ES&T
CRITICAL REVIEW

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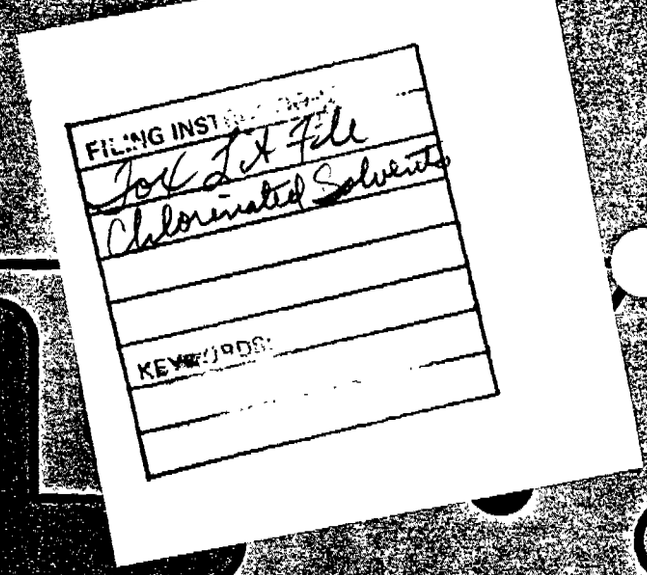

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Halogenated aliphatic compounds are prevalent groundwater contaminants and are significant components of hazardous wastes and landfill leachates. Most hazardous halogenated aliphatic compounds released from industrial, commercial, and agricultural sources are brominated or chlorinated alkanes and alkenes that contain between one and three carbon atoms. Chlorinated ethanes and ethenes are in common use as cleaning solvents in dry-cleaning operations and semiconductor manufacture. Some brominated compounds, such as 1,2-dibromoethane (EDB) and 1,2-dibromo-3-chloropropane (DBCP), are used as pesticides (*1*, *2*). In addition, brominated and chlorinated methanes are produced as a result of chlorination of water (*3*). The production and use of halogenated aliphatic compounds and their apparent hazard to human health (Table 1) (*4–6*) have prompted investigations concerning their fate in the human body, in subsurface waters, and in treatment facilities. In most of these environments, photolysis is not an important transformation process, but other abiotic transformations can be significant. Often, biologically mediated transformations are the most important.

This article summarizes and systematizes the current understanding of abiotic and biotic chemistry of halogenated aliphatic compounds. Knowledge of abiotic transformations can provide a conceptual framework for understanding biologically mediated transformations. Most abiotic transformations are slow, but they can still be significant within the time scales commonly associated with groundwater movement. In contrast, biotic transformations typically proceed much faster, provided that there are sufficient substrate and nutrients and a microbial population that can mediate such transformations. Recent studies, which describe transformations of halogenated aliphatic compounds in microbial and mammalian systems, are also discussed in this article. These studies reveal broad patterns of transformation in biological systems in general.

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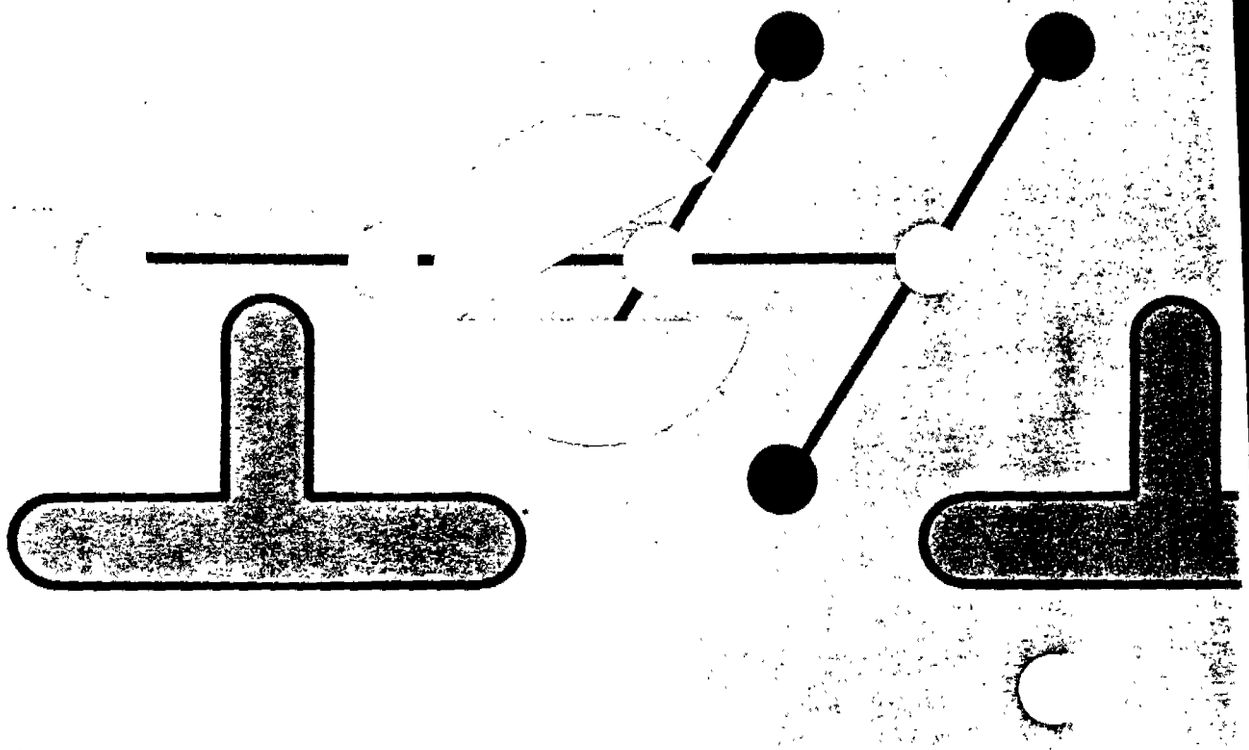

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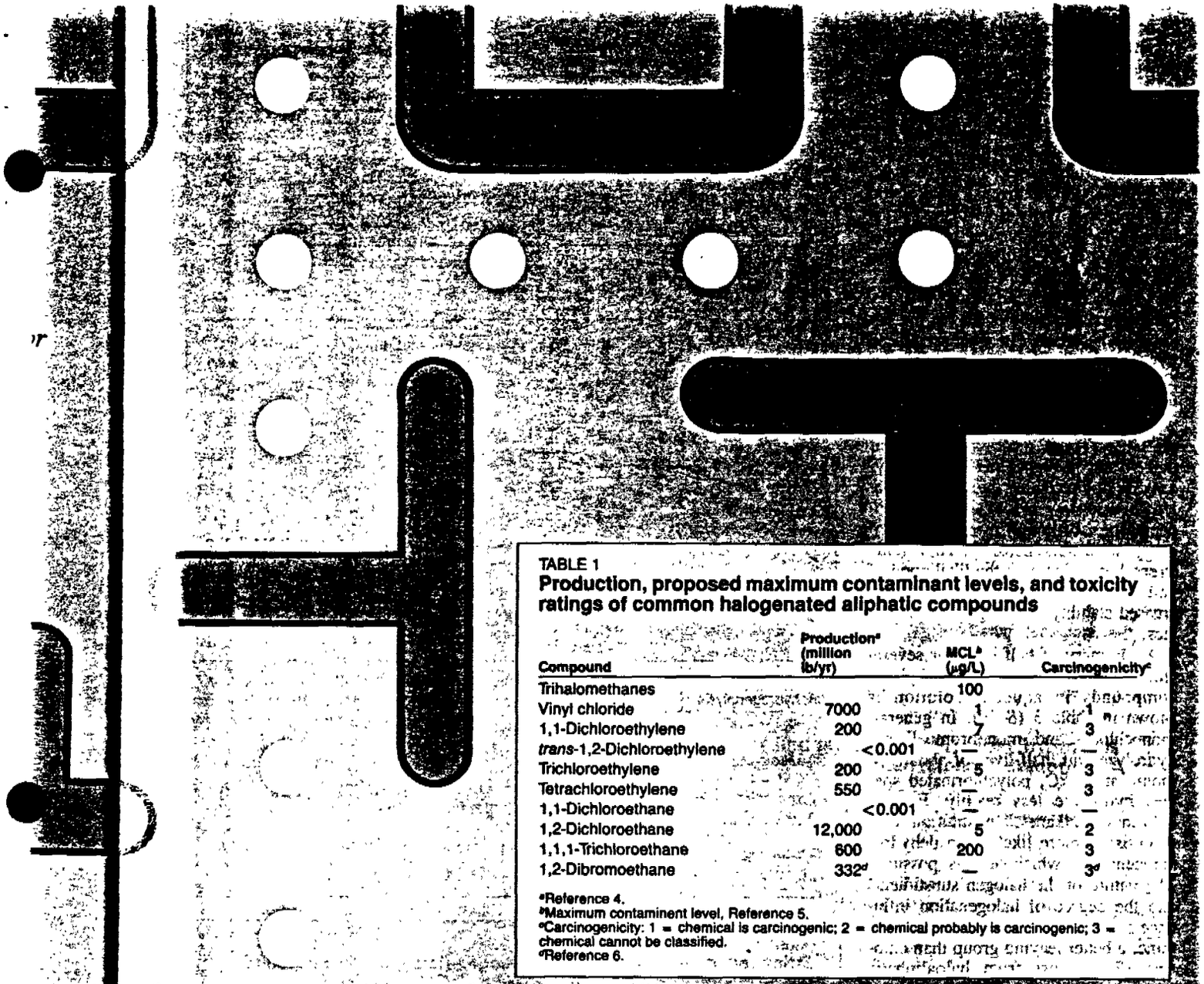


TABLE 1
Production, proposed maximum contaminant levels, and toxicity ratings of common halogenated aliphatic compounds

Compound	Production[a] (million lb/yr)	MCL[b] (μg/L)	Carcinogenicity[c]
Trihalomethanes		100	
Vinyl chloride	7000	1	1
1,1-Dichloroethylene	200	7	3
trans-1,2-Dichloroethylene		—	—
Trichloroethylene	200	5	3
Tetrachloroethylene	550	—	3
1,1-Dichloroethane	<0.001	—	—
1,2-Dichloroethane	12,000	5	2
1,1,1-Trichloroethane	600	200	3
1,2-Dibromoethane	332[d]	—	3[d]

[a]Reference 4.
[b]Maximum contaminent level, Reference 5.
[c]Carcinogenicity: 1 = chemical is carcinogenic; 2 = chemical probably is carcinogenic; 3 = chemical cannot be classified.
[d]Reference 6.

reaction mechanisms and transformation products. They also have differences. For each, the transformation of halogenated aliphatic compounds can be divided into two general classes: reactions that require external electron transfer (oxidations and reductions) and those that do not (substitutions and dehydrohalogenations). External electron transfer is defined as the transfer of electrons to and from some agent other than the halogenated compound itself. Processes discussed in this article and terms that frequently appear are defined in the side bar. Examples of transformations are listed in Figure 1. Common abbreviations for the various halogenated aliphatic compounds are listed in Table 2.

