

Potential of Organic Cation-Saturated Montmorillonite as Treatment for Poisoning by Weak Bases

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Abstract □ The preferential adsorption of the protonated form of weak bases by montmorillonite causes an increase in the pK_{eff} of atrazine. The effect on the acid-base equilibrium of atrazine is related to the exchangeable cation on the surface of montmorillonite. The greatest effect was produced by the presence of 3-hydroxypropylammonium-saturated montmorillonite, which caused the pK_{eff} of atrazine to increase 5.3 units to 6.9. This shift in pK_{eff} causes the protonated form of atrazine to be the predominate species in the pH range encountered in the GI tract and should result in a high degree of adsorption of atrazine. Fraction-bound studies confirmed this hypothesis by demonstrating virtually complete adsorption of atrazine by 3-hydroxypropylammonium-saturated montmorillonite up to pH 6. The fraction-bound studies also verified that protonated atrazine is adsorbed more completely by 3-hydroxypropylammonium-saturated montmorillonite than by bentonite USP or sodium-saturated montmorillonite. It is believed that saturation of the clay surface by an organic cation alters the surface environment of the clay, which results in enhanced adsorption of the protonated form of atrazine. The potential utility of montmorillonite saturated with an organic cation as an adsorbent for the emergency treatment of poisoning by weak bases is suggested.

Keyphrases □ Montmorillonite—saturation with organic cations for potential treatment of poisoning by weak bases □ Adsorbents—montmorillonite saturated with organic cations, potential treatment of poisoning by weak bases □ Poisoning—weak bases, potential treatment with organic cation-saturated montmorillonite

A major limitation in the use of clays as adsorbents in the treatment of poisoning is that their strongest adsorption mechanism is chemisorption of cations due to the negative charge of clays arising from isomorphous substitution (1). Clays such as montmorillonite have a high adsorptive capacity for cations but do not interact strongly with neutral molecules (2). Thus, weak bases, which constitute a large chemical class of potential poisons, are well adsorbed by montmorillonite if the pK is high so that the protonated form of the weak base is present in the pH range encountered in the GI tract. However, montmorillonite is a less effective adsorbent if the pK of the weak base is low since these weak bases then exist as neutral molecules in the GI tract.

It was observed recently that the first acid-base equilibrium of tetracycline was displaced in the presence of montmorillonite while the second and third acid-base equilibria were not altered (3). The presence of montmorillonite thus caused the protonated form of tetracycline to be present in a montmorillonite suspension over a wider pH range than occurs in an aqueous solution. As a result, adsorption of tetracycline by montmorillonite occurred over a wider pH range than was expected based on solution pK values. The nature of the exchangeable cation influenced the magnitude of the shift in the first acid-base equilibrium of tetracycline (4). For example, sodium-saturated montmorillonite caused a greater shift than did calcium-saturated montmorillonite.

It was hypothesized that montmorillonite that was specially treated to replace the naturally occurring inorganic cations with an organic exchangeable cation might have a desirable effect on the acid-base equilibrium of weak bases. 3-Hydroxypropylammonium hydrochloride was chosen as the organic cation because it is a cation in the pH range of interest and is relatively small.

Atrazine (2-chloro-4-ethylamino-6-isopropylamine-5-triazine) was chosen as a model weak base because it was expected to be neutral in the pH range of the GI tract due to its pK of 1.64 (5).

EXPERIMENTAL

Materials—Atrazine¹ and bentonite USP² were obtained commercially. Montmorillonite (Wyoming bentonite) was a reference standard³. The presence of organic matter in the bentonite USP sample was established by the peroxide method (6). Thirty milliliters of 30% H₂O₂ was added to 15 ml of a 1% clay suspension and heated in a steam bath for 15 min. The treated clay was centrifuged along with an untreated reference suspension. The presence of organic matter was indicated when the color of the sample sediment was significantly lighter than the reference sediment.

