

Chemistry and Mineralogy of Arsenic

Peggy A. O'Day¹

Arsenic has diverse chemical behavior in the natural environment. It has the ability to readily change oxidation state and bonding configuration, which creates rich inorganic and organic chemistry. This behavior is a consequence of the electronic configuration of its valence orbitals, with partially filled states capable of both electron donation and overlap in covalent bonds. In natural compounds, arsenic bonds primarily to oxygen and sulfur, generating a variety of aqueous species and minerals. The affinity of arsenic for these two elements, along with its stable bonding to methyl groups, constitutes the structural basis for most organic and biosynthetic compounds. The agile chemistry of arsenic helps to explain its contradictory action as both a toxin and a curative, and its sometimes-elusive behavior in the environment.

KEYWORDS: chemical bonding, arsenic sulfides, arsenic oxides, organoarsenicals, arsenic toxicity

INTRODUCTION

Arsenic is an elusive element, with a mysterious ability to change color, behavior, reactivity, and toxicity. For example, two arsenic sulfide minerals, red-colored realgar (As_4S_4) and bright yellow orpiment (As_2S_3), were described by the ancient Greeks, but they considered them to be two entirely different substances (Irgolic 1992). As noted in the lead article in this issue, arsenic has a long history with humans, having been used as both a poison and a curative, in metallurgy, for decoration and pigmentation, and in pyrotechnics and warfare (Miller et al. 2002; Nriagu 2002). Arsenic trioxide (As_2O_3), for example, is a tasteless, odorless, white powder. It is the form of arsenic favored historically for eliminating enemies and aged relatives, while Schweinfurt green (copper acetoarsenite) is a bright green, very toxic powder that was formerly used extensively as a pigment in wallpaper (National Research Council 1977; Cullen and Reimer 1989). Today, elevated levels of arsenic in groundwater aquifers threaten human health in widespread areas worldwide, but the spatial unpredictability of dissolved arsenic concentrations leaves scientists at a loss to explain contamination at one site and clean water in the neighbor's well next door (see Charlet and Polya this issue). The chemical variability of arsenic stems from its electronic structure and bonding properties, which give rise to a variety of forms in the solid, aqueous, and gas states.

As a metalloid, third-row, group V element, arsenic is seated beneath nitrogen and phosphorus in the periodic table and thus has an excess of electrons and unfilled orbitals that

stabilize formal oxidation states from +5 to -3. The electron configuration for neutral arsenic is $[\text{Ar}]3d^{10}4s^24p_x^14p_y^14p_z^1$, a state that supplies up to five valence electrons for participation in chemical bonding and empty p orbitals for electron occupation. Although the electronegativity of arsenic is greater than that of nitrogen and similar to that of phosphorus by most measures (Allred and Hensley 1961), arsenic has a greater oxidation potential (i.e. the ability to lose electrons) than nitrogen and phosphorus, which increases its cationic character. However, the assignment of formal oxidation states to arsenic is not very meaningful from a

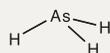
chemical standpoint because arsenic bonding overall is essentially covalent (Cotton and Wilkinson 1988). Arsenic bonds readily to a variety of ligands, which strongly influences its chemical behavior. Compared to nitrogen and phosphorus, the potential participation of lone pair electrons and outer d orbitals in arsenic bonding stabilizes some different types of molecular configurations than are found in the lighter group elements. While arsenic can combine with many other elements to form covalent compounds, it most commonly bonds to oxygen and sulfur in nature. The ability of arsenic to shift from an electropositive state, such as in oxo-anions, to an electronegative state, as in metal arsenides, is a consequence of electron occupation of bonding and antibonding orbitals of arsenic and its myriad of ligands. This facile chemistry has led to extensive investigation of synthetic compounds of arsenic, both inorganic and organic. This article, however, focuses primarily on natural forms of arsenic and presents a brief survey of its speciation and occurrence in solid, aqueous, and biological compounds in environments at and near the Earth's surface.

AQUEOUS AND GAS SPECIATION

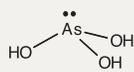
In aqueous solutions, arsenic forms the oxo-anions arsenite, $\text{H}_3\text{As}^{3+}\text{O}_3$ [or commonly written $\text{As}^{3+}(\text{OH})_3$] and arsenate, $\text{H}_3\text{As}^{5+}\text{O}_4$. From the pK_a 's (acid dissociation constant) shown in FIGURE 1, aqueous arsenic species in most natural waters (pH ~4–10) are the neutral species H_3AsO_3 for As^{3+} , and H_2AsO_4^- and HAsO_4^{2-} for As^{5+} (National Research Council 1977; Cullen and Reimer 1989). The redox potential of arsenic oxo-anions is such that arsenite is expected to be the stable aqueous form under moderately reducing conditions, roughly from oxidation potentials (Eh) of about +300 mV at pH 4 to -200 mV at pH 9, while arsenate is stable in oxidized aqueous solutions (Inskeep et al. 2002;

¹ School of Natural Sciences
University of California, Merced
Merced, CA 95340, USA
E-mail: poday@ucmerced.edu

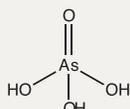
Inorganic Arsenic



Arsenine
AsH₃

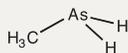


Arsenious acid or
Arsenite (As³⁺(OH)₃)
pK_{a1,2,3} = 9.23, 12.13, 13.40

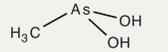


Arsenic acid or
Arsenate (H₃As⁵⁺O₄)
pK_{a1,2,3} = 2.20, 6.97, 11.53

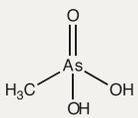
Methylated Arsenic Compounds



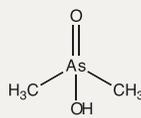
Methylarsine
AsH₂CH₃



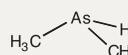
Monomethylarsinous
acid or MMAs(III)
As(OH)₂CH₃