Substitution

Halogenated aliphatic compounds undergo substitution and dehydrohalo-

Definitions of terms

Coupling—a reaction in which two alkyl or aryl groups connect together.

Dehydrohalogenation—elimination of HX to form an alkene.

Dihalo-elimination—reductive elimination of two halide substituents to form an alkene.

Electrophile—a reacting specie that accepts an electron pair.

Elimination—a reaction in which two groups, such as hydrogen and chlorine, are lost from adjacent carbon atoms so that a double bond is formed.

Epoxidation—a reaction in which an epoxide is generated.

Hydrogenolysis—a reduction in which a carbon–halogen bond is broken and hydrogen replaces the halogen substituent.

Hydroxylation—addition of a hydroxyl group.

Ionization potential—the difference between the energy of ultraviolet radiation used to bombard a molecule and the energy of th ejected electron.

Monooxygenase—an enzyme that catalyzes reactions in which one atom of O_2 appears in the product and the other in H_2O.

Nucleophile—a reacting specie that brings an electron pair.

Solvolysis—a reaction in which the solvent serves as the nucleophile.

Substitution—a reaction in which one substituent on a molecule is replaced by another.

genation in water in the absence of inorganic or biochemical catalysts. In general, these reactions proceed slowly, with half-lives of days to centuries. However, rates can be accelerated by the activity of biologically derived enzymes such as hydrolases or glutathione *S*-transferases.

Solvolysis of halogenated aliphatic compounds in water (hydrolysis) leads initially to the production of alcohols (*7*) (Figure 1, Ia). If these alcohols are halogenated, then subsequent hydrolysis to acids or diols can occur. Hydroxy substitution generally occurs at the halogenated carbon. In general, these substitution reactions are bimolecular. Nevertheless, pseudo-first-order kinetics are observed in aqueous solutions in which water is the dominant nucleophile. These reactions are potentially faster at higher pH, and the hydroxide ion acts as the nucleophile. However, below pH 11, a pH dependence for substitution reactions is generally not observed (*8*, *9*). High ionic strength may increase the likelihood of unimolecular reactions as a result of increased stability of charged intermediates.

A summary of half-lives for several chlorinated and brominated aliphatic compounds in aqueous solution is shown in Table 3 (*8*-*20*). In general, monochloro- and monobromoalkanes hydrolyze with half-lives of about one month at 25 °C; polychlorinated species hydrolyze less readily. For dichlorinated alkanes, substitution (hydrolysis) is more likely than dehydrohalogenation, which also is possible. The nature of the halogen substituents and the degree of halogenation influence substitution rates (Figure 2). Bromine, a better leaving group than chlorine (*7*), is lost from haloaliphatic compounds more readily than is chlorine. Increased halogenation leads to slower substitution reactions and longer half-lives (*8*, *9*). Abiotic substitution reactions might also be enhanced by catalysts such as clays (*20*).

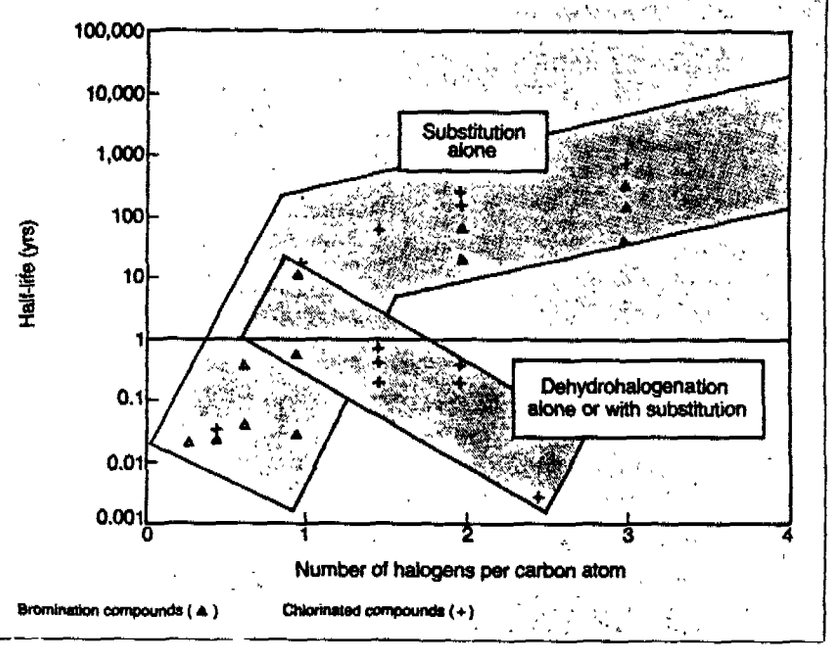
Sulfides also react with halogenated aliphatics via substitution to produce mercaptans (*21*) (Figure 1, Ib). Chemically, the sulfhydryl group (SH-) is more reactive than the hydroxyl group (OH-) or water (*7*), although concentrations in natural waters are usually not high enough for sulfhydryl-related reactions to dominate.

Substitution reactions also can occur in mammalian systems (Table 4) (*22*-*29*). Glutathione reacts with halogenated aliphatic compounds to produce sulfur-containing compounds. Under proper conditions, these compounds are further transformed into mercapturic acids (*28*). Some chlorinated alkanes are transformed into alcohols in

FIGURE 1
Abiotic and biotic reactions f halogenated aliphatic compounds

Reactions	Examples
I. Substitution	
(a) solvolysis, hydrolysis $RX + H_2O \longrightarrow ROH + HX$	$CH_3CH_2CH_2Br + H_2O \longrightarrow CH_3CH_2CH_2OH + HBr$
(b) conjugation and other nucleophilic reactions $RX + N^- \longrightarrow RN + X^-$	$CH_3CH_2Br + HS^- \longrightarrow CH_3CH_2SH + Br^-$
II. Dehydrohalogenation $-\overset{|}{C}-\overset{|}{C}- \longrightarrow \diagdown C=C \diagup + HX$	$CCl_3CH_3 \longrightarrow CCl_2CH_2 + HCl$
III. Oxidation	
(a) α-hydroxylation $-\overset{|}{C}-X + H_2O \longrightarrow -\overset{|}{C}-X + 2H^+ + 2e^-$	$CH_3CHCl_2 + H_2O \longrightarrow CH_3CCl_2OH + 2H^+ + 2e^-$
(b) halosyl oxidation $-\overset{|}{C}-X + H_2O \longrightarrow -\overset{|}{C}-X^+O^- + 2H^+ + 2e^-$	$CH_3CHCl_2 + H_2O \longrightarrow CH_3CHClO^- + 2H^+ + 2e^-$
(c) epoxidation $C=C + H_2O \longrightarrow \diagdown C(O)C \diagup + 2H^+ + 2e^-$	$CHClCCl_2 + H_2O \longrightarrow CHClOCCl_2 + 2H^+ + 2e^-$
(d) biohalogenation (alkenes) $C=C + X^- + H_2O \longrightarrow -\overset{OH}{\overset{|}{C}}-\overset{X}{\overset{|}{C}}- + H^+ + 2e^-$	$CH_2CH_2 + Cl^- + H_2O \longrightarrow CH_2OHCH_2Cl + H^+ + 2e^-$
IV. Reduction	
(a) hydrogenolysis $RX + H^+ + 2e^- \longrightarrow RH + X^-$	$CCl_4 + H^+ + 2e^- \longrightarrow CHCl_3 + Cl^-$
(b) dihalo-elimination $-\overset{|}{C}-\overset{|}{C}- + 2e^- \longrightarrow \diagdown C=C \diagup + 2X^-$	$CCl_3CCl_3 + 2e^- \longrightarrow CCl_2CCl_2 + 2Cl^-$
(c) coupling $2RX + 2e^- \longrightarrow R\text{-}R + 2X^-$	$2CCl_4 + 2e^- \longrightarrow CCl_3CCl_3 + 2Cl^-$

FIGURE 2
Estimated half-lives for some halogenated aliphatic compounds



live mice, but the responsible agents are unknown. Such reactions may be simple substitution reactions—the oxidation states of carbon in both reactant and product are the same. Examples are the conversion of tetrachloromethane to carbon dioxide or dichloromethane to carbon monoxide. These reactions might in reality be a sequential combination of reductions and oxidations. For example, tetrachloromethane can be reduced to trichloromethane and subsequently oxidized to carbon dioxide via phosgene (*30*). However, for many of the transformations in mammalian systems, complete mechanistic interpretations are not yet possible because there is insufficient information.

Dehydrohalogenation

Halogenated alkanes in water also can undergo elimination reactions that produce alkenes (Figure 1, IIa). Elimination of HX is termed dehydrohalogenation or, less frequently, dehydrodehalogenation. These reactions consist of removal of a halogen from one carbon atom and concomitant (E2) or subsequent (E1) removal of a hydrogen atom from an adjacent carbon. Although the formal oxidation state of a halogenated aliphatic compound decreases as a result of the loss of a halogen, it increases with loss of hydrogen. Dehydrohalogenation reactions thus do not include external electron transfer, and no net change occurs in the oxidation state of the reacting molecule.

