complexes the activation energy was found to be $125.7 \text{ kJ mol}^{-1}$. Thus, the presence of a water molecule does indeed help to stabilize the TS. Regardless, in agreement with the above results the diselenolene complex catalyses the oxo-transfer reaction with a rate very similar to that of the analogous dithiolene complex, thus, is expected to catalyse the O-atom transfer with a similar if not faster rate.

While many ligands have been synthesized to mimic MPT, from the work of Ryde et al.⁵⁰ it was concluded that to correctly describe the MPT-metal-complex within an active site the full MPT ligand must be used. In particular, it was concluded that while the reduction potentials may be similar the kinetics of the reactions may differ with respect to changes in ligand size. Thus, future work will involve the investigation of more complete active site models of the diselenolene analogue of MPT ligand in SO active site models.

Conclusions

From the results obtained in the present study the diselenolene SO biomimetic complex is able to catalyse the O-atom transfer with lower values of $\Delta_r G^\ddagger$ in comparison to the analogous dithiolene complex. In particular, for the complex it was found that the diselenolene complex has an activation energy that is on average 1.2 kJ mol^{-1} lower. However, the thermodynamics suggest the oxidation of sulfite is less favourable for the diselenolene complex than that seen for the dithiolene complex where the aqueous Gibbs reaction energy for the dithiolene complex. Such results provide incentive for the synthesis of diselenolene complexes.

With the use of the various means to correct for dispersion in combination to using the B3LYP functional it was found that the activation energy for O-atom transfer is lowered by more than 30.5 kJ mol^{-1} for both the diselenolene and dithiolene complexes. Thus, it seems that for oxo-transfer reactions catalysed by biomimetic mononuclear Mo-containing complexes the proper treatment of dispersion interaction is necessary.

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Supporting Information

The xyz coordinates of the complexes discussed in the present article are provided in **Table S1**.

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Table 1. Relative aqueous Gibbs energies (in kJ mol^{-1}) for the diselenolene complex obtained at the IEFPCM-DFTi/BS2//BP86/BS1 level of theory. Relative energies obtained for dithiolene complex at the DFTi/BS2//BP86/BS1 level of theory are included in parentheses. Energies are relative to the aqueous Gibbs energies of the isolated reactants (i.e., $\text{L}'\text{LMoO}_2$ and HSO_3^-).

	B3LYP/BS2	M06/BS2	B3LYP- D3/BS2	B3LYP- D3BJ/BS2
$\Delta_r G^\ddagger$	141.4 (142.3)	119.1 (119.2)	117.7 (118.8)	123.4 (135.6)
$\Delta_r G$	47.8 (39.6)	18.4 (1.3)	46.1 (44.5)	50.6 (39.9)

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Figure 1. The biomimetic diselenolene complex used to model the oxo-transfer reaction of SO in the oxidation of sulfite. The non-attacking O_a was modeled as both protonated and deprotonated, however, for purposes of clarity the proton was not included in the figure.

Figure 2. (a) The LUMO of the $L'MoO(OH_2)$ complex (the water has been ignored for purposes of clarity) and (b) the HOMO of HSO_3^- . Obtained at the IEFPPCM-B3LYP/BS2//BP86/BS1 and generated using GaussView 5.

Figure 3. The structure of the oxidized diselenolene complex, L'MoO₂, with key bond lengths provided in angstroms. Bond lengths for the dithiolene complex are provided in the parentheses.

Figure 4. The structure of the TS for the oxo-transfer process with key bond lengths provided in angstroms. Bond lengths for the dithiolene complex are provided in the parentheses.

Figure 5. The structure of the reduced diselenolene complex product complex, $L'MoOH(OH_2)$, with key bond lengths provided in angstroms. Bond lengths for the dithiolene complex are provided in the parentheses.

Figure 6. **a)** The structure of the oxidized diselenolene complex, $L'MoO_2$, in the absence of the water molecule. **b)** The structure of the TS for the oxo-transfer process in the absence of the water molecule. Key bond lengths provided in angstroms (Å). Bond lengths for the dithiolene complex are provided in the parentheses.

A Computational Investigation Into The Catalytic Activity Of A Diselenolene Sulfite Oxidase Biomimetic Complex

*Eric A. C. Bushnell**

Department of Chemistry, Brandon University, 270-18th Street, Brandon, Manitoba R7A 6A9,
Canada.

Author to whom correspondence should be addressed:

Email: bushnelle@brandonu.ca

Phone: 204 571 7899

TOC Image.