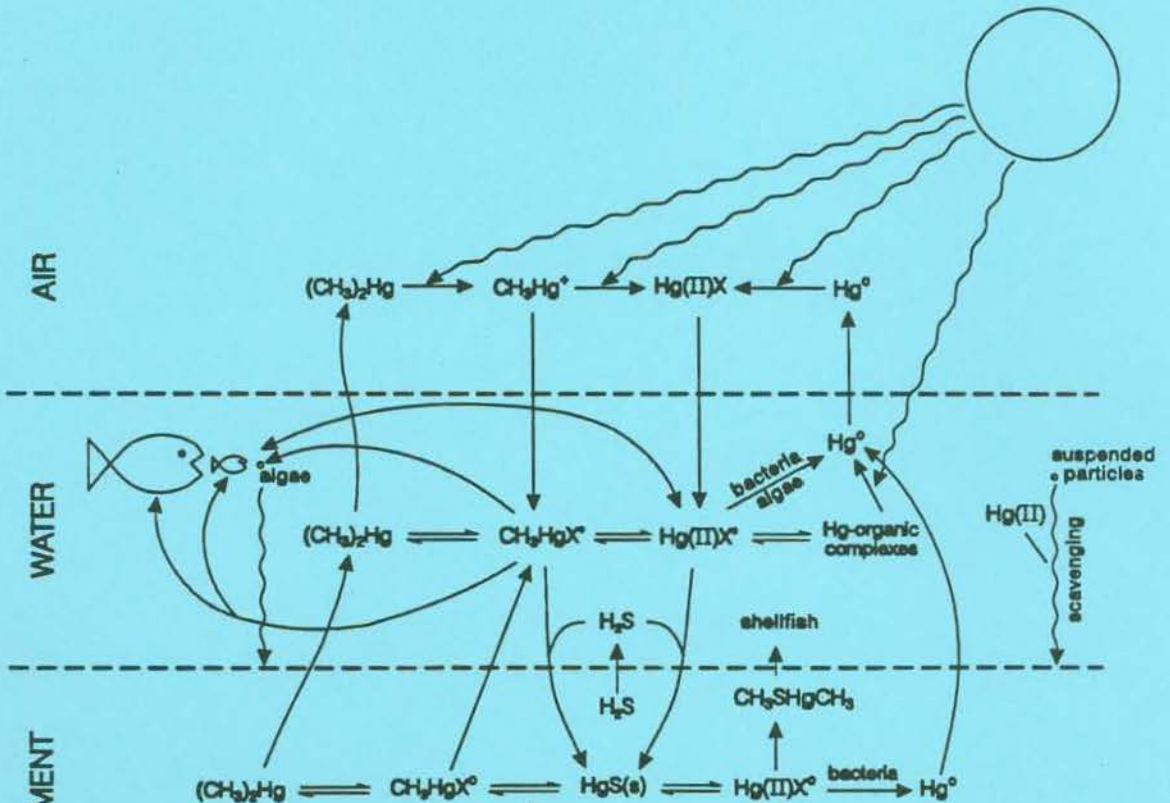
New Jersey Geological Survey
Geological Survey Report 27

Natural Sources of Mercury in the Kirkwood-Cohansey Aquifer System of the New Jersey Coastal Plain



N.J. Department of Environmental Protection and Energy - Division of Science and Research

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Cover Illustration: Biogeochemical cycle of mercury in the environment. Simplified from a diagram by Gary Gill, University of California, Santa Cruz.

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by
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Division of Science and Research
Geological Survey
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Trenton, NJ 08625

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TABLE OF UNITS

WEIGHT (WT)	EQUIVALENT
kilogram (kg)	1000 grams (g)
milligram (mg)	10^{-6} gram
nanogram (ng)	10^{-9} gram
picogram (pg)	10^{-12} gram

VOLUME (V) IN LITERS (L)

wt/wt (solids)		wt/v (liquids)
1 part per million (ppm)	1 ug/g or 1 mg/kg	1 mg/L
1 part per billion (ppb)	1 ng/g or 1 ug/kg	1 ug/L
1 part per trillion (ppt)	1 pg/g or 1 ng/kg	1 ng/L

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Natural Sources of Mercury in the Kirkwood-Cohansey Aquifer System of the New Jersey Coastal Plain

ABSTRACT

Mercury (Hg) deposits are formed by low temperature and low pressure hydrothermal processes in tectonically active areas. Sandstone and limestone host many of the larger deposits. The large ionic radius of mercury precludes its incorporation into the crystal lattice of most common minerals. Glauconite, which is virtually absent from the Kirkwood-Cohansey aquifer system, is the only mineral known to contain mercury in the New Jersey Coastal Plain. Heavy minerals of the Kirkwood-Cohansey aquifer system may contain traces of natural mercury, although no site-specific, quantitative data are available. Partial data on the mercury concentration in rocks which were a source of the Kirkwood-Cohansey sediments and in soils overlying the Cohansey Sand suggest that the natural background concentration is approximately 10 nanograms Hg/g (ng Hg/g).

The natural background concentration of aqueous mercury in New Jersey ground waters has not been determined. The standard cold-vapor atomic-absorption-spectrometry protocol is not sufficiently sensitive to measure aqueous mercury concentrations below the method detection limit of 0.1 microgram per liter (ug/L). Pristine surface waters analyzed with more sensitive techniques have approximately 1 to 5 ng Hg/L. The low mercury concentrations in the sediments of the Kirkwood-Cohansey aquifer system, together with the low solubility and high particle reactivity of mercury, indicate that ground water in the aquifer system exceeding 10 ng Hg/L is probably contaminated.

INTRODUCTION

The heavy metal mercury (Hg), like many other heavy metals, is dispersed in various components of the environment in different chemical and physical forms. Its properties and interactions with its surroundings determine its transport, transformations, removal mechanisms, and volatility. Mercury is introduced into the environment by a variety of complex natural processes and by human activities.

Mercury, exceeding the 2-microgram-per-liter (ug/L) maximum contaminant level (MCL) set by State and Federal potable water standards, has been detected in water samples obtained from domestic wells in many municipalities throughout southern and southeastern New Jersey. The widespread geographic distribution of this aqueous mercury in the