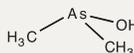
Monomethylarsonic
acid or MMAs(V)
AsO(OH)₂CH₃



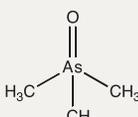
Dimethylarsinic
acid or DMAs(V)
AsO(OH)(CH₃)₂



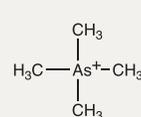
Dimethylarsine
AsH(CH₃)₂



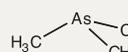
Dimethylarsinous
acid or DMAs(III)
As(OH)(CH₃)₂



Trimethylarsine
oxide or TMAO
AsO(CH₃)₃

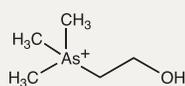


Tetramethylarsonium
ion or TETRA
As⁺(CH₃)₄

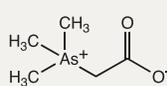


Trimethylarsine
As(CH₃)₃

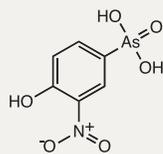
Organoarsenic Compounds



Arsenocholine
(CH₃)₃As⁺CH₂CH₂O



Arsenobetaine
(CH₃)₃As⁺CH₂COO⁻



Roxarsone
C₆H₆AsNO₆

Organoarsenic Lipids

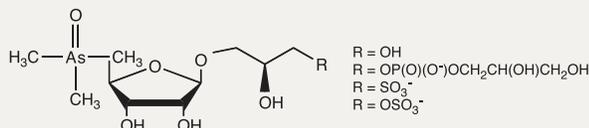


FIGURE 1 Summary of important inorganic, organic, and biological forms of arsenic in the environment. For inorganic aqueous species, stepwise acid dissociation constants ($pK_{a_n} = -\log(K_{a_n})$, where n is the number of protons dissociated and K_a is the equilibrium constant) are given. The position of lone-pair electrons is shown for inorganic As³⁺. A wide variety of organoarsenic compounds and lipids have been identified; several of the major environmental species are shown here.

Nordstrom and Archer 2003). The fact that the stable equilibrium state of arsenic changes over the range of Eh and pH conditions commonly encountered in natural environments, roughly within the range of NO₃⁻/N₂ and Fe³⁺/Fe²⁺ redox potentials (depending on the reaction stoichiometry), is a controlling factor in arsenic cycling between abiotic and biotic compartments in the environment.

The structural configuration of As³⁺ has three pyramidal bonds and a lone electron pair occupying the fourth arm of a tetrahedron (FIG. 1). Spectroscopic evidence shows that arsenite retains this pyramidal structure in solution with three oxygen ligands and the lone electron pair (Ramirez-Solis et al. 2004). With the first pK_a of arsenite at 9.23, the neutral species will dominate in most natural aqueous solutions, but deprotonated forms are expected to be important under very alkaline conditions. As⁵⁺ forms a regular tetrahedron when bonded to oxygen ligands, forming the stable arsenate [AsO₄]³⁻ anion, similar in structure to the orthophosphate anion [PO₄]³⁻. Its chemistry in solution

also has similarities to phosphoric acid (H₃PO₄), with the important exception of the greater oxidizing potential of arsenate compared to phosphate (Cotton and Wilkinson 1988). The second and third acid dissociation constants for arsenate (pK_{a2} = 6.97; pK_{a3} = 11.53) are only slightly more acidic than the corresponding constants for phosphate (pK_{a2} = 7.21; pK_{a3} = 12.32) (Butler 1998). As such, under equilibrium oxidized conditions, dissolved arsenate and phosphate will be present as aqueous species of similar charge and chemical structure over the pH range of natural waters, with only slight offsets in speciation as a function of pH. This similarity points out the importance of competitive chemical behavior between arsenate and phosphate in natural systems if arsenate reduction does not come into play.

Because arsenic is typically present in natural waters at low concentrations (micromolar to nanomolar), its adsorption and desorption behavior on mineral surfaces plays an important role in regulating its aqueous concentration in groundwaters and surface waters. Both arsenite and arsenate have a strong, pH-dependent sorption affinity for iron hydroxide and oxyhydroxide minerals such as ferrihydrite and goethite. Surface coatings of these iron oxides on detrital minerals are thought to be important sorbents of arsenic in groundwater aquifers and have been exploited as remediation technologies for arsenic removal (Stollenwerk 2003). Other mineral sorbents, such as clays, aluminum oxyhydroxides, and manganese oxides, may also take up arsenic, particularly in low-iron settings. Under fully oxidized conditions, it is established that arsenate binds strongly to Fe³⁺ oxide minerals as an inner-sphere complex, probably predominantly as a bidentate, binuclear surface complex (Foster 2003). In this case, competition between arsenate and phosphate for sorption

sites can be a significant factor in blocking arsenate adsorption (Dixit and Hering 2003). What is less clear are the relationships among arsenic and redox-active substrates when environmental conditions are less oxidized and microorganisms participate in the oxidation and reduction of inorganic species such as arsenic, nitrogen, iron, and manganese. Newly discovered microorganisms that use arsenite and arsenate as a basis for their metabolism are thought to play an important role in regulating the kinetics of arsenic redox reactions in the environment (Oremland and Stolz 2005; see also Lloyd and Oremland this issue). Recent studies have also pointed out the controlling roles of iron and sulfur in influencing arsenic uptake and release from solution and the complex interplay among adsorption and precipitation processes, changes in oxidation states and mineral stabilities, and the rates of these processes as mediated by microbial activities in surface and subsurface environments (O'Day et al. 2004; Oremland and Stolz 2005).

