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S1

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FEB - 5 2001

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JOURNAL OF THE AMERICAN
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Activation of the C–H Bond of Methane by Intermediate Q of Methane Monooxygenase: A Theoretical Study

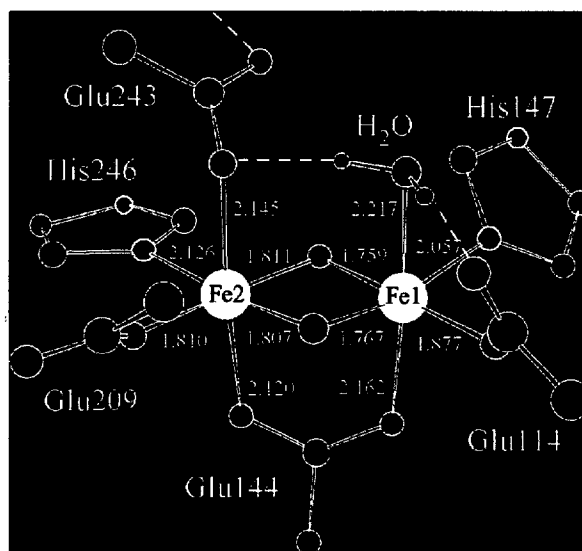
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Journal of the American Chemical Society

List of Figures

Figure S1. Core structure of the original minimized Q model (see ref. 6). Numbers indicate bond distances (Å) and dashed lines indicate hydrogen bonding interactions. The Fe–Fe distance is 2.672 Å.



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Figure S2. Core structure of the minimized radical intermediate state. The numbers indicate distances (Å) from the Fe atoms to the μ -oxo atoms. The Fe–Fe distance is 2.966 Å and the distance from the oxygen atom of the μ -OH to the carbon atom of the methyl radical is 2.930 Å. Dashed lines represent hydrogen bonds.

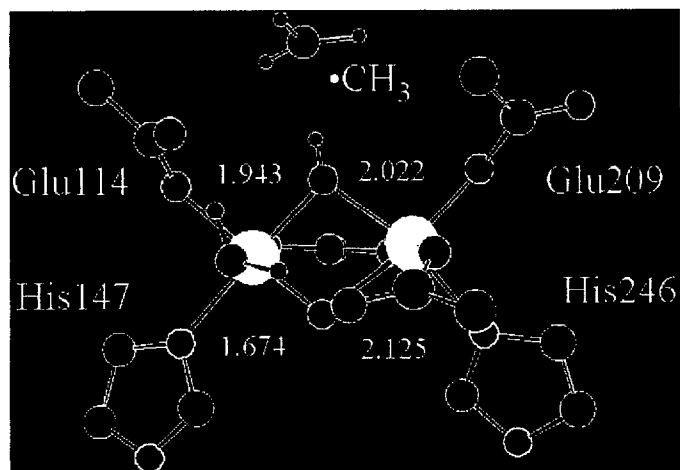


Figure S3. Cores of the minimized structures along the concerted reaction path prior to methanol formation viewed down the Fe–Fe axis. (a) The C–O–H angle is 0° . (b) The C–O–H angle is 27° . (c) The C–O–H angle is 54° . (d) The C–O–H angle is 81° . (e) The C–O–H angle is 106° .