Metal-ion analysis by atomic absorption spectrometry⁴ was used to identify the exchangeable cations in the bentonite USP, and X-ray diffraction⁵ was used to identify the nonclay components.

Sodium-saturated montmorillonite was prepared by washing a 2% montmorillonite suspension with 1 M NaCl. The washing procedure was repeated five times, and excess salt was removed by repeated washing with water until the addition of silver nitrate to the supernate gave a negative chloride test.

Calcium-saturated montmorillonite was prepared in the same manner using 1 M CaCl₂ as the exchanging solution.

3-Hydroxypropylammonium-saturated montmorillonite was prepared similarly using a 1 M 3-hydroxypropylammonium hydrochloride solution as the exchanging solution.

To confirm that 3-hydroxypropylammonium was the exchangeable cation after the washing procedure, the following comparison was made. Since ammonium washing is commonly used to remove calcium from montmorillonite (7), the amount of calcium exchanged by washing calcium-saturated montmorillonite with 1 M ammonium acetate was compared to the amount of calcium replaced by washing an identical aliquot of calcium-saturated montmorillonite with 1 M 3-hydroxypropylammonium chloride. Two aliquots of a 2% calcium-saturated montmorillonite suspension were washed five times with either 1 M ammonium acetate or 1 M 3-hydroxypropylammonium chloride. Following centrifugation, the calcium content of the pooled supernate from all five washings was determined by atomic absorption spectrometry⁴. Complete exchange of calcium by 3-hydroxypropylammonium chloride was indicated by the recovery from three individually tested clay samples of 72.9 ± 2.5 mEq of Ca²⁺/100 g following ammonium acetate washing and 69.8

¹ Ciba-Geigy Corp., Ardsley, N.Y.

² R. F. Revson and Co., New York, N.Y.

³ Clay Mineral Repository, Department of Geology, University of Missouri, Colorado, Mo.

⁴ Techtron 6, Varian Associates, Palo Alto, Calif.

⁵ Siemens AG Kristalloflex 4 generator, type F diffractometer, Karlsruhe, West Germany.

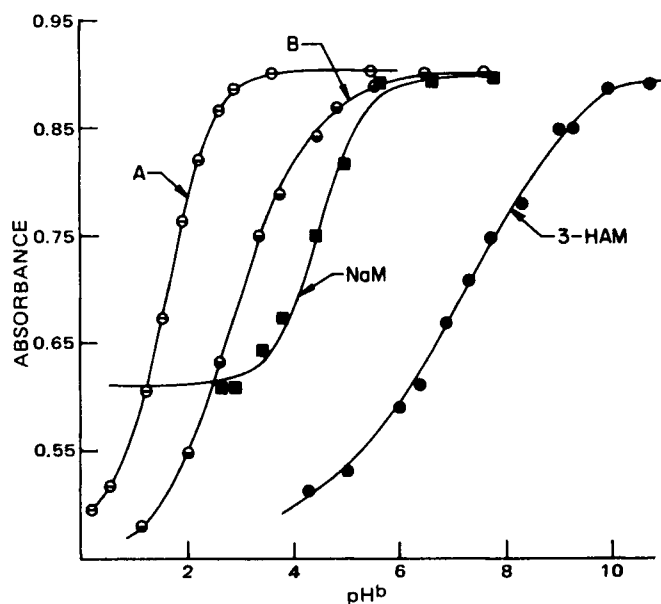


Figure 1—Acid-base titration of atrazine in clay suspensions. Key: \circ , aqueous solution; \odot , bentonite USP; \blacksquare , sodium-saturated montmorillonite; and \bullet , 3-hydroxypropylammonium-saturated montmorillonite.

± 3.1 mEq of $\text{Ca}^{2+}/100$ g following 3-hydroxypropylammonium chloride treatment.

UV Spectroscopic Titrations—Displacement of the pK of atrazine in clay suspensions was determined by spectroscopic titration. The pK_{eff} and the partial molar Gibbs free energy change upon addition of the clay, $\Delta\bar{G}_i$, for atrazine and atrazine- H^+ were calculated from the spectroscopic titration curve using the procedure of Feldkamp and White (8).