Because the solid forms of arsenic sulfide are fairly insoluble and precipitate rapidly (see below), aqueous As³⁺ sulfide species (thioarsenites) are not well known. The exact stoichiometry of aqueous thioarsenite species is controversial, but the most important species are probably As(OH)(SH)₂⁰ and its two deprotonated forms, and As(OH)₂(SH)⁰ and its deprotonated form, although other species with only sulfur (–S) and thiol (–SH) ligands have been proposed (Nordstrom

and Archer 2003; Wilkin et al. 2003). Thioarsenite species are believed to dominate in aqueous solutions only at high dissolved sulfide concentrations in the absence of iron (Wilkin et al. 2003), but their occurrence and potential importance in low-temperature and hydrothermal solutions is unknown.

Arsine gas (AsH_3), which is formally the most reduced form of arsenic (formal valence is -3 , analogous to ammonia, NH_3), is notable for its extreme toxicity. It is a volatile gas that is only slightly soluble in water. Because of its volatility, its importance in the environment as a microbiological end product may be overlooked (Cullen and Reimer 1989; Francesconi and Kuehnelt 2002).

MINERALOGY

Arsenic Oxides

The affinity of arsenic to bond with other elements and species means that it is rarely found as a native element, with the occasional exception in hydrothermal ores. The simple As^{3+} oxides, arsenolite and claudetite (both As_2O_3), are polymorphs with similar thermodynamic stability, with claudetite thought to be slightly more stable at standard conditions (Nordstrom and Archer 2003). These minerals form naturally as secondary weathering products of arsenic sulfides but are more commonly found as the oxidation products of the roasting of arsenic-bearing ore minerals or coal. Condensation of combustion vapors makes “white arsenic” powder characteristic of arsenic trioxide (National Research Council 1977). The arsenolite structure is somewhat unusual, consisting of $[\text{As}_4\text{O}_6]$ cages linked by bridging oxygen atoms (FIG. 2). Arsenic trioxides are moderately soluble in water and are still used as an ingredient in insecticides. A large number of alkali, alkaline-earth, and metal arsenite salts can be made by linking As^{3+} -oxo-anion groups to a variety of monovalent and divalent cations (TABLE 1). These compounds tend to be rare in the natural environment, occurring primarily as hydrothermal or metamorphic alteration products at mildly reducing conditions, but have been exploited industrially as pigments and pesticides for a long time. For example, copper arsenite, known as Scheele’s green, became a popular (and very toxic) pigment following its discovery in 1775 and was used extensively as an insecticide. The solubility of arsenite salts depends on the type of cation in the compound, with alkali arsenites being the most soluble and metal arsenites being the least soluble (National Research Council 1977).

Arsenate minerals comprise a large class with extensive substitution and solid solution, and new minerals continue to be identified. Mineralogically, arsenates are usually considered a subclass of the phosphate mineral group (in the Dana classification) because of the similarity in size and charge of the phosphate and arsenate anionic unit (TABLE 1). A typical structural motif in arsenate and phosphate minerals is bonding of geometrically invariant $[\text{AsO}_4]^{3-}$ tetrahedra to octahedrally coordinated transition metal ions (e.g. variscite group), or to large, divalent cations such as lead or calcium (e.g. apatite group), with anions such as OH^- , Cl^- , and F^- for charge balance. Variations and multiples of this bonding pattern tend to create relatively open structures that allow for extensive substitution of cations, anions and anion groups, and water (FIG. 2). For example, minerals within the common vivianite group may contain a variety of transition metal cations arranged as $\text{Me}^{2+}(\text{O},\text{H}_2\text{O})_6$ octahedra between layers of $[(\text{As},\text{P})\text{O}_4]^{3-}$ tetrahedra, giving rise to brightly colored minerals (Anthony et al. 2000). Similar to phosphate minerals found in soils and surface environments, arsenate minerals occur in a variety of soil and oxidized environments with a range of waters of hydration,