Monohalogenated aliphatics apparently do not undergo dehydrohalogenation in water under normal environmental conditions (see Table 3), and such reactions are unlikely to occur (*7*). Polychlorinated alkanes undergo dehydrohalogenation under extreme basic conditions (*17*), and at pH 7 (*12*). These reactions generally follow bimolecular kinetics, depending on hydroxide ion concentration. Under normal pH conditions (near pH 7), dehydrohalogenation by interaction with weaker bases (e.g., water) might be important. The number and kind of halogen substituents have a strong influence on dehydrohalogenation rates. When more chlorine substituents are attached to the carbon atom that loses a chlorine substituent, faster rates are observed. Brominated compounds tend to undergo dehydrohalogenation with fewer halogen substituents and more rapidly than their chlorinated analogues (Figure 2). Dehydrohalogenation reactions do not appear to occur with vicinal dichloroalkanes (chlorine on adjacent carbon atoms) (*12*), but they do occur, at least partially, with vicinal dibromoalkanes (*9*). This increased rate of dehydrohalogenation from compounds that contain

TABLE 2
Abbreviations used for chemical sp cies

Abbreviation	Chemical name	Alternative chemical name
A	Ethane	
BCM	Bromochloromethane	
BDCM	Bromodichloromethane	
BF	Tribromomethane	Bromoform
BM	Bromomethane	
BTCM	Bromotrichloromethane	
CA	Chloroethane	
CF	Trichloromethane	Chloroform
CM	Chloromethane	Methyl chloride
CT	Tetrachloromethane	Carbon tetrachloride
DBCM	Dibromochloromethane	
DBCP	1,2-Dibromo-3-chloropropane	
DBDCM	Dibromochloromethane	
DBM	Dibromomethane	
DCA	Dichloroethane	
DCE	Dichloroethene	
E	Ethene	Ethylene
EDB	Dibromoethane	Ethylene dibromide
HCE	Hexachloroethane	
M	Methane	
MC	Dichloromethane	Methylene chloride
PCA	Pentachloroethane	
PCE	Tetrachloroethene	Perchloroethylene
TCBM	Tribromochloromethane	
TCA	1,1,1-Trichloroethane	Methyl chloroform
TCE	Trichloroethene	
TEBM	Tetrabromomethane	Carbon tetrabromide
TECA	Tetrachloroethane	
VC	Chloroethene	Vinyl chloride

TABLE 3
Environmental half-lives and products from abiotic hydr lysis or dehydrohalogenation of halogenated aliphatic compounds at 20 °C

Compound	Half-life years (reference)	Product(s) (reference)
Methanes		
Dichloromethane	1.5 (*10*), 704 (*8*)	
Trichloromethane	1.3 (*10*), 3500 (*8*)	
Tetrachloromethane	7000 (*8*)	
Bromomethane	0.10 (*8*)	
Dibromomethane	183 (*8*)	
Tribromomethane	686 (*8*)	
Bromochloromethane	44 (*8*)	
Bromodichloromethane	137 (*8*)	
Dibromochloromethane	274 (*8*)	
Ethanes		
Chloroethane	0.12 (*11*)[a]	Ethanol (*11*)[a]
1,2-Dichloroethane	50 (*12*)	
1,1,1-Trichloroethane	0.5 (*10*), 1.7 (*12*)	Acetic acid (*12–14*)
	0.8 (*15*)[b], 2.5 (*16*)[c]	1,1-Dichloroethylene (*14–16*)
1,1,2-Trichloroethane	170 (*12*)	1,1-Dichloroethene (*17*)
1,1,1,2-Tetrachloroethane	384 (*12*)	Trichloroethene (*12*)
1,1,2,2-Tetrachloroethane	0.8 (*12*)	Trichloroethene (*12*)
1,1,2,2,2-Pentachloroethane	0.01 (*12*)	Tetrachloroethene (*12*)
Bromoethane	0.08 (*8*)	
1,2-Dibromoethane	2.5 (*9*)	Bromoethene (*9*)
	2.5 (*18*)	Ethylene glycol (*18*)
Ethenes		
Trichloroethene	0.9 (*10*), 2.5 (*15*)[b]	
Tetrachloroethene	0.7 (*10*), 6 (*15*)[b]	
Propanes		
1-Bromopropane	0.07 (*8*)	
1,2-Dibromopropane	0.88 (*9*)	Bromopropene (*9*)
1,3-Dibromopropane	0.13 (*9*)	Bromopropanol (*9*)
1,2-Dibromo-3-chloropropane	35 (*19*)	Bromochloropropene (*19*)

[a]Extrapolated by 2 from Reference 11. [b]At 10 °C in sea water. [c]At 20 °C.

bromine substituents is consistent with the findings of Burlinson et al., who noted that bromine is eliminated from DBCP six times faster than is chlorine (*19*).

Few halogenated aliphatic compounds undergo dehydrohalogenation in mammalian systems, but there are some. 1,1,2,2-Tetrachloroethane and 1,1,1,2,2-pentachloroethane undergo dehydrohalogenation to trichloroethene and tetrachloroethene, respectively, in live mice and under reducing conditions in hepatic microsomes (Table 4).

Reaction rates. Most experiments that are used to determine reaction rates in water are performed at elevated temperatures, because reaction rates are too slow at environmental temperatures. Rates measured at higher temperatures may then be extrapolated to lower temperatures, using the Arrhenius equation (*7*):

$$\ln \frac{k_2}{k_1} = \frac{E_a}{R}\left(\frac{T_2 - T_1}{T_1 T_2}\right)$$

in which k is a rate constant, E_a is the activation energy (kJ/mol), R is the universal gas constant (8.314 J/mol-K), and T is the temperature (K). Activation energies for abiotic transformation of halogenated aliphatic compounds in aqueous solutions are about 100 ± 10 kJ/mol (*8*, *9*). This translates to a 3.5-fold decrease in reaction rate for each 10 °C decrease in temperature. Many of the half-lives listed in Table 3 were extrapolated in this manner from studies conducted at higher temperatures.

Rates are often determined by use of aqueous solutions that contain high concentrations of organic solvents (e.g., 10% dioxane) (*8*). However, different investigators often report different rates, mechanisms, and products for the same compound (Table 3). In some cases, substitution may prevail at one temperature and dehydrohalogenation at another. These difficulties are at least partially responsible for the differences in reported rates (Table 3). Therefore, caution is required in using extrapolated rates, and more research is needed.

With the caution noted above, re-

FIGURE 3
Products from epoxidation of carbon–carbon double bonds

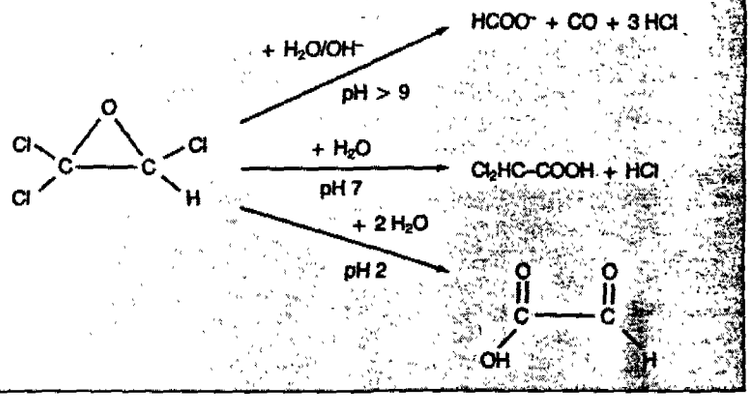
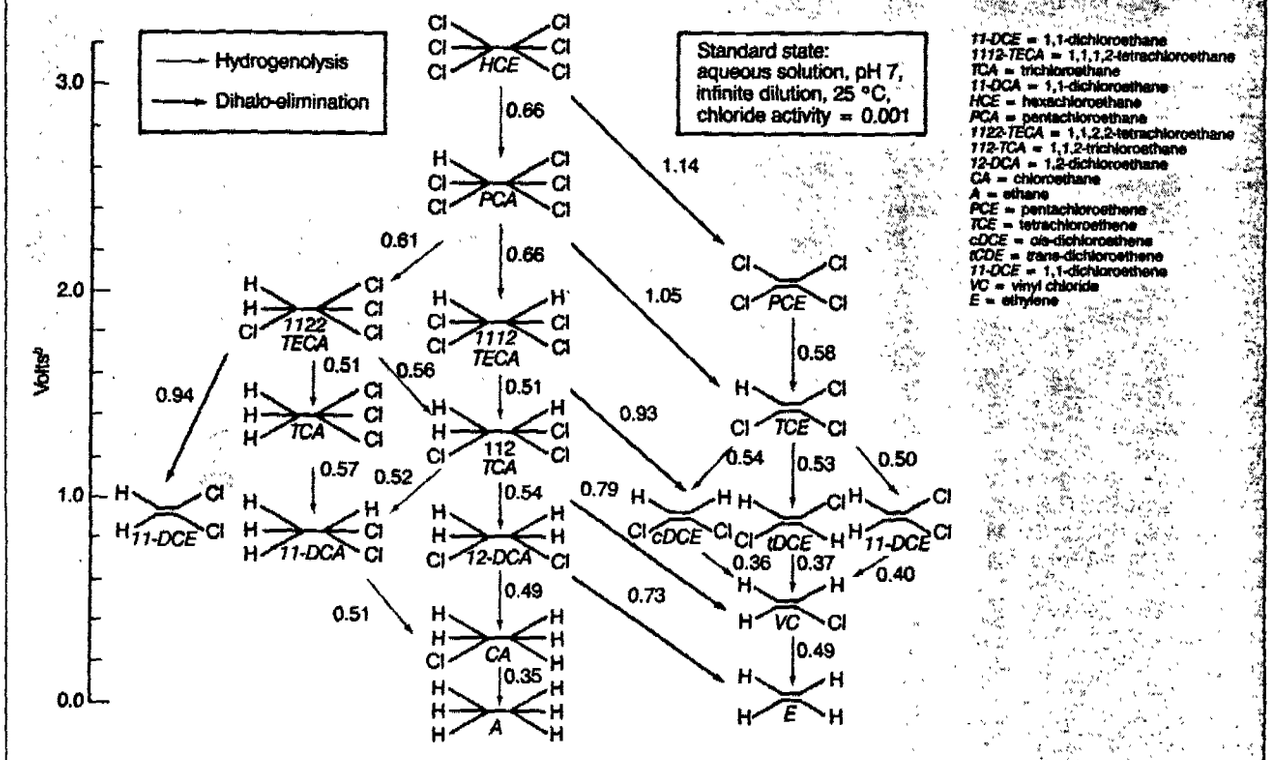


