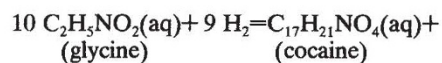


and products can lead to ridiculous results. For example, consider the synthesis of cocaine from glycine:



Using the free energies of formation $\Delta G_f^\circ = -88.58 \pm 0.16 \text{ kcal mol}^{-1}$ for glycine⁴ and $\Delta G_f^\circ = -65.8 \pm 10.0 \text{ kcal mol}^{-1}$ for cocaine (our estimate) and the standard ΔG_f° for NH_3 , CO_2 and H_2O (refs 4,5) gives $\Delta G_{\text{react}}^\circ = -64.0 \pm 10.0 \text{ kcal}$ at 25 °C and an equilibrium constant $K_{\text{eq}} = 10^{47}$. Using this equilibrium constant, and taking NH_3 fugacity = 10^{-3} atm and CO_2 fugacity = 25 atm, as specified by Shock and Schulte (even though these values are unrealistic), we calculate the cocaine to glycine ratio as a function of the H_2 fugacity, f_{H_2} . Taking glycine as $4 \times 10^{-3} \text{ M}$, which would be the concentration if 10 p.p.m. glycine were dissolved in the interstitial water (10% by volume) of the Murchison parent body⁶, we find that the cocaine and glycine concentrations will be equal at $f_{\text{H}_2} = 4 \times 10^{-6} \text{ atm}$ ($\log f_{\text{H}_2} = -5.4 \pm 0.8$). A cocaine concentration of $4 \times 10^{-3} \text{ M}$ is close to saturation ($6 \times 10^{-3} \text{ M}$) (ref. 7), and so cocaine would precipitate out at slightly higher f_{H_2} values. At $f_{\text{H}_2} = 7 \times 10^{-4} \text{ atm}$, 99% of the glycine would be converted to cocaine. These f_{H_2} values are in agreement with those calculated from the estimated redox potentials during aqueous alteration on the carbonaceous chondrite parent body⁸. As far as we know, no meteorites contain profuse amounts of cocaine.

Although the assumption of thermodynamic equilibrium generally leads to a good description of inorganic reactions, thermodynamic equilibrium is attained only rarely with organic compounds. Calculations based on thermodynamic equilibrium can generate misleading conclusions for organic mixtures.

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SHOCK AND SCHULTE REPLY — Natural systems exist in states of partial equilibrium in which some species are preserved far from equilibrium by kinetic barriers and others coexist at stable or metastable equilibrium. To identify metastable equilibrium states, realistic physical and chemical parameters that prevail in natural systems must be evaluated. Evidence from nature, elucidated with thermodynamic calculations, indicates that over millions of years the complex mixtures of organic compounds in sedimentary basins approach metastable equilibrium states at temperatures as low as 100 °C (ref. 9). At low temperatures, the enormous lengths of time required to reach metastable equilibrium states make laboratory experiments

impossible. But such states may be reached on laboratory time scales at higher temperatures, as demonstrated in our reinterpretation¹⁰ of experiments conducted by Miller and Bada¹¹, in which a metastable state among aqueous amino acids was established at 250 °C. Our model for organic synthesis on meteorite parent bodies is based on these observations, with constraints that were likely to prevail during aqueous alteration.

Although humorous, Miller and Bada's use of cocaine and glycine equilibrium is misleading, owing to hand-picked thermodynamic data and compositional constraints. Their calculated abundance of cocaine is a strong function of both $\Delta G_{\text{react}}^\circ$ and their assumed concentration of glycine. Although their methods are not referenced, it is clear that the large uncertainty in their estimated ΔG_f° for aqueous cocaine propagates directly into $\Delta G_{\text{react}}^\circ$, and causes K_{eq} for the glycine to cocaine reaction to lie between 10^{40} and 10^{54} . The law of mass action for this reaction yields

$$a_{\text{cocaine}} = K_{\text{eq}} \frac{(a_{\text{glycine}})^{10} (f_{\text{H}_2})^9}{(f_{\text{CO}_2})^3 (f_{\text{NH}_3})^9 (a_{\text{H}_2\text{O}})^{10}}$$

and it can be seen that calculated cocaine activities (a) will also be subject to 14 orders of magnitude of uncertainty. This uncertainty can be masked, and results can be calculated that are consistent with abundant cocaine, by a careful choice of the activity of glycine, given its power of ten.