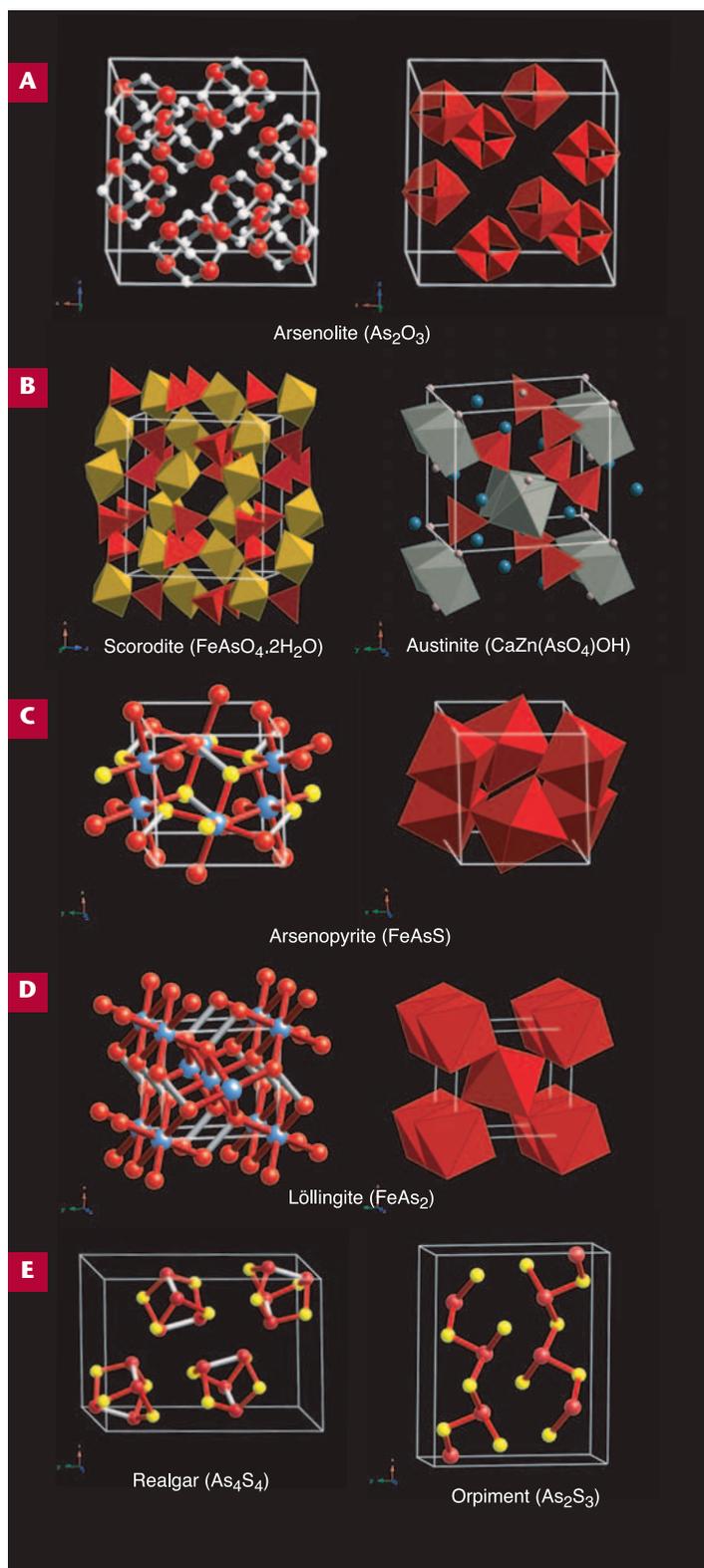


FIGURE 2 Examples of molecular structures of arsenic minerals. Atom colors: red – As; yellow – S; white – O; light blue – Fe; dark blue – Ca; pink – H. (A) Atomic and polyhedral views of arsenolite (As^{3+} oxide); (B) two arsenate minerals, scorodite and austinite, showing linkages of arsenate tetrahedra (red) between divalent cation octahedra (Fe^{3+} – yellow; Zn^{2+} – gray); (C) atomic and polyhedral views of arsenopyrite, with octahedrally coordinated Fe^{2+} (blue) and As–S bonds; (D) atomic and polyhedral views of löllingite, with octahedrally coordinated Fe^{2+} (blue) and As–As bonds; (E) two common arsenic sulfide minerals, realgar and orpiment; molecular cages in realgar have As–As and As–S dimers, while the chain-like structure in orpiment has only As–S bonds.

depending on the degree of desiccation. They are also commonly found as weathering products of arsenic-bearing ore deposits, where sulfidic ore minerals are often coated with surface layers of oxidized and hydrated arsenate minerals (Anthony et al. 2000). The ability of arsenate minerals and their solid solutions to sequester arsenic and limit its aqueous mobility depends on the solubility of these compounds, which is variable. Copper, lead, and calcium arsenates were widely used as herbicides and insecticides from the 1870s to 1970s, with worldwide use peaking in the 1940s (Nriagu 2002). Copper arsenate—as chromated copper arsenate (CCA) solutions—continues to be used as a wood preservative in many countries and was not phased out for residential use in the United States until 2004 (Katz and Salem 2005). The widespread and extensive use of arsenate and arsenite compounds in agriculture and industry has added a significant load of arsenic that may participate in biogeochemical activity to surface environments.

Arsenic Sulfides

Arsenopyrite, orpiment, and realgar are the most common arsenic sulfide minerals (TABLE 1), occurring primarily in hydrothermal and magmatic ore deposits. As a pigment and dye, orpiment was sought in ancient times for its golden color (from Latin *auri pigmentum*). Realgar (from Arabic *rahi al ghar*, “powder of the mine”) was a common red pigment for paints and dyes in paintings and manuscripts. It is unstable in air, however, and alters to pararealgar, a yellow-orange powder, which is seen now in old, unrestored paintings or manuscripts that have a yellow or orange hue over the original red (Clark 1999). Other transition metals, such as Co, Ni, and Cu, also combine with arsenic and sulfur to form a variety of minor sulfides and sulfosalts, often with extensive solid solution. More recently, spectroscopic methods have verified the formation of orpiment- and realgar-type structures in low-temperature, sulfate-reducing environments, probably related to microbiological sulfur and arsenic reduction (O’Day et al. 2004).