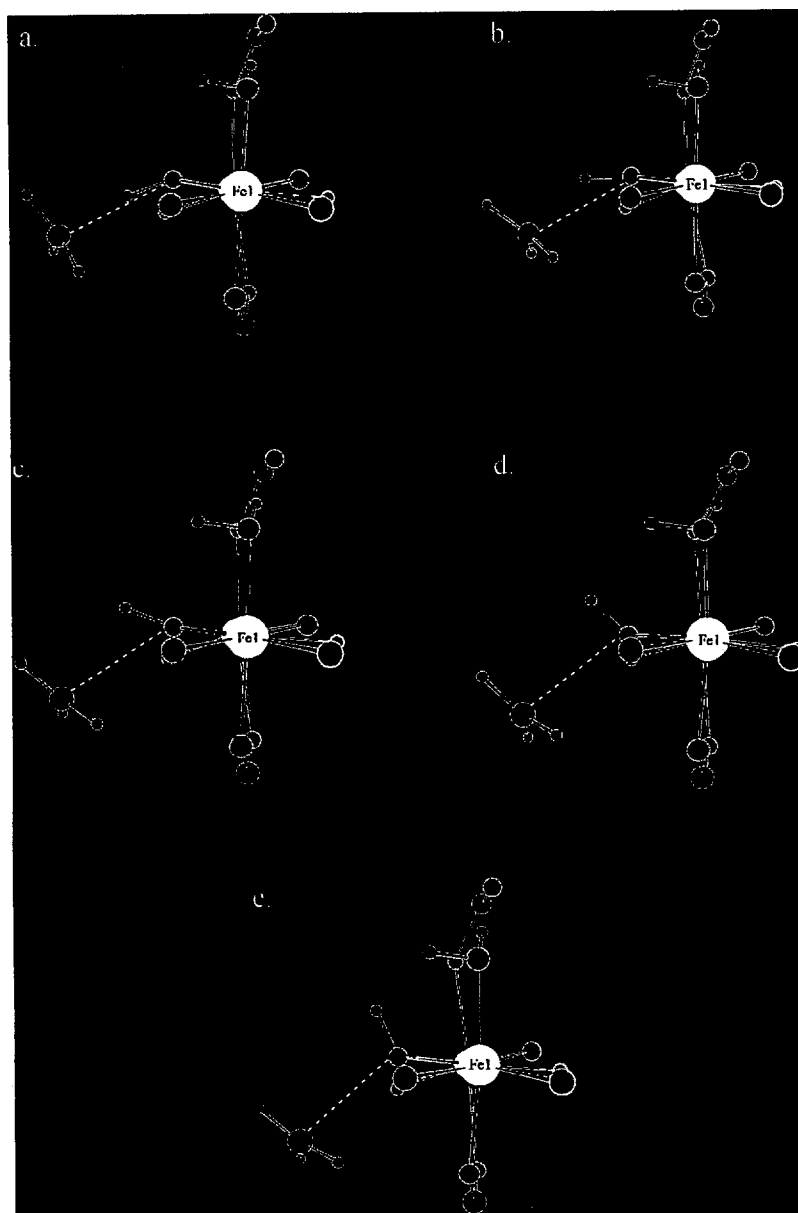
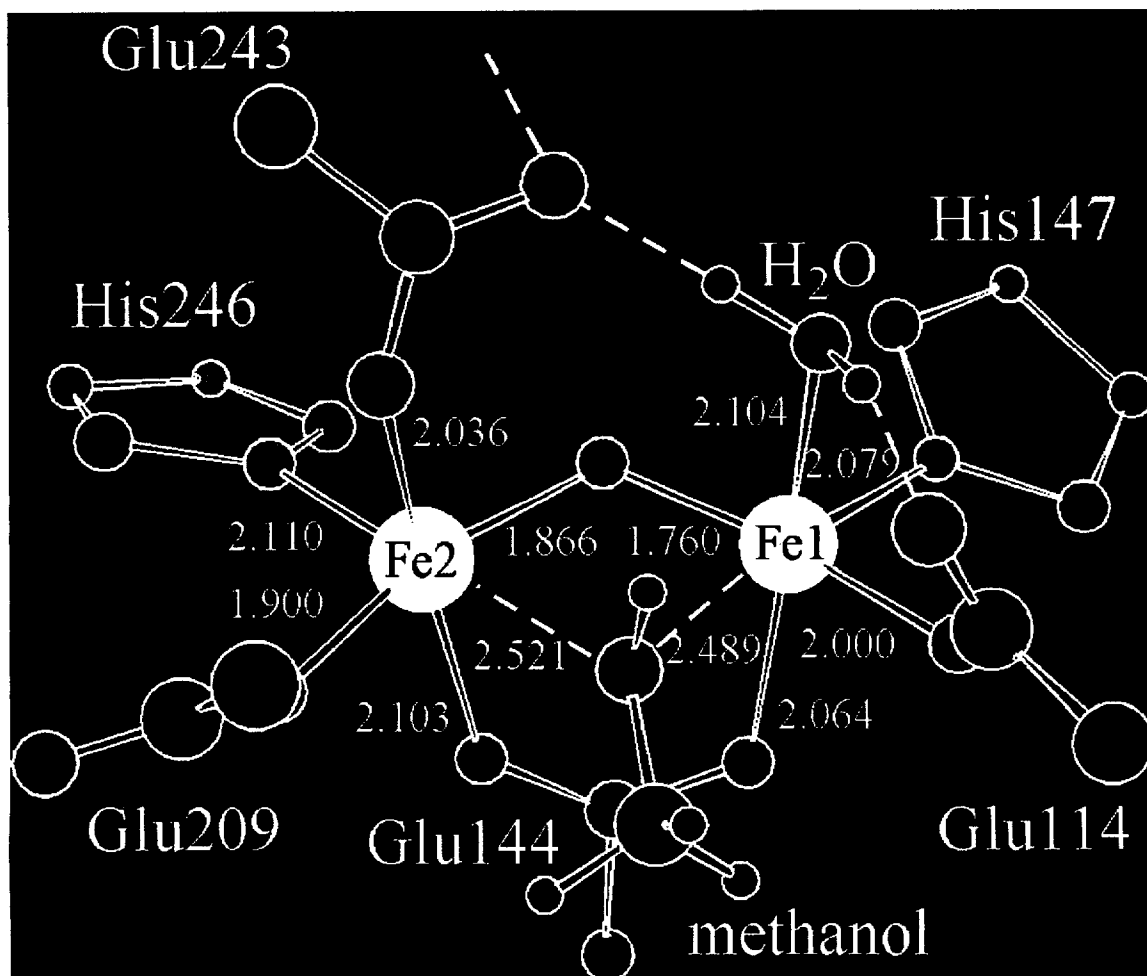