The UV spectra of the protonated and neutral forms of atrazine show the greatest difference in absorbance at 223 nm. Thus, titration curves were constructed by preparing a series of atrazine-clay suspensions containing 5 mg of atrazine and 200 mg of clay/liter at different pH^b (bulk pH) conditions and determining the absorbance at 223 nm.

Titration of atrazine in aqueous solution was done using the same procedure except that the clay was omitted.

Adsorption Studies—The fraction of atrazine bound by the clay at different pH^b conditions was determined using the samples from the spectroscopic titration experiment. A sample of each suspension was centrifuged, and 15 ml of supernate was collected. Sufficient hydrochloric acid was added to ensure that all of the atrazine was in the protonated form ($\text{pH}^b = 0.5$). The absorbance was measured at 223 nm.

The fraction of atrazine bound, f , was calculated from:

$$f = \frac{A_0 - (A_s - A_r)}{A_0} \quad (\text{Eq. 1})$$

where A_0 is the absorbance of an atrazine solution (5 mg/liter) containing only the protonated form of atrazine, A_s is the absorbance of the sample supernate, and A_r is the absorbance of the reference supernate.

RESULTS AND DISCUSSION

The effect of bentonite USP, sodium-saturated montmorillonite, and 3-hydroxypropylammonium-saturated montmorillonite on the acid-base equilibrium of atrazine is shown in Fig. 1. In aqueous solution, the pK of atrazine was found to be 1.64, which agrees with previously reported values (5).

In general, pK_{eff} and $\Delta\bar{G}_i$ depend on the composition of the system, i.e., pH, ionic strength, temperature, pressure, other solutes, and concentration. Therefore, the reported values for pK_{eff} and $\Delta\bar{G}_i$ represent average values over the pH range of interest.

The presence of bentonite USP caused the titration curve of atrazine to shift to higher pH values, indicating that the protonated form of atrazine interacts with the clay to a greater extent than does the neutral form of atrazine. This interaction caused a shift in the apparent dissociation constant, pK_{eff} , of atrazine. The magnitude of the interaction of each species of atrazine with the clay can be characterized by $\Delta\bar{G}_i$ (8).

As seen in Table I, the apparent dissociation constant of atrazine in-

Table I—Effect of Bentonite USP, Sodium-Saturated Montmorillonite, and 3-Hydroxypropylammonium-Saturated Montmorillonite on the Acid-Base Equilibrium of Atrazine

| Sample | pK_{eff} | $\Delta\bar{G}_{\text{BH}^+}$, kcal/mole | $\Delta\bar{G}_B$, kcal/mole |
|---|--------------------------|---|-------------------------------|
| Aqueous solution | 1.64 | — | — |
| Bentonite USP suspension | 2.80 | -1.46 | ~ 0 |
| Sodium-saturated montmorillonite suspension | 4.40 | -3.61 | ~ 0 |
| 3-Hydroxypropylammonium-saturated montmorillonite | 6.90 | -7.21 | ~ 0 |

creased from 1.64 to 2.80 in the presence of bentonite USP. The change in the partial molar Gibbs free energy of the protonated form of atrazine was -1.46 kcal/mole, indicating that this species of atrazine interacted with the clay. In contrast, virtually no interaction occurred between the neutral atrazine molecule and the clay since $\Delta\bar{G}_B$ was approximately zero.

The acid-base equilibrium of atrazine was affected more strongly by sodium-saturated montmorillonite. The value of pK_{eff} increased by almost 3 units, reflecting the increased interaction of the protonated form of atrazine with the sodium-saturated montmorillonite (Table I).

Although bentonite USP is predominantly a sodium-saturated montmorillonite (9, 10), the effect of bentonite USP on the acid-base equilibrium of atrazine was not as great as that produced by sodium-saturated montmorillonite. The sample of bentonite USP contained sodium as the major exchangeable cation, although 7.1 and 2.7% of the exchange capacity was satisfied by calcium and magnesium ions, respectively. In addition, X-ray diffraction showed the presence of quartz, gypsum, and calcite, while the peroxide test indicated the presence of organic material.