Compared to the structure and bonding properties found in oxide minerals, arsenic sulfides are quite different from the oxides and even differ substantially within the group of sulfides. Arsenic and sulfur bonds in these structures are strongly covalent, with different arrangements of As–S and As–As dimeric units creating a common structural basis. The structure of arsenopyrite is characterized by iron atoms octahedrally coordinated by three arsenic and three sulfur atoms and linked through both edges and corners (FIG. 2). Each arsenic or sulfur atom is tetrahedrally coordinated to three iron atoms and to one sulfur or arsenic atom to form [As–S]²⁻ dimers. Arsenopyrite and structurally related sulfide minerals, which are derivatives of the pyrite (FeS₂) structure where iron octahedra share only corners, are more distorted and of lower symmetry than cubic pyrite (Vaughan and Craig 1978; Harmer and Nesbitt 2004). Although less commonly found in nature, the related mineral löllingite (FeAs₂), which has the marcasite (FeS₂) structure and edge- and corner-shared iron octahedra, provides an interesting comparison (although technically it is an arsenide mineral, see below). Löllingite has [As–As]²⁻ dimers in place of the [S–S]²⁻ dimers in marcasite, which have longer bonds and are slightly less electronegative than the corresponding [S–S]²⁻ dimers, presumably because of the greater electronegativity of sulfur compared to arsenic (Harmer and Nesbitt 2004). This creates more distortion in the iron octahedra and shorter Fe–Fe interatomic distances (Tossell et al. 1981).

Realgar and its polymorphs have discrete [As₄–S₄] molecular cage-like units with linked As–As and S–S dimers (FIG. 2). Molecular units in the structure are connected by van der

Waals forces (Mullen and Nowacki 1972). In contrast, the structure of orpiment is comprised of chains of [As–S₃] molecular units connected by bridging sulfur atoms and cross-linked by van der Waals forces to form a corrugated layered structure (FIG. 2) (Mullen and Nowacki 1972; Vaughan and Craig 1978). However, both have similar As–S bond lengths (as do their polymorphs) and both can be built from similar [As₂–S₂] molecular units, with an additional sulfur atom bonded to the [As₂–S₂] unit in the case of orpiment (Mullen and Nowacki 1972). These variations in covalent bonding and atomic arrangements relate to the macroscopic properties of these minerals, with both orpiment and realgar stable over a wide temperature range. Orpiment, however, appears to possess a greater range of stability than realgar as a function of reduced sulfur fugacity (Nordstrom and Archer 2003). The difference between strongly covalent As–S compounds and those containing cationic transition metals such as Fe, Co, Ni, and Cu stems in a general way from the energy levels and geometry of overlap between *p* valence orbitals of sulfur and arsenic and the *d* orbitals of the transition metal (Vaughan and Craig 1978). While the bonding interactions can be described qualitatively with molecular orbital arguments, a more thorough understanding of subtle differences in structure and reactivity awaits quantitative descriptions from *ab initio* calculations of electron density and distribution.

Metal Arsenides

A large number of metal arsenides are known and can be considered as alloys of metals, generally with the form MeAs_n, where *n* = 1, 2, or 3 and Me is a metallic element. Electron counting would indicate a negative formal oxidation state for arsenic in these compounds. However, bonding is strongly covalent in these semiconducting solids, and they are better described by band gap formalism (Partik and Lutz 1999). The well-known industrial semiconductor GeAs is a typical example. In nature, the most common arsenides form with Fe, Co, Ni, and Cu (TABLE 1), but are typically rare, occurring in hydrothermal and magmatic ore deposits in association with a variety of sulfide minerals. They often form solid solutions with each other and with sulfide minerals in structural arrangements of common sulfides (e.g. pyrite, pyrrotite, marcasite, galena).

ORGANIC AND BIOLOGICAL COMPOUNDS

Similar to nitrogen and phosphorus, arsenic has rich organic chemistry. Its ability to bind to a variety of organic ligands with different coordination geometries and its greater redox potential than phosphorus help to explain why mechanisms of arsenic toxicity in living organisms are still incompletely understood despite much investigation (Carter et al. 2003). A large number of organoarsenic compounds are found in the environment as a consequence of a variety of biomethylation and other biosynthetic pathways (Cullen and Reimer 1989). The synthetic organic chemistry of arsenic has also been explored in detail, beginning in earnest in the early part of the 20th century by Paul Ehrlich. As noted by Vaughan (this issue), Ehrlich synthesized hundreds of organoarsenic compounds in an effort to combat syphilis, which had reached epidemic levels similar to that of HIV today, and empirically isolated the most effective candidate for drug development, called Salversan (Lloyd et al. 2005). Interestingly, the actual chemical structure of Salversan was misidentified as containing a double As–As bond (arsphenamine). Recent work has revealed that it is actually a mixture of cyclic As–As compounds with aminophenol groups (Lloyd et al. 2005). Throughout the 20th century, a variety of organoarsenic compounds were synthesized and manufactured for a range of applications. For example, synthetic alkyl- and arylarsenicals were

developed as agricultural pesticides; mono- and disodium methanoarsonate and dimethylarsenic acid have been used worldwide as herbicides from World War II to today (Nriagu, 2002); roxarsone (4-hydroxy-3-nitrophenylarsonic acid) is still in common use in poultry feed to promote growth and weight gain. Examples of some important organoarsenic compounds are shown in FIGURE 1.