FIGURE 4
Estimated relative half-reaction reduction potentials[a]



[a]In volts, for dechlorination of chlorinated alkanes and alkenes. Relative potentials are illustrated by the vertical position of the compounds. Box describes the calculations of reduction potentials.
[b]Scale of reduction potential with respect to ethane.

ported reaction rates from Table 3 are plotted as a function of the number of halogen substituents per carbon atom in Figure 2. With the possible exception of tetrachloromethane, compounds that are susceptible to substitution reactions, such as monohaloalkanes or 1,3-dihaloalkanes, and those that are susceptible to dehydrohalogenation, such as polyhaloalkanes, behave similarly in water and mammalian systems. Increased halogenation tends to decrease substitution reaction rates and increase dehydrohalogenation rates. Consequently, most highly halogenated aliphatic compounds, with the exception of C_1 compounds, mainly undergo dehydrohalogenation (Figure 2), although some undergo both reactions (*14*). Rates of dehydrohalogenation and substitution in mammalian systems generally have not been reported and are no doubt quite complex because of the many potential facilitating enzymes present. Hence, comparison of these rates with rates in water cannot be made.

Oxidations and reductions

Unlike substitutions and dehydrohalogenations, oxidations and reductions require external electron acceptors and donors, respectively (Figure 1, III and IV). Generally, organic compounds acting as electron donors undergo oxidation reactions. However, because of the electronegative character of halogen substituents on aliphatic compounds, polyhalogenated aliphatic compounds often behave as electron acceptors or oxidants and are reduced in the process. Thus, halogenated aliphatic compounds may be either oxidized or reduced, depending on their structure and environmental conditions. In most reactions described to date, the electron acceptors and donors used to oxidize and reduce halogenated aliphatic compounds are derived from biological systems.

Oxidations. Biologically mediated oxidation of organic compounds has been studied extensively. Organic compounds generally represent reduced forms of carbon, and, as such, oxidation is energetically favorable. In contrast, halogenated aliphatic compounds are relatively oxidized by the presence of halogen substituents: the more halogen substituents, the more oxidized the compound, and the more susceptible it is to reduction. Thus, with increased halogenation, reduction becomes more likely than does oxidation.

Most oxidations observed in mammalian systems (Table 5) (*23–26, 31–43*) involve monooxygenase that contains cytochrome P450. Cytochrome P450 is a heme-containing protein (with iron–porphyrin active sites) that can mediate both oxidation and reduc-

Calculations for reduction potentials

The procedure for estimating half-reaction reduction potentials contained in Figures 4–6 is as follows. Three steps were involved in the calculations for T = 25 °C (298 K). The first was estimation of the aqueous-phase free energy of formation for the compound, the second was computation of free energy changes for a given half-reaction, and the third was calculation of reduction potentials using the Nernst relationship.

1. Aqueous-phase free energy of formation values were estimated from published gas-phase free energy of formation [ΔG°_f (g)] data (*52*) and published (*71*) and estimated (*68*) values of Henry's constant (H), which related activity in the gas phase to activity in the aqueous phase at equilibrium.

$$\Delta G^\circ_f (aq) = \Delta G^\circ_f (g) + RT\ln H$$

2. Free energy changes for a given half-reaction were computed to be consistent with general principles and with Figure 5 based on the equation

$$\tfrac{1}{2}RX + \tfrac{1}{2}H_+ + e^- \longrightarrow \tfrac{1}{2}RH + \tfrac{1}{2}X^-$$ as follows:

$$\Delta G^\circ (aq) = \Sigma G^\circ_f (aq) \text{ for products} - \Sigma G^\circ_f (aq) \text{ for reactants}$$

ΔG° (aq) = standard free energy change for half-reaction,

and values thus calculated were adjusted to the desired reference state

$([H^+] = 10^{-7}, [Cl^-] = 10^{-3}, [Br^-] = 10^{-5})$, using:

$$\Delta G^{\circ\prime} = \Delta G^\circ + \tfrac{1}{2}RT\ln([X^-]/[H^+])$$

3. Reduction potentials were obtained from the Nernst relationship:

$$E^{\circ\prime} = \Delta G^{\circ\prime}/nF$$

$$\text{or } pE^{\circ\prime} = nFE^{\circ\prime}/2.3RT$$

$E^{\circ\prime}$ = reduction potential (volts)
R = universal gas constant (8.314 J/K-mol)
n = electron equivalents transferred (*52*)
F = Faraday's constant (96,487 J/volt-equivalent)
T = temperature (K)

TABLE 4
Substitution and dehydrohalogenation reactions of halogenated aliphatics in mammalian systems

Compound	Product(s)	Systems[a]	Reference
Methanes			
Dichloromethane	Carbon monoxide	hm/N	(22)
Tetrachloromethane	Carbon dioxide	h/GO	(23)
Dibromomethane	Carbon monoxide	hm/NO	(22)
Ethanes			
1,1,2-Trichloroethane	Dichloroethanol	M	(24)
1,1,2,2-Tetrachloroethane	Trichloroethanol	M	(25)
	Trichloroethene	M	(25)
1,1,1,2-Tetrachloroethane	Trichloroethanol	M	(26)
Pentachloroethane	Tetrachloroethene	M	(27)
Ethenes			
Chloroethene	Glutathione-dependent sulfur-containing organic compound	R/G	(28)
1,1-Dichloroethene	Glutathione-dependent sulfur-containing organic compound	R/G	(29)

[a]Slashes separate conditions for an individual experiment. hm = hepatic (rat liver) microsomes; R = live rats; M = live mice; N = NADH dependence; G = glutathione dependence; O = presence of oxygen.

tion reactions. Cytochrome P450-containing monooxygenase mediates oxidation of halogenated aliphatic compounds by three general mechanisms: by incorporation of oxygen in the carbon–hydrogen bond (α-hydroxylation) (*30, 44*) (Figure 1, IIIa); by oxidation of a halogen substituent (*44, 45*) (Figure 1, IIIb); and by oxidation of a carbon–carbon double bond via epoxidation (*30, 44, 46–48*) (Figure 1, IIIc).

The first mechanism leads to a substitution product, an alcohol. However, mechanistic studies have shown that atomic oxygen, derived from molecular oxygen, is inserted into the carbon–hydrogen bond (*22, 33*). Subsequently, for halogenated alcohols, the hydrogen of the hydroxy group and a halogen substituent leave as the hydrogen ion (H^+) and the halide ion (X^-), resulting in an aldehyde. Halogenated formaldehyde can be chemically transformed into carbon monoxide.

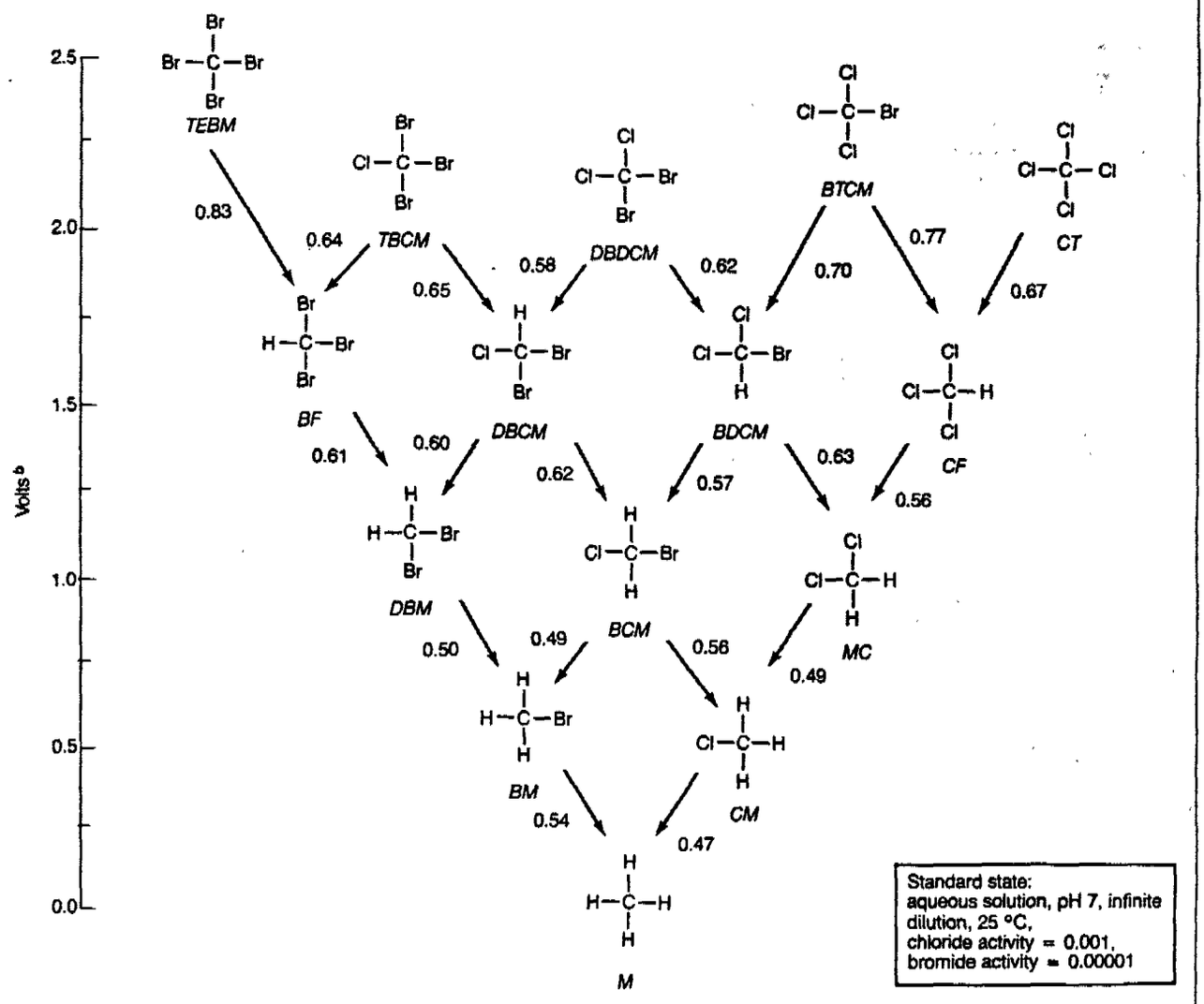
The second mechanism, halogen oxidation, proceeds via an unstable halosyl intermediate ($CH_2X^+{=}O^-$). Presumably, this species hydrolyzes rapidly to produce an alcohol and hypochlorite ion (*49*). Because an alcohol is produced, the overall reaction resembles a substitution reaction. No net oxidation of the organic compound occurs (*30*). Also, because halosoaliphatic compounds have not yet been detected, this mechanism might not actually occur with halogenated aliphatic compounds.