To arrive at their activity of aqueous glycine, Miller and Bada need a bulk glycine concentration of 10 p.p.m., and a water to rock ratio during alteration of 0.1. Their parent-body glycine concentration exceeds by 33% the highest concentration of glycine in Murchison extracts¹². It is important to remember that amino acid concentrations reported for meteorites are actually those of acid-hydrolysed, hot-water (100 °C) extracts, in which hydrolysis increases the free amino acid concentration by as much as 800% (ref. 12). For the water to rock ratio, they assume that the Murchison parent body contained 10% by volume interstitial water, and cite DuFresne and Anders⁶ (whose paper was published seven years before the meteorite fell). In fact, DuFresne and Anders state that the Orgueil meteorite contains 10% water, but this is the amount of H_2O structurally bound in hydrated silicates, which must be a small fraction of the water present during alteration. Oxygen isotopes indicate minimum water to rock ratios of 0.5 and 0.8 for Murchison and Orgueil, respectively¹³, but these values require the assumption that the minerals analysed formed simultaneously in the same aqueous environment. This appears unwarranted given present knowledge of the paragenesis of meteorite alteration¹⁴. It is more likely that water to rock ratios during meteorite alteration were much like those in terrestrial hydrothermal systems. If so, the concentrations of many organic compounds in meteorites may have accumulated slowly

from dilute solutions in the same way that massive ore deposits form from vast quantities of solution carrying a few p.p.m. metal.

By overestimating the amount of glycine, and underestimating the water to rock ratio, Miller and Bada obtain a glycine concentration ($10^{-2.4}$) consistent with metastable equilibrium only if cocaine were found in meteorites. In our calculations, we take account of all the aqueous organic compounds for which thermodynamic data can be calculated¹⁵, place mass-balance constraints on each element, and minimize the Gibbs function for the chemical system. We calculate an aqueous glycine activity of $10^{-6.8}$ during metastable aqueous alteration of pyrene at 100 °C, 100 bars, $f_{\text{NH}_3} = 10^{-3}$, and f_{H_2} set by the nickel–bunsenite mineral assemblage (f_{CO_2} is set to $10^{1.4}$ by the phase rule). The corresponding activity of aqueous cocaine is $10^{-38.7}$, consistent with the absence of cocaine in carbonaceous chondrites.

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- Shock, E. L. & Schulte, M. D. *Nature* **343**, 728 (1990).
- Wright, I. P. & Gilmour, I. *Nature* **345**, 110–111 (1990).
- Henze, H. R. & Blair, C. M. *J. Am. chem. Soc.* **53**, 3042–3046 (1931).
- Miller, S. L. & Smith-Magowan, D. *J. phys. Chem. Ref. Data* **19**, 1049–1073 (1990).
- Stull, D. R., Westrum, E. F. Jr & Sinke, G. C. *The Chemical Thermodynamics of Organic Compounds* (Wiley, New York, 1969).
- DuFresne, E. R. & Anders, E. *Geochim. cosmochim. Acta* **26**, 1085–1114 (1962).
- The Merck Index 2420* (Merck, Rahway, New Jersey, 1983).
- Zolensky, M. E., Bourcier, E. L. & Gooding, J. L. *Icarus* **78**, 411–425 (1989).
- Shock, E. L. *Geology* **17**, 572–573 (1989).
- Shock, E. L. *Geochim. cosmochim. Acta* **54**, 1185 (1990).
- Miller, S. L. & Bada, J. L. *Nature* **334**, 609–611 (1988).
- Shock, E. L. & Schulte, M. D. *Geochim. cosmochim. Acta* **54**, 3159–3173 (1990).
- Clayton, R. N. & Mayeda, T. K. *Earth planet. Sci. Lett.* **67**, 151–161 (1984).
- Tomeoka, K. & Buseck, P. R. *Geochim. cosmochim. Acta* **49**, 2149–2163 (1985).
- Shock, E. L. & Heigeson, H. C. *Geochim. cosmochim. Acta* **54**, 915–945 (1990).

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