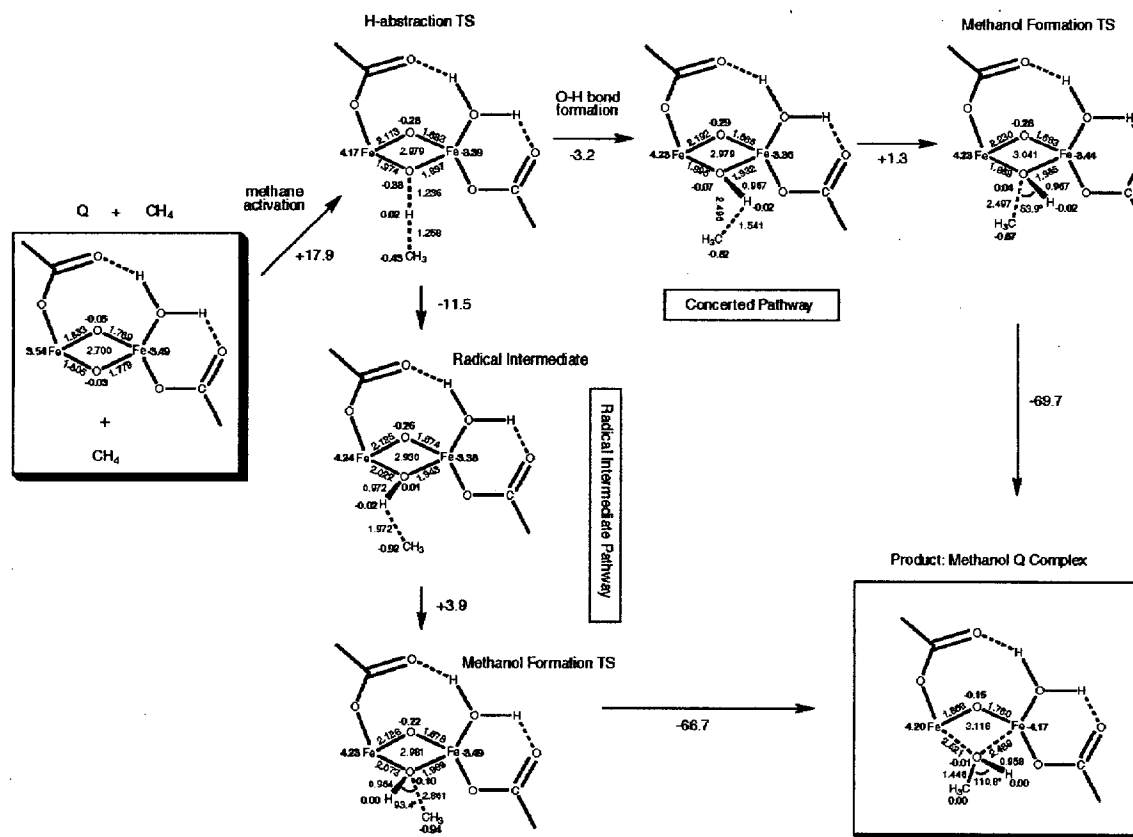