One of the most common classes of natural organoarsenic compounds are methylated forms of As^{3+} and As^{5+} , such as the mono- and dimethyl oxoacids in their simplest forms, which can be generated by replacing a hydroxyl (-OH) ligand by a methyl group (-CH₃) in inorganic arsenate or arsenite structures (FIG. 1). One or more of the methyl or hydroxyl groups around arsenic can be replaced by other organic ligands or larger organic moieties such as sugars, lipids, or cyclic groups to create a wide variety of arsenic-bearing organic compounds. Organic compounds with As^{3+} often

exhibit pyramidal, tetrahedral, or trigonal bipyramidal geometries, with the lone electron pair assuming one of the coordination positions. These compounds generally behave as soft Lewis bases (electron donors) unless the organic ligand is a strong electron withdrawing group, in which case they can act as Lewis acids (electron acceptors) (Garje and Jain 1999). Organic compounds with As^{5+} typically have tetrahedral (4 ligands) or trigonal bipyramidal (5 ligands) geometries.

Many organoarsenic compounds have arsenic substitution for nitrogen in an organic moiety, for example arsenobetaine and arsenocholine, which are major forms of arsenic found in marine animals (FIG. 1) (Francesconi and Kuehnelt 2002). Like nitrogen, arsenic is known to substitute into organic ring structures (pyridine or benzenes analogs) (Garje and Jain 1999). With improvements in analytical detection methods, a large number of previously unidentified

TABLE 1 ARSENIC MINERAL GROUPS AND EXAMPLES OF COMMON MINERALS

<i>Elemental Arsenic</i>	<i>Arsenic(V) Oxides (cont'd)</i>
Native arsenic As Arsenolamprite As	Pharmacosiderite group: AB₄(AsO₄)₃(OH)₄•5–7H₂O A is K, Na; B is Al ³⁺ or Fe ³⁺ AB₄(AsO₄)₃(OH)₅•5–7H₂O A is Ba; B is Al ³⁺ or Fe ³⁺ Sodium-pharmacosiderite NaFe ³⁺ ₄ (AsO ₄) ₃ (OH) ₄ •6–7H ₂ O Barium-pharmacosiderite BaFe ₄ (AsO ₄) ₃ (OH) ₅ •5H ₂ O
<i>Arsenic(III) Oxides</i>	Mixite-Agardite group: ACu₆(XO₄)₃(OH)₆•3H₂O A is Me ²⁺ , Ca, REE, Bi Mixite BiCu ₆ (AsO ₄) ₃ (OH) ₆ •3H ₂ O Agardite-(Y) (Y, Ca)Cu ₆ (AsO ₄) ₃ (OH) ₆ •3H ₂ O
Arsenolite As ₂ O ₃ Claudetite As ₂ O ₃ [AsO₂]⁻ group NaAsO ₂ Cu ²⁺ (AsO ₂) ₂ Cu ²⁺ (AsO ₂)(OH) [As₂O₄]²⁻ group Trippkeite Cu ²⁺ As ₂ O ₄ Leiteite ZnAs ₂ O ₄ Manganarsenite Mn ²⁺ ₃ As ₂ O ₄ (OH) ₄ [AsO₃]³⁻ group Reinerite Zn ₃ (AsO ₃) ₂ Rouseite Pb ₂ Mn ²⁺ (AsO ₃) ₂ •2H ₂ O Cafarsite Ca ₈ (Ti,Fe ^{2+,3+} ,Mn) ₆₋₇ (AsO ₃) ₁₂ •4H ₂ O [As₂O₅]⁴⁻ group Pb ₂ As ₂ O ₅ Gebhardtite Pb ₈ (As ₂ O ₅) ₂ OCl ₆	Arsenate sulfates Sarmientite Fe ₂ (AsO ₄)(SO ₄)(OH)•5H ₂ O Zýkaite Fe ₄ (AsO ₄) ₃ (SO ₄)(OH)•15H ₂ O Uranyl arsenates Arsenuranylite Ca(UO ₂) ₄ (AsO ₄) ₂ (OH) ₄ •6H ₂ O Zeunerite Cu(UO ₂) ₂ (AsO ₄) ₂ •12H ₂ O
<i>Arsenic(V) Oxides</i>	<i>Arsenic Sulfides</i>
X can be either P or As, sometimes V Apatite group: A₅(XO₄)₃(OH, F, Cl) A is usually a large divalent cation (Me ²⁺), such as Ca, Ba, Pb, Sr Johnbaumite Ca ₅ (AsO ₄) ₃ (OH) Mimetite Pb ₅ (AsO ₄) ₃ (Cl) Adelite group: AB(XO₄)(OH) A is Ca, Pb; B is Fe ²⁺ , Co, Cu, Zn Austinite CaZn(AsO ₄)(OH) Conichalcite CaCu(AsO ₄)(OH) Variscite group: A(XO₄)•2H₂O A is Me ³⁺ , usually Al or Fe Scorodite FeAsO ₄ •2H ₂ O Mansfieldite AlAsO ₄ •2H ₂ O Vivianite group: A₃(XO₄)₂•8H₂O A is Me ²⁺ , usually Co, Ni, Zn, Fe, Mn, or Mg Hörnesite Mg ₃ (AsO ₄) ₂ •8H ₂ O Erythrite Co ₃ (AsO ₄) ₂ •8H ₂ O	Arsenopyrite FeAsS Cobaltite CoAsS Gersdorffite NiAsS Orpiment As ₂ S ₃ Realgar AsS or As ₄ S ₄
	<i>Arsenic Sulfosalts</i>
	Enargite Cu ₃ AsS ₄ Proustite Ag ₃ AsS ₃
	<i>Arsenides</i>
	Domeykite Cu ₃ As Löllingite FeAs ₂ Nickeline (aka Niccolite) NiAs Nickel-skutterudite (Ni,Co)As ₂₋₃ Rammelsbergite NiAs ₂ Safflorite CoAs ₂ Skutterudite CoAs ₂₋₃ Sperryllite PtAs ₂
	References Anthony et al. 2000; Materials Data Inc., mineral database; Web Minerals (http://webminerals.com); The Mineral Database (http://www.mindat.org)