Thus, the smaller effect of bentonite USP on the acid-base equilibrium of atrazine may be due to the screening effect of the divalent exchangeable

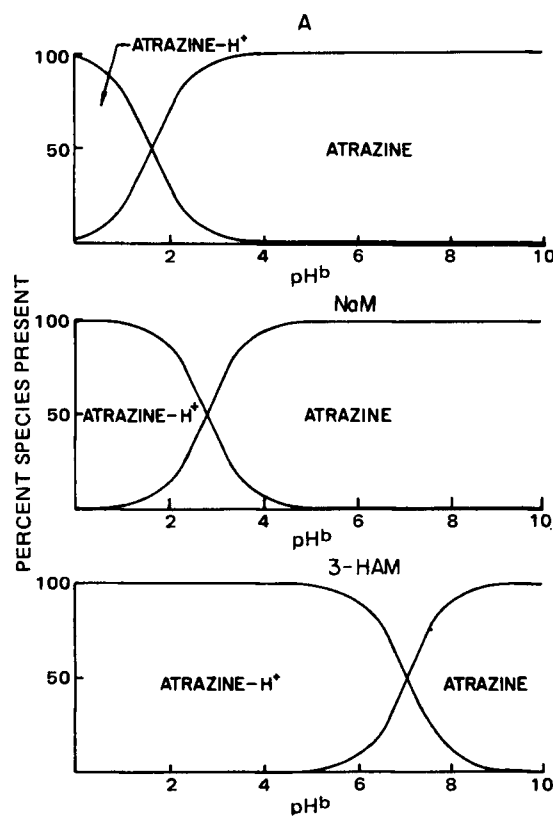


Figure 2—Distribution of ionic species of atrazine in clay suspensions based on pK_{eff} . Key: A, aqueous solution; NaM, bentonite USP suspension; and 3-HAM, 3-hydroxypropylammonium-saturated montmorillonite.

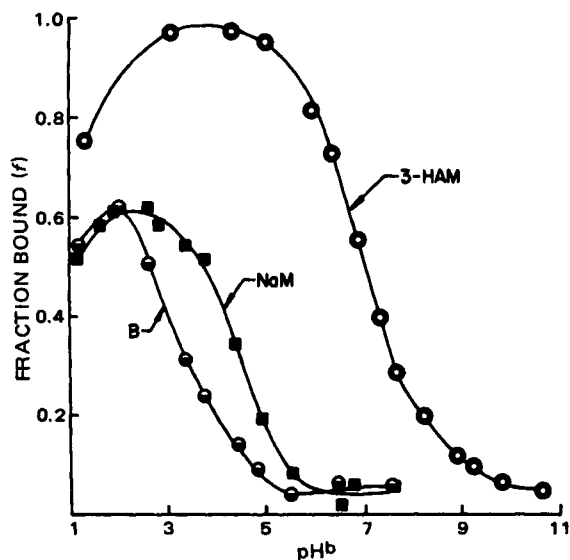


Figure 3—Effect of pH^b on the fraction of atrazine bound, f , in clay suspensions. Key: \circ , bentonite USP; \blacksquare , sodium-saturated montmorillonite; and \circ , 3-hydroxypropylammonium-saturated montmorillonite.

cations. It also is possible that the organic material in bentonite USP reduces the protonated atrazine–clay interaction. Similar findings were reported by Feldkamp (11), who observed a reduced ability of charged sites to interact with the protonated form of bases in soils containing organic matter.