α-Hydroxylation of halogenated aliphatic compounds would result in the formation of acids and alcohols as described above. In contrast, β-elimination of a halosyl intermediate could result in an alkene. Therefore, the observation of alkene formation from halogenated propanes was reported by Tachizawa et al. to be indicative of a halosyl mechanism (*45*). They documented propene formation and noted that brominated alkanes undergo transformation to alkenes more readily than do chlorinated alkanes.

In mammalian systems, dihalogenated aliphatic compounds are susceptible to oxidation by either of the above mechanisms. For example, transformation of dihalomethanes to carbon monoxide under aerobic conditions has been reported (Table 4) (*22*). Overall, this is a substitution reaction, but it involves an oxidation step. Oxidation proceeds sequentially from halogenated alcohol to halogenated aldehyde before final reduction to carbon monoxide. Yllner observed that mice transformed polychlorinated ethanes to chlorinated aliphatic acids (*24–27, 34*).

The following characteristics of the third mechanism, epoxidation or the oxidation of a carbon–carbon double bond, are well documented for mammalian systems. Epoxidation is the first step in alkene oxidation that is pro-

FIGURE 5
Estimated relative half-reaction reduction potentials[a]



[a]In volts for dehalogenation of brominated and chlorinated methanes.
[b]Relative potentials are illustrated by the scale on the left.

moted by cytochrome P450-containing monooxygenase. The oxygen that is incorporated into halogenated alkenes is derived from molecular oxygen (*22, 33, 48*). The epoxide is normally short-lived and might undergo one of several different reactions. Halogenated aldehydes or acyl chlorides are common intermediates and are often subsequently transformed into acids (oxidation), alcohols (reduction), or hydrolyzed to acids or carbon monoxide (via acyl chlorides) (*30, 44, 48*).

Epoxide chemistry in aqueous solutions partially explains the fate of epoxides in mammals. In aqueous solution, for example, trichloroethene epoxide decomposes to formyl chloride and dichloromethanol. Subsequently, formyl chloride eliminates hydrogen chloride (HCl) to form carbon monoxide, and dichloromethanol hydrolyzes to form formate (*49*). These two products predominate at pH > 9. At lower pH, other products dominate: at pH 7, dichloroacetic acid is produced; and at pH 2, glyoxylic acid is produced.

All the products shown in Figure 3 have been observed in mammalian systems. In addition, transformation of chlorinated ethenes proceeds via chlorine migration to produce chloral (2,2,2-trichloroacetaldehyde) (*50*) (Table 5). The production of compounds such as chloral in mammalian systems, but not in aqueous solutions, may be the result of the interaction between the chlorinated epoxide and the cytochrome P450-based monooxygenase (*47*). It also may be the result of the formation of an intermediate other than the epoxide (incorporation of oxygen into the halogenated alkene) and the concomitant formation of a cationic or radical intermediate (*50*).

Ozonation of halogenated alkenes could serve as a chemical model for the epoxidation of these compounds in mammalian systems. The reaction is largely an electrophilic attack at the double bond by ozone. Ozonation rates of chlorinated ethenes decrease as the number of chlorine substituents increases (*51*). In addition, the inductive effect of additional chlorine substituents is more important in the reduction of reaction rates than the increased steric hindrance of these substituents. Ionization potential (IP) is an adequate predictor of relative ozonation rates (Table 6) (*52*). Mesomeric delocalization of positive charge by chlorine substituents decreases both IP and ozonation rates. Therefore, IP might be a reasonable predictor of relative rates of epoxidations of halogenated alkenes in biological systems.

Another substance that can be involved in the oxidation of halogenated aliphatic compounds by biological systems is glutathione. Glutathione-mediated oxidations generally occur in the soluble or cytosolic fraction of cells (*30*). Oxidation is initiated by nucleophilic attack of glutathione on the electrophilic carbon (generally one bound to a halogen) (*31*). Dihalomethanes are oxidized to formaldehyde and formic acid following conjugation with cytosolic glutathione (Table 5).

One final category of oxidation involving halogenated compounds is the phenomenon of biohalogenation. This process is widespread in nature, occurring in certain species of bacteria, fungi, algae, higher plants, and animals. It is brought about by the activity of haloperoxidases in the presence of hydrogen peroxide (Figure 1, IIId). The chemistry of these transformations is similar to that of hypohalous acids; unsaturated substrates such as ethene may be converted to halohydrins or dihalides by this process (*53*).

Reductions. Certain transition metals and transition metal complexes

TABLE 5
Oxidati n of halogenated aliphatic compounds in mammalian systems

Compound	Product(s)	System[a]	Reference
Methanes			
Dichloromethane	Formaldehyde	hm/N/O	(*31*)
	Carbon dioxide	hm/O	(*32*)
Trichloromethane	Carbon dioxide	h/G/O	(*23*)
	Carbon dioxide via phosgene	hm/P/O	(*33*)
Ethanes			
1,2-Dichloroethane	Chloroacetic acid, carbon dioxide	M	(*34*)
1,1,2-Trichloroethane	Dichloroacetic acid, chloroacetic acid, carbon dioxide	M	(*24*)
1,1,2,2-Tetrachloroethane	Trichloroacetic acid	M	(*25*)
	Dichloroacetic acid, carbon dioxide	M M	(*25, 35*) (*25*)
1,1,1,2-Tetrachloroethane	Trichloroacetic acid	M	(*26*)
Pentachloroethane	Trichloroacetic acid	M	(*27*)
1,2-Dibromoethane	Bromoacetaldehyde	R/G	(*36*)
Ethenes			
Chloroethene	Chloroacetic acid	hm/O	(*37*)
	2-Chloroacetaldehyde, glycolaldehyde, 2-chloroethanol	hm/P/N	(*38*)
1,1-Dichloroethene	Chloroacetic acid	hm/O	(*37*)
1,2-Dichloroethene	Dichloroacetic acid	hm/O	(*37*)
Trichloroethene	Dichloroacetic acid	R, M	(*39, 40*)
	Trichloroethanol, Trichloroacetic acid	hm/O hm/P, R	(*25, 39, 41*)
	Carbon monoxide	hm/P	(*41*)
	Carbon dioxide	hm/P	(*41*)
	Glyoxylic acid	hm/P	(*41*)
Tetrachloroethene	Trichloroacetic acid	hm/O, hm/P/N	(*37, 42*)
Bromoethene	Bromoacetaldehyde	hm/P/N	(*43*)

[a]Commas separate different experimental systems that result in similar products. Slashes separate conditions for an individual experiment. hm = hepatic (rat liver) microsomes; R = live rats; M = live mice. N = NADH dependence; P = cytochrome P450 dependence; G = glutathione dependence; O = presence of oxygen.

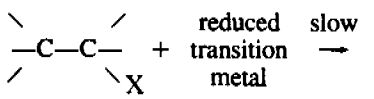
TABLE 6
Ionization potentials (IP) and ozonation rates (k) for some halogenated aliphatic compounds

Compound	No. of chlorines	IP[a]	k[b] (L/mol s)
Tetrachloroethene	4	9.32	1.0
Trichloroethene	3	9.45	3.6
1,2-Dichloroethene	2	9.6	591
Chloroethene	1	9.99	1180
Ethene	0	10.51	>20,000

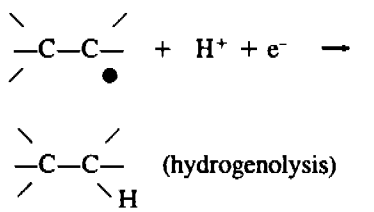
[a]Reference 52.
[b]Reference 51.

reduce halogenated aliphatic compounds (Table 7) (*54–61*). As a result, these metals and metal complexes are themselves oxidized. Because transition metal complexes are frequently located at the active sites of the macromolecules that are used for electron transfer in living organisms, reactions between metal complexes and halogenated aliphatic compounds are useful models that simulate transformations in living organisms. Transition metals may also play a role in the abiotic reduction of certain halogenated aliphatic compounds in groundwater.