Figure S4. Core structure of the minimized models following methanol formation depicting methanol bound very weakly to the iron center. Numbers indicate bond distances (Å) and dashed lines represent hydrogen bonds.



S5

Figure S5. Overall reaction scheme for hydrogen atom abstraction and methanol formation starting from Q + CH₄. All energies^a are given in kcal/mole. Spins are printed in bold. Distances are given in Å.



^aDifferences in energies for the net reaction of Q + CH₄ → methanol Q complex stem from using the small mixed basis set to study the concerted pathway versus using the large mixed basis set to study the radical intermediate pathway.

Table S1. Basis set usage for quantum chemical DFT calculations performed with the Jaguar 4.0 *ab initio* electronic structure code using the B3LYP functional.¹

	Structural optimizations and quadratic synchronous transit (QST) optimizations (small mixed basis set)	Singlepoint calculations (large mixed basis set)
Periphery of structure	6-31G	6-31G**
Reactive core	6-31G**	cc-pVTZ (-f)
Iron atoms	lacvp**	lacv3p**

The three dimensional map of the potential energy surface for the concerted reaction pathway was performed using the small mixed basis set. We have, however, computed a substantial number of points using the large mixed basis set and find that the relative energies among points on the surface are only minimally affected.

¹ Jaguar 4.0, Schrodinger, Inc., Portland, Oregon, 2000.

Table S2. Absolute energies (au), energies relative to the reactants Q + CH₄ (kcal/mole), bond distances (Å), and bond angles (degrees) of the minimized structures along the concerted reaction pathway (see Figure S3) and radical intermediate pathway prior to and after methanol formation (see Figure S4). Rotation angles of C and H are given with respect to the Fe–O–Fe plane.

a) Concerted reaction pathway

Absolute energy (small mixed basis set)	Energy relative to Q + CH ₄	C–O distance	Rotation angle of C	Rotation angle of H	C–O–H angle
-2987.9955	+15.3	2.50	0	0	0
-2987.9964	+14.7	2.50	7	0	7
-2987.9956	+15.2	2.50	7	20	27
-2987.9944	+15.9	2.50	14	40	54*
-2987.9981	+13.6	2.50	21	60	81
-2988.0004	+12.2	2.50	21	85	106

* transition state for concerted reaction pathway

b) Radical intermediate pathway

Absolute energy (large mixed basis set)	Energy relative to Q + CH ₄	C–O distance	Rotation angle of C	Rotation angle of H	C–O–H angle
radical intermediate					
-2989.0132	+6.4	2.93	n/a	n/a	-8
transition state					
-2989.0070	+10.3	2.86	n/a	n/a	93

c) Concerted reaction pathway

Structure	Absolute energy (small mixed basis set)	Energy relative to Q + CH ₄	Fe1-O distance	Fe2-O distance
A	-2988.0020	+11.2	2.10	2.04
B	-2988.0533	-21.0	2.28	2.23
C	-2988.0947	-47.0	2.45	2.43
D	-2988.1055	-53.8	2.52	2.49

Table S3. Mulliken spin populations for the reactant, transition state, radical intermediate, and various geometries along the concerted reaction and radical intermediate methanol formation pathways. Fe1, Fe2, O3, and O4 are as labeled in figures 1, 2, and 3. H refers to the hydrogen abstracted by methane, and CH₃ to the methyl fragment resulting from that abstraction.

	Fe1	Fe2	O3	O4	H	CH ₃
Q (figure 1)	3.54	-3.49	-0.03	-0.06	n/a	n/a
H abstraction transition state (figure 2)	4.17	-3.39	-0.38	-0.28	0.02	-0.43
Radical intermediate (figure S2)	4.24	-3.38	0.01	-0.26	-0.02	-0.92
Concerted pathway transition state (figure 3)	4.23	-3.44	0.04	-0.28	-0.02	-0.82
Radical intermediate transition state	4.23	-3.49	0.10	-0.22	0.00	-0.94
Methanol-bound product (figure S4)	4.20	-4.17	-0.01	-0.15	0.00	0.00
Concerted methanol pathway (figure S3)						
C-O-H angle = 7°	4.23	-3.36	-0.07	-0.29	-0.02	-0.82
C-O-H angle = 27°	4.23	-3.35	-0.04	-0.31	-0.03	-0.85
C-O-H angle = 54°	4.23	-3.44	0.04	-0.28	-0.02	-0.87
C-O-H angle = 81°	4.22	-3.83	0.17	-0.16	-0.01	-0.68
C-O-H angle = 106°	4.22	-3.98	0.20	-0.12	-0.01	-0.55
Structures following methanol formation (table S4)						
A	4.18	-3.82	0.16	-0.23	-0.01	-0.57
B	4.20	-4.17	0.01	-0.19	0.00	-0.01
C	4.19	-4.18	-0.01	-0.11	0.00	0.00
D	4.20	-4.17	-0.01	-0.15	0.00	0.00