The presence of 3-hydroxypropylammonium-saturated montmorillonite produced the greatest effect on the acid–base equilibrium of atrazine. The pK_{eff} of atrazine in a 3-hydroxypropylammonium-saturated montmorillonite suspension was 6.9, an increase of more than 5 units in comparison to the pK of atrazine. This shift was caused by the strong interaction of the protonated form of atrazine with the 3-hydroxypropylammonium-saturated montmorillonite, as evidenced by the magnitude of ΔG_{BH^+} and the virtual absence of any interaction of atrazine with the specially treated clay (Table I).

The interaction of atrazine with the clay surfaces caused a substantial shift in pK_{eff} , which resulted in an altered distribution of the protonated and neutral forms of atrazine. Figure 2 demonstrates the dramatic shift in the pH region in which the protonated form of atrazine predominated due to the presence of 3-hydroxypropylammonium-saturated montmorillonite.

The changes in the acid–base equilibrium of atrazine in the presence of bentonite USP, sodium-saturated montmorillonite, or 3-hydroxypropylammonium-saturated montmorillonite resulted in dramatic changes in the adsorption profile of atrazine (Fig. 3). Bentonite USP and sodium-saturated montmorillonite both adsorbed $\sim 60\%$ of the atrazine, although the maximum adsorption occurred at a higher pH^b (2.6) for sodium-saturated montmorillonite than for bentonite USP (2.0). The fraction of atrazine bound by 3-hydroxypropylammonium-saturated montmorillonite approached 100% at pH^b values up to 5.

The pH^b of maximum adsorption of atrazine reflects the pK_{eff} of atrazine in the presence of each clay. At low pH^b conditions, both protons and protonated atrazine cations compete for the negatively charged sites on the clay surface. The pH^b of maximum adsorption occurs when the interaction of protonated atrazine with the clay surface predominates. At pH^b conditions favoring the formulation of the neutral atrazine species based on pK_{eff} , the fraction bound curves decreased. Virtually no adsorption occurred at higher pH^b conditions, where the unionized atrazine would predominate. This observation confirms that ΔG_B is virtually zero as reported in Table I.

The fraction-bound study also suggests that saturation of montmo-

llonite with an organic cation such as 3-hydroxypropylammonium increases the interaction between the protonated form of atrazine and the clay. It is believed that the 3-hydroxypropylammonium cation induced a highly diffuse, electrical double layer at the surface of montmorillonite. Thus, 3-hydroxypropylammonium was less effective than sodium in countering the negative surface charge of montmorillonite.

A number of factors may be responsible for this effect. The distribution of the electrostatic charge on the organic cation might render it less effective than sodium in satisfying the surface charge. Geometric considerations also may prevent effective balancing of the surface charge by the organic cation.

It is not surprising that the protonated form of atrazine was able to replace the exchangeable cations in montmorillonite since large organic cations are adsorbed by van der Waals forces in addition to electrostatic forces (1). Hendricks (12) reported that large organic cations adsorbed by montmorillonite were nearly impossible to replace by smaller cations.

In addition to the formation of a highly diffuse, electrical double layer, the strong interaction of atrazine with 3-hydroxypropylammonium-saturated montmorillonite may be enhanced by a surface environment that is highly compatible with protonated atrazine. This is possible if the exchangeable organic cation induces a structured environment at the clay surface in which the polarity of the surface phase is similar to the polarity of protonated atrazine. As a consequence, protonated atrazine will exhibit a greater preference for the clay phase than for the solution phase.

Surface modification of montmorillonite through organic cation saturation may have an important therapeutic application in the treatment of poisoning. For weak bases with low pK values, the uncharged base should exist throughout the small intestine where systemic absorption is most likely. Conventional clay adsorbents such as bentonite USP do not strongly interact with neutral molecules and, therefore, are not effective in treating poisoning by weak bases. However, when montmorillonite is saturated with an organic cation such as 3-hydroxypropylammonium, the fraction of weak base bound and the pH^b range over which adsorption takes place should be greatly increased. Evaluation of the toxicity of small organic cations that may serve as exchangeable cations in montmorillonite may lead to the development of organic cation-saturated montmorillonite, which may prove valuable in the treatment of poisoning by weak bases.

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