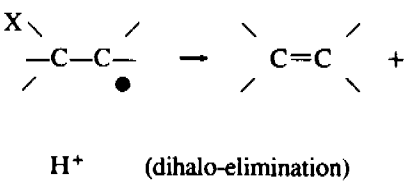
Initially, most reductions by transition metal complexes involve the transfer of a single electron and the formation of an alkyl radical. This occurs with a variety of transition metals, including nickel (*61*), iron (*62*), chromium (*63*) and cobalt (*64*), although some two-electron reductions also occur with cobalt (*54, 65*). Formation of an alkyl radical upon removal of a halogen substituent is the first and, in most cases, the rate-limiting step in the two-step reduction of halogenated aliphatic compounds:



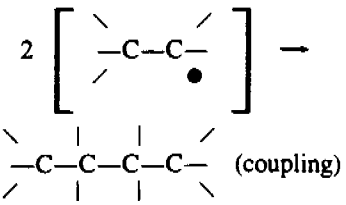
The alkyl radical that results from the above step can undergo several reactions. The simplest of these involves scavenging a hydrogen atom from the immediate surrounding matrix—possibly from the complex itself (*55*):



Another involves the loss of a second halogen substituent from a carbon atom adjacent to the radical carbon to form an alkene (*66*). The alkene that results from this last step is more stable and has two fewer halogen substituents, thus decreasing the likelihood of further reduction:



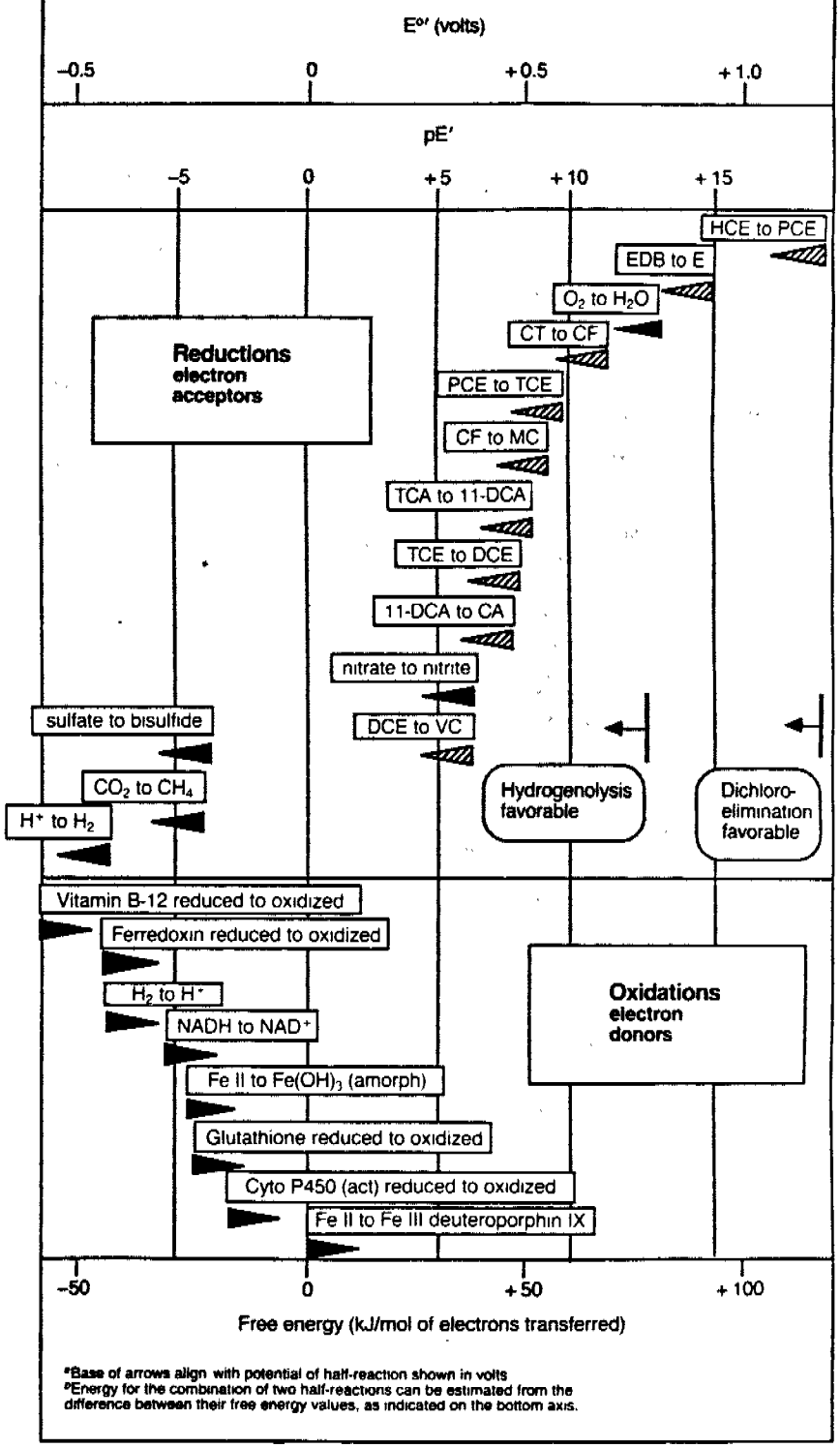
A final possibility is dimerization of the radicals:



Reduction of polyhalogenated alkanes can result in the production of both alkanes and alkenes, as illustrated in Figure 1.

Formation of the alkyl radical appears to involve either the transfer of an electron to the reduced transition metal, with a standard reduction potential as the driving force, or the transfer of a halogen atom, a process governed by

FIGURE 6
Half-life reduction potentials for reducing and oxidizing agents[a,b]



[a]Base of arrows align with potential of half-reaction shown in volts
[b]Energy for the combination of two half-reactions can be estimated from the difference between their free energy values, as indicated on the bottom axis.

carbon–halogen bond energies. Regardless of the exact mechanism, however, relative rates for reduction of halogenated aliphatic compounds should follow certain patterns (*61*). In general, smaller carbon–halogen bond energies are conducive to faster one-electron (two-step) reductions. An example is the reduction of halogenated aliphatics by iron(II) porphyrins. Because the rate-limiting step in the two-step reduction is probably the formation of the carbon radical (*62*), the heat of formation of the alkyl radicals is one measure of the carbon–halogen bond strength and should be inversely proportional to the rate of reduction.

This is shown in Table 8 for pseudo-first-order reduction rates derived from data from Klecka and Gonsior (*58*). As another measure, Eberson (*67*) suggested that although rates might differ with different reductants (iron porphyrin and the like), for a given reductant, the relative rates of reduction of halogenated aliphatic compounds should correlate with their relative standard reduction potentials (assuming no change in mechanism). Relative standard reduction potentials can be estimated for many halogenated aliphatic compounds using the values as shown in Figures 4 and 5. The calculation method is described in the sidebar on p. 727 (*68–71*).

Highly halogenated aliphatic compounds have higher relative standard potentials than do their less halogenated counterparts, as indicated by the vertical positioning of compounds in Figures 4 and 5. Thus more energy is released upon reduction of the more highly halogenated compounds.

Another type of comparison between reduction potentials is illustrated in Figure 6. Here, biologically relevant reductants, as well as oxidants, are included. Note that hexachloroethane (HCE) is a stronger electron acceptor than is oxygen, and several halogenated compounds, such as tetrachloromethane, tetrachloroethene, and trichloromethane, are stronger acceptors than nitrate. This suggests environmental conditions under which their reduction is likely. Also, as illustrated in the lower portion of Figure 6, several biologically active donors, and even ferrous ion, have lower reduction potentials than do most of the halogenated aliphatic compounds, and they could be involved in halogen removal by reductions. Thermodynamic considerations can help indicate which halogenated aliphatic compounds might be coupled by reduction with the oxidation of individual electron donors typically found in biological systems.

Many of the reductions indicated above occur in mammalian systems (*30, 44*). All three kinds of reduction—hydrogenolysis, in which a hydrogen atom replaces a halogen substituent (Figure 1, IVa); dihalo-elimination, in which two halogens are removed from adjacent carbons (Figure 1, IVb); and coupling (Figure 1, IVc)—have been observed in mammalian systems (Table 9) (*27, 72, 81*). Hexachloroethane, pentachloroethane, and tetrachloromethane are reductively dehalogenated (by hydrogenolyis) to pentachloroethane, tetrachloroethane, and trichloromethane, respectively. Also, hexachloroethane and pentachloroethane are reduced (by dihalo-elimination) to the alkenes, tetrachloroethene and trichloroethene.

Most research in mammalian systems implicates cytochrome P450 as the active reducing agent. Reduction results when halogenated aliphatics outcompete with oxygen (when present) for the electrons supplied by nicotinamide adenine dinucleotide phosphate (NADPH) (*44*). The mechanism involves formation of either a carbon radical or a di-

TABLE 7
Reduction of halogenat d aliphatic compounds by transition metal c mpl xes

Compound	Products	Reductant	Reference
Methanes			
Chloromethane	Alkylated co-complex	Co(I) chelates	(*54*)
Dichloromethane	Methane	$Cr(II)SO_4$	(*55*)
	Cl-alkylated B_{12}	B_{12}-Co(III) (methylcobalamine)	(*56*)
Trichloromethane	Methane	$Cr(II)SO_4$	(*55*)
	Dichloromethane	Fe(II)P	(*57*)
	Dichloromethane	Fe(II)P	(*58*)
	Cl-alkylated B_{12}	B_{12}-Co(III)	(*56*)
Tetrachloromethane	Methane	$Cr(II)SO_4$	(*55*)
	Chloroform	Fe(II)P	(*57, 58*)
	Cl-alkylated B_{12}	B_{12}-Co(III)	(*56*)
Bromomethane	Methane	$Cr(II)SO_4$	(*55*)
	Alkylated co-complex	Co(I)-complex	(*54*)
Dibromomethane	Methane, ethene	Fe(II)P	(*57*)
Tribromomethane	Br_2-alkylated B_{12}	B_{12}-Co(III)	(*56*)
Ethanes			
Chloroethane	Alkylated co-complex	Co(I)-complex	(*54*)
1,1-Dichloroethane	Ethane, ethanol	$Cr(II)SO_4$	(*55*)
1,1,1-Trichloroethane	Ethane, ethanol, ethene, chloroethene	$Cr(II)SO_4$	(*55*)
	1,1-Dichloroethane	Fe(II)	(*57*)
	1,1-Dichloroethane	Fe(II)P	(*58*)
Hexachloroethane	Tetrachloroethene	Fe(II)P	(*57, 59*)
	Tetrachloroethene	$Cr(II)SO_4$	(*60*)
Bromoethane	Ethane	Ni(I)	(*60*)
1,1-Dibromoethane	Ethane, ethanol	$Cr(II)SO_4$	(*55*)
1,2-Dibromoethane	Ethene	Fe(II)	(*57*)
	Ethene	Fe(II)P	(*58*)
Propanes			
1-Chloropropane	Alkylated co-complex	Co(I)-complex	(*54*)
1,1-Dichloropropane	Propane, propanol, propene	$Cr(II)SO_4$	(*55*)
1-Bromopropane	Alkylated co-complex	Co(I)-complex	(*54*)
1,2-Dibromo-3-chloropropane	Propene, allyl chloride	$Cr(II)SO_4$	(*60*)

Note: The homolytic cleavage of cobalt–carbon bonds requires 15–30 kcal/mol and can occur at relatively low temperatures.