organoarsenic compounds have been found throughout the biosphere in microorganisms, plants, invertebrates, and vertebrates. Methylation of inorganic arsenic by microorganisms has been known since the 1930s, and most natural arsenolipids and arsenosugars detected in the environment are thought to be end products of arsenic detoxification by microorganisms and invertebrates (Dembitsky and Levitsky 2004; Francesconi and Kuehnelt 2002). A general detoxification pathway for inorganic arsenate (aqueous $\text{H}_2\text{As}^{5+}\text{O}_4^-$ or $\text{HAs}^{5+}\text{O}_4^{2-}$) by microorganisms, all enzymatically assisted, is thought to be: an initial reduction to arsenite; methylation and reoxidation to mono- and dimethyl oxoacids (methylarsonate and dimethylarsinate, the metabolites most commonly found in the environment); possibly final reduction and methylation to trimethylarsine oxide, dimethylarsine, or trimethylarsine, volatile forms of arsenic that are difficult to detect (Dembitsky and Levitsky 2004; Francesconi and Kuehnelt 2002). The biosynthesis of many of the more complex organoarsenic compounds detected in organisms in the environment is still largely unknown.

The ability of arsenic to behave as both a toxin and a curative has been exploited throughout human history, but the details of the biochemical mechanisms behind its effects are complex and incomplete. The chemistry of arsenic discussed above informs in a general way the behavior of arsenic *in vivo*. Once ingested, human organs can metabolize arsenic by a variety of mechanisms, including methylation, oxidation and reduction reactions, and protein binding (Carter et al. 2003). Toxicity from arsenic has been attributed primarily to two general biochemical scenarios. The affinity of reduced arsenic for sulfur noted above leads to its binding to protein dithiol groups $(-\text{SH})_2$, which is thought to interfere with pyruvate dehydrogenase and other enzyme activity, resulting in decreased cellular respiration and mitochondrial toxicity. For As^{5+} with its similarity to phosphate, esters of As^{5+} hydrolyze much more rapidly than phosphate esters; thus, replacement of phosphate by arsenate leads to rapid hydrolysis and interruption of ATP (adenosine triphosphate) synthesis (National Research Council 1999; Carter et al. 2003). Recent work, however, has pointed out the inadequacy of these mechanisms to explain all of the observed toxicity, as well as the therapeutic effects, of arsenic (Miller et al. 2002; Carter et al. 2003). For example, long-term exposure to arsenic is known to increase the incidence of some forms of cancer, such as skin, bladder, lung, and kidney (National Research Council

1999). But paradoxically, low doses of arsenite (As^{3+} administered as AsO_3) hold promise as an effective treatment for some forms of leukemia and some types of tumors (Miller et al. 2002). This seemingly contradictory behavior stems from the ability of arsenic to participate in a range of complex cellular redox reactions that typically involve thiol and disulfide groups on cysteines of proteins such as glutathione or thioredoxin. These enzyme systems are responsible for regulating redox signaling reactions and levels of reactive oxygen species that cause oxidative damage in cells (Miller et al. 2002).

SUMMARY

Much of the behavior of arsenic in the environment is determined by what it bonds to in different abiotic and biotic compartments. In oxidized settings, the stronger electronegativity of oxygen shifts arsenic to a more cationic state and stabilizes the As^{3+} and As^{5+} oxo-anion groups that form the basis of the major arsenic oxide mineral classes, aqueous species, and adsorbed complexes. The stability of As-S and As-As dimeric units in reduced conditions, a consequence of the similar electronegativity of these elements and strong covalent bonding, comprises the structural basis for the generation of a variety of sulfide and arsenide minerals and synthetic compounds. The biomethylation of arsenic by living organisms dominates its organic chemistry in the environment, and its chemical similarities to nitrogen and phosphorus help explain the diversity of natural and synthetic organic compounds. Perhaps increased understanding of the subtleties of bonding and rates of exchange between arsenic and its ligands in cells and biological fluids will further elucidate mechanisms associated with both the detrimental and beneficial effects of arsenic on living systems.

ACKNOWLEDGMENTS

Many thanks to David Vaughan for the invitation to contribute to this issue. The manuscript benefited from helpful reviews by David Vaughan and an anonymous reviewer. I thank Ernst Burke (Vrije Universiteit Amsterdam) for corrections to Table 1 and Pierrette Tremblay for editorial assistance. Thanks to the National Science Foundation (Divisions of Earth Sciences and Bioengineering and Environmental Systems) for support of my research on arsenic, and to my students and colleagues for their help and advice. ■

REFERENCES

- Allred AL, Hensley AL Jr (1961) Electronegativities of nitrogen, phosphorus, arsenic, antimony and bismuth. *Journal of Inorganic & Nuclear Chemistry* 17: 43-54
- Anthony JW, Bideaux RA, Bladh KW, Nichols MC (2000) *Handbook of Mineralogy Volume III: Arsenates, Phosphates, Vanadates*. Mineral Data Publishing, Tucson
- Butler JN (1998) *Ionic Equilibrium: Solubility and pH Calculations*. John Wiley & Sons, Inc., New York, 559 pp
- Carter DE, Aposhian HV, Gandolfi AJ (2003) The metabolism of inorganic arsenic oxides, gallium arsenide, and arsine: a toxicological review. *Toxicology and Applied Pharmacology* 193: 309-334
- Clark RJH (1999) Raman microscopy: sensitive probe of pigments on manuscripts, paintings and other artefacts. *Journal of Molecular Structure* 480-481: 15-20
- Cotton FA, Wilkinson G (1988) *Advanced Inorganic Chemistry*, 5th edition. John Wiley & Sons, New York
- Cullen WR, Reimer KJ (1989) Arsenic speciation in the environment. *Chemical Reviews* 89: 713-764
- Dembitsky VM, Levitsky DO (2004) Arsenolipids. *Progress in Lipid Research* 43: 403-448
- Dixit S, Hering JG (2003) Comparison of arsenic(V) and arsenic(III) sorption onto iron oxide minerals: Implications for arsenic mobility. *Environmental Science & Technology* 37: 4182-4189
- Foster AL (2003) Spectroscopic investigations of arsenic species in solid phases. In: Welch AH, Stollenwerk KG (eds) *Arsenic in Groundwater: Geochemistry and Occurrence*, Kluwer Academic Publishers, Boston, pp 27-65
- Francesconi KA, Kuehnelt D (2002) Arsenic compounds in the environment. In: Frankenberger WT Jr (ed) *Environmental Chemistry of Arsenic*, Marcel Dekker, New York, pp 51-94
- Garje SS, Jain VK (1999) The chemistry of organo-arsenic, antimony and bismuth compounds: An overview. *Main Group Metal Chemistry* 22: 45-58
- Harmer SL, Nesbitt HW (2004) Stabilization of pyrite (FeS_2), marcasite (FeS_2), arsenopyrite (FeAsS) and löllingite (FeAs_2) surfaces by polymerization and auto-redox reactions. *Surface Science* 564: 38-52

- Inskeep WP, McDermott TR, Fendorf S (2002) Arsenic (V)/(III) cycling in soils and natural waters: Chemical and microbiological processes. In: Frankenberger WT Jr (ed) *Environmental Chemistry of Arsenic*, Marcel Dekker, New York, pp 183-215
- Irgolic K (1992) Chapter 11: Arsenic. In: Stoeppler M (ed) *Hazardous Metals in the Environment*, 12, Elsevier, Amsterdam, pp 287-350
- Katz SA, Salem H (2005) Chemistry and toxicology of building timbers pressure-treated with chromated copper arsenate: a review. *Journal of Applied Toxicology* 25: 1-7
- Lloyd NC, Morgan HW, Nicholson BK, Ronimus RS (2005) The composition of Ehrlich's salvarsan: Resolution of a century-old debate. *Angewandte Chemie-International Edition* 44: 941-944
- Miller WH, Schipper HM, Lee JS, Singer J, Waxman S (2002) Mechanisms of action of arsenic trioxide. *Cancer Research* 62: 3893-3903
- Mullen DJE, Nowacki W (1972) Refinement of crystal-structures of realgar, AsS and orpiment, As₂S₃. *Zeitschrift Fur Kristallographie* 136: 48-65
- National Research Council (1977) *Arsenic: Medical and Biological Effects of Environmental Pollutants*. National Academy of Sciences, Washington, DC
- National Research Council (1999) *Arsenic in Drinking Water*. National Academy Press, Washington, DC
- Nordstrom DK, Archer DG (2003) Arsenic thermodynamic data and environmental geochemistry. In: Welch AH, Stollenwerk KG (eds) *Arsenic in Goundwater: Geochemistry and Occurrence*, Kluwer Academic Publishers, Boston, pp 1-25
- Nriagu J (2002) Arsenic poisoning through the ages. In: Frankenberger WT Jr (ed) *Environmental Chemistry of Arsenic*, Marcel Dekker, New York, pp 1-26
- O'Day PA, Vlassopoulos D, Root R, Rivera N (2004) The influence of sulfur and iron on dissolved arsenic concentrations in the shallow subsurface under changing redox conditions. *Proceedings of the National Academy of Sciences* 101: 13703-13708
- Oremland RS, Stolz JF (2005) Arsenic, microbes and contaminated aquifers. *Trends In Microbiology* 13: 45-49
- Partik M, Lutz HD (1999) Semiempirical band structure calculations on skutterudite-type compounds. *Physics and Chemistry of Minerals* 27: 41-46
- Ramirez-Solis A, Mukopadhyay R, Rosen BP, Stemmler TL (2004) Experimental and theoretical characterization of arsenite in water: Insights into the coordination environment of As-O. *Inorganic Chemistry* 43: 2954-2959
- Stollenwerk KG (2003) Geochemical processes controlling transport of arsenic in groundwater: A review of adsorption. In: Welch AH, Stollenwerk KG (eds) *Arsenic in Goundwater: Geochemistry and Occurrence*, Kluwer Academic Publishers, Boston, pp 67-100
- Tossell JA, Vaughan DJ, Burdett JK (1981) Pyrite, Marcasite, and Arsenopyrite Type Minerals - Crystal Chemical and Structural Principles. *Physics and Chemistry of Minerals* 7: 177-184
- Vaughan DJ, Craig JR (1978) *Mineral Chemistry of Metal Sulfides*. Cambridge University Press, Cambridge
- Wilkin RT, Wallschlagel D, Ford RG (2003) Speciation of arsenic in sulfidic waters. *Geochemical Transactions* 4: 1-7 ■

ADVERTISING