TABLE 8
Pseudo-first-order reduction rates and heat of formation f carbon radicals for some chlorinated aliphatic compounds

Compound	k (d^{-1})[a]	Heat of radical formation[b] (kJ/mol)
Dichloropropane	<0.001	117.6
Trichloromethane	0.00165	100.8
1,1,1-Trichloroethane	0.058	92.0
Tetrachloromethane	115	78.2

[a]Reference 58.
[b]*References 52 and 67.*

halocarbene complex with cytochrome P450.

Evidence for a carbon radical follows from two general observations: the observed production of hexachloroethane from carbon tetrachloride (Figure 1, IVc and Table 9), apparently as a result of trichloromethyl radical dimerization, and indications of radical formation in chemical studies that involve iron(II) porphyrin. Formation of a carbon radical depends on the strength of the carbon–halogen bond (and standard reduction potential). This bond is weaker for brominated than for chlorinated compounds. Thus brominated aliphatics should be more susceptible to reduction by cytochrome P450 than are chlorinated compounds. The number of halogen substituents also is an important factor in determining the feasibility of radical formation.

Evidence for the production of a dihalogenated carbene intermediate comes from observations of the reduction of polyhalogenated methanes. A dihalogenated carbene complex would be expected to hydrolyze to carbon monoxide, and carbon monoxide has been produced from trichloromethane and tetrachloromethane (Table 9). However, compounds having less than three halogen substituents apparently do not undergo reduction to carbon monoxide by cytochrome P450 (*73*).

Halogenated aliphatic compounds with few halogen substituents generally are not reduced or are reduced relatively slowly in mammalian systems. For example, 1,2-dichloroethane is not significantly reduced under anaerobic conditions by cytochrome P450 (*82*). However, both 1,2-dichloroethane and 1,2-dibromoethane are transformed to ethene in mammalian systems (Table 9). Livesey and Anders indicated that this reduction requires the presence of reduced glutathione in hepatic microsomes (*80*). They also postulated the following two-step process, involving nucleophilic attack by glutathione (GSH) and a thiol sulfur (RSH):

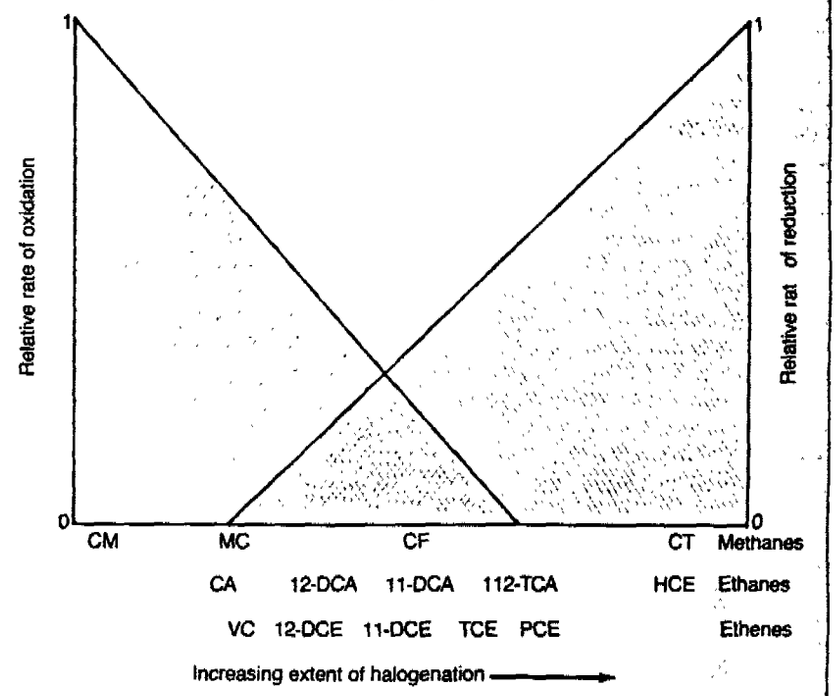
$$GSH + Cl{-}CH_2{-}CH_2{-}Cl \rightarrow GS{-}CH_2{-}CH_2{-}Cl + HCl$$

$$RSH + GS{-}CH_2{-}CH_2{-}Cl \rightarrow GSSR + HCl + CH_2{=}CH_2$$

Microbially mediated reactions

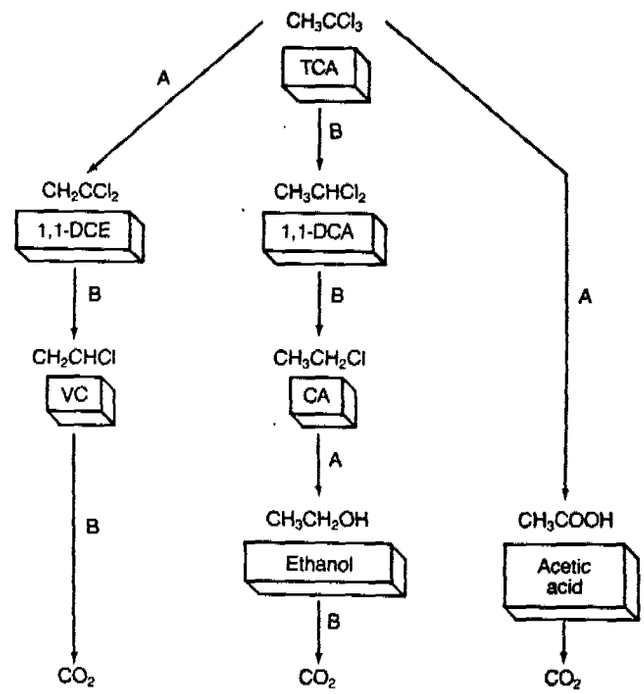
Some of the dehalogenating agents found in mammalian systems are manifest in microbial populations as well. Many microorganisms contain cytochrome P450 that is similar to mammalian P450 even in regard to halogenated compound transformation (*83*). For example, cytochrome P450 from *Pseudomonas putida* closely resembles microsomal P450 (*84*), and whole cells can use it to mediate the reduction of carbon tetrachloride and bromotrichloromethane to chloroform (*85*, *86*). Glutathione also is widely distributed among gram-negative bacteria (87), and it is used by *Hyphomicrobium sp.* in the metabolism of dichloromethane (*89*). In general, however, microorga-

FIGURE 7
Relative rates of reduction and oxidation[a]



[a]As a function of the extent of halogenation.

FIGURE 8
Pathways for the transformation of TCA under methanogenic conditions[a]



[a]A indicates abiotic reactions; B indicates biotic reactions.
Source: Reference 97

nisms are capable of more diverse biochemical reactions than are mammalian systems.

Microorganisms obtain energy from a wide variety of electron donors and acceptors under different redox conditions (Table 10). Aerobic metabolism dominates where sufficient oxygen is present. Where oxygen is depleted, however, other electron acceptors, such as nitrate, sulfate, and carbon dioxide, are used. Differences in available electron acceptors and in the resulting redox conditions also appear to affect the potential and pathways for transformation of different halogenated aliphatic compounds. Another factor affecting the potential for transformation is the reactivity of enzymes and coenzymes associated with different microorganisms.

Regardless of the metabolic differences between microorganisms and mammalian systems, the types of reactions mediated by bacteria and mammalian systems are similar. Like mammalian systems, bacteria mediate substitution reactions with monohalogenated or dihalogenated aliphatic compounds (Table 11) (*18, 88–111*). For example, aerobic bacteria isolated from a contaminated soil transform 1,2-dichloroethane to chloroethanol, which is subsequently mineralized to carbon dioxide (*100*). However, the pathways for the observed mineralization of many halogenated organics are unknown. A compound such as tetrachloromethane, which is mineralized to carbon dioxide (Table 11), may undergo reduction to dichloromethane and subsequent oxidation to carbon dioxide, as previously described for mammalian systems. In addition, different organisms may participate in different steps of the overall mineralization of a compound.

Bacteria also oxidize chlorinated alkenes, presumably via epoxidation (Table 11). Because many halogenated aliphatic compounds are eventually mineralized to carbon dioxide, other oxidation pathways may be involved. Some net oxidations, such as the mineralization of dichloromethane to carbon dioxide, could proceed either by oxidation via phosgene ($COCl_2$) or by substitution via alcohols. In general, oxidation pathways are not well known. Ionization potentials, which are used to predict ozonation rates for halogenated alkenes, might also be used to model oxidations in microbial systems. However, the number of halogen substituents may be a more reasonable predictor of oxidations—the more halogen substituents, the less susceptible the compound is to oxidation. This is consistent with Figure 6.

Polychlorinated methanes, ethanes, and ethenes are reduced by microbial consortia or mixed cultures (Table 11). Generally, reduction entails the replacement of halogen substituents by hydrogen (hydrogenolysis) (vertical arrows in Figure 4). However, reduction can also involve the loss of two halogens (dihalo-elimination) (wide arrows in Figure 4), as in the case of hexachloroethane transformation to pentachloroethane and of 1,2-dibromoethane transformation to ethylene (Table 11). These two dihalo-eliminations can occur under aerobic conditions, whereas hydrogenolysis has only been observed under anaerobic conditions. Thus reductions proceed by the same general pathways, regardless of whether transition metals, mammalian systems, or microorganisms provide the reductant.

Methanogens, which grow under some of the most severely reducing conditions (Table 10), do not have the cytochrome systems that are present in aerobic organisms. However, methanogens do have nickel-containing enzymes or cofactors such as F430 (*112*). Reduced nickel complexes can reduce halogenated aliphatic compounds (Table 7). Indeed, several of the microbial reductants have much greater reducing potentials than the mammalian enzymes do (see Table 12) (*54, 67, 84, 113*), and this may lead to a broader reductive dehalogenation ability.

For comparison, Figure 7 illustrates the half-reaction reduction potentials for halogenated aliphatic compounds that function as electron acceptors. Possible electron donors are shown as well. Common electron acceptors, such as oxygen, nitrate, sulfate, and carbon dioxide, also are plotted in Figure 6. Here, the various couples are arranged according to their standard half-reaction reduction potentials at pH 7. Each arrow points in the direction for which the stated transformation is thermodynamically possible. In the direction opposite to the arrow, the reverse reaction is thermodynamically favorable. Thus a direct, graphic reading can be obtained for the free-energy change associated with the coupling of two half-reactions. For example, combining the

TABLE 9
Reductions of halogenated aliphatic compounds in mammalian systems

Compound	Product(s)	System[a]	Reference
Methanes			
Trichloromethane	Carbon monoxide	hm/P/r	(*72, 73*)
	Dichloromethane		(*74*)
Tetrachloromethane	Carbon monoxide	hm/P/N	(*75*)
	Trichloromethane	R, hm/P	(*73, 75–77*)
		r	(*74, 78, 79*)
	Hexachloroethane	R, B	(*77, 78*)
Bromotrichloromethane	Trichloromethane	R	(*77*)
	Hexachloroethane		
	Bromodichloromethane		
	Carbon monoxide	hm/P/r	(*73*)
Tribromoethane	Carbon monoxide	hm/P/r	(*73*)
Tetrabromomethane	Carbon monoxide	hm/P/r	(*73*)
Ethanes			
1,2-Dichloroethane	Ethene	hm/G/O	(*80*)
Pentachloroethane	Trichloroethanol	M	(*27*)
	Trichloroethene	M, hm/r	(*27, 79*)
	1,1,2,2-Tetrachloroethane	hm/r, hm P/N/r	(*79*)
Hexachloroethane	Pentachloroethane, Tetrachloroethane	hm/r, S, hm/P/N	(*79, 81*)
1,2-Dibromoethane	Ethene	hm/G/O	(*80*)

[a]Commas separate different experimental systems that result in similar products. Slashes separate information regarding each experiment. hm = hepatic (rat liver) microsomes; R = live rats; B = live rabbits; M = live mice; S = live sheep; N = NADH dependence; P = cytochrome P450 dependence; G = glutathione dependence; O = presence of oxygen; r = reduced or anaerobic conditions reported.

TABLE 10
Electron acceptors in microbial processes

Environment	Electron acceptor	Process	Order of preference
Aerobic	O_2	Aerobic metabolism	1
	NO_3^-	Denitrification	2
Anaerobic	SO_4^{2-}	Sulfate reduction	3
	CO_2	Methanogenesis	4

reduction of hexachloroethane to pentachloroethane with the oxidation of Fe(II) to $Fe(OH)_3$ yields a favorable free-energy change of about 140 kJ per mole of electrons transferred. The reduction of hexachloroethane to pentachloroethane and 1,2-dibromoethane to ethene have higher reduction potentials than those associated with oxygen reduction to water (Figure 6), and these dihalo-eliminations are energetically favored in aerobic systems. This is consistent with the observed transformations of hexachloroethane and 1,2-dibromoethane under aerobic conditions.

In addition, the low potential for reduction of carbon dioxide to methane, compared with the reduction potential for hydrogenolysis of polyhalogenated aliphatic compounds (Figure 6) is consistent with their reported reductive transformations under methanogenic conditions (Table 11). For example, the sequential reduction of tetrachloroethene to trichloroethene, to dichloroethene, and finally to chloroethene (vinyl chloride) occurs under methanogenic conditions (*106*), as does the sequential reduction of tetrachloroethane to 1,1-dichloroethane, and finally to chloroethane (*16, 96, 102*). These pathways follow the hydrogenolysis sequences illustrated by the narrow arrows in Figure 4 for these compounds.

Microbial and mammalian systems follow the same general trends with regard to the oxidation and reduction of halogenated aliphatic compounds: The more halogenated the aliphatic compound, the faster the relative rate of reduction; the less halogenated the compound, the faster the rate of oxidation. Substitution reactions follow the same general trends. Many useful generalizations can be drawn from oxidation–reduction potentials of halogenated aliphatic compounds. Dehydrohalogenation has not yet been reported for microbial systems.

TABLE 11
Biotransformations of halogenated aliphatic compounds by microorganisms

Compound	Product(s)	System[a]	Reference
Methanes			
Chloromethane	Formaldehyde	E	(*88*)
Dichloromethane	Carbon dioxide	O/M	(*89*)
	Carbon dioxide	O/P	(*90*)
	Carbon dioxide	O/M	(*91*)
	Carbon dioxide	O/P	(*92*)
	Formaldehyde	E	(*93*)
Trichloromethane	Carbon dioxide	A/M/m	(*94*)
	Carbon dioxide	O/S	(*95*)
	Dichloromethane	A/M	(*96*)
Tetrachloromethane	Carbon dioxide	A/M/m	(*94*)
	Chloroform	A/M/n	(*97*)
	Carbon dioxide		
	Chloroform	A/S	(*98*)
Bromomethane	Formaldehyde	E/mo	(*89*)
Ethanes			
1,1-Dichloroethane	Chloroethane	A/M/m	(*95*)
1,2-Dichloroethane	Carbon dioxide	O/P/p	(*96*)
	Chloroethanol	O/P/x	(*97*)
	Carbon dioxide	A/M/m	(*94*)
1,1,1-Trichloroethane	1,1-Dichloroethane	A/S	(*98*)
		A/M/m	(*99*)
		A/M	(*102*)
	Not identified	A/M/m	(*94*)
1,1,2,2-Tetrachloroethane	1,1,2-Trichloroethane	A/M/m	(*94*)
		A/M	(*102*)
Hexachloroethane	Tetrachloroethane	O/M/s	(*103*)
Bromoethane		O/P/x	(*101*)
1,2-Dibromoethane	Ethene	O/S	(*104*)
	Ethene	A/M/m/r	(*18*)
	Carbon dioxide	O/S	(*105*)
Ethenes			
Chloroethene	Carbon dioxide	A/M/m	(*106*)
	Carbon dioxide	O/P/mb	(*109*)
Dichloroethene	Chloroethene	A/M/m	(*99, 106*)
	Chloroethene	A/S, A/M	(*102, 107*)
	Carbon dioxide		
Trichloroethene	Dichloroethene	A/M/m	(*106*)
	Dichloroethene	A/S	(*98, 108*)
	Dichloroethene	A/M	(*102*)
	Carbon dioxide	O/P	(*110*)
	Carbon dioxide	O/S	(*111*)
Tetrachloroethene	Trichloroethene	A/M/m	(*94, 106*)
		A/M	(*102*)
Propanes			
1-Chloropropane	—	O/P/x	(*101*)
1,2-Dichloropropane	—	O/P/x	(*101*)
1,2-Dibromo-3-chloropropane	Propanol	O/S	(*104*)

[a]Comma separates different experimental systems that result in similar products. Slashes separate information regarding each experiment. O = aerobic; A = anaerobic, which often is methanogenic (m), but often is not explicitly stated; M = mixed culture; P = pure culture; S = soil or aquifer used as biological seed; E = enzyme derived from microorganism; m = methanogenic culture; x = *Xanthobacter*; mo = monooxygenase; mb = Mycobacterium; p = *Pseudomonas*.

Environmental applications

Application of these general principles to environmental problems is complex . For example, Figure 8 illustrates the different pathways possible for the transformation of 1,1,1-trichloroethane (*97*), which can undergo two abiotic transformations as well as reductive dehalogenation by anaerobic microorganisms. Abiotically, the half-life for 1,1,1-trichloroethane at 25 °C is about two years (Table 3), and biologically it could be much less. The abiotic processes are dehydrohalogenation (*14, 15, 99*), as well as hydrolysis (*12, 13, 14*). Acetic acid, the product of hydrolysis, is fairly inert chemically, but it can be mineralized rapidly by microorganisms. Dehydrohalogenation occurs at about one-fifth the rate of hydrolysis at 40 °C (*19*). The product of dehydrohalogenation, 1,1-dichloroethene, can be transformed further by reductive dehalogenation to chloroethene (vinyl chloride) under methanogenic conditions (Table 11, Figure 8). Under the biological transformation route, 1,1,1-trichloroethane is reduced to 1,1-dichloroethane and then transformed abiotically by hydrolysis to ethanol (Table 3), which can in turn be rapidly mineralized by microorganisms. The products and complex pathways shown in Figure 7 are consistent with field observations of products consistently found present in groundwaters contaminated with 1,1,1-trichloroethane (*114*). Other halogenated aliphatic compounds are also likely to undergo complex transforma-

tions under natural environmental conditions.

Conclusions

The fate of halogenated aliphatic compounds in the environment is dependent on their particular chemical properties and potential chemical and biological transformations. The most likely transformations to occur under given environmental conditions are controlled mainly by the number and type of halogen substituents. Increased halogenation or substitution of bromine for chlorine substituents increases the electrophilicity and oxidation state of the compound, making it more susceptible to dehydrohalogenation and reduction and less susceptible to substitution and oxidation (Figure 7). Oxidations and reductions are more common reactions in mammalian and microbiological systems, where they are mediated by enzymes or coenzymes. For oxidations, initial products are generally alcohols or epoxides. For reductions, products are generally less halogenated than were their precursors. A variety of transition metal complexes, including iron porphyrins, are potential mediators of these reactions.

TABLE 12
Standard potentials (E^o) of bi l gically rel vant electron donors or reductants

Reductants	E^o (volts)	Reference
Vitamin B_{12}	–0.59 to –0.8	(*54*)
Co(I) tetraphenylporphin	–0.56	(*67*)
Ferrodoxin (reduced)	–0.43	(*11*)
H_2	–0.42	(*84*)
Cr(II)	–0.41	(*67*)
NADH + H^+	–0.32	(*84*)
Cytochrome P450 (unactivated)	–0.30	(*111*)
Glutathione (reduced)	–0.23	(*84*)
Cytochrome P450 (activated)	–0.17	(*111*)
Fe(II) deuteroporphin IX	0.00	(*67*)
Ubiquinone (reduced)	0.10	(*84*)
Cytochrome c (+2)	0.22	(*84*)
Fe(II)	0.77	(*84*)
H_2O	0.82	(*84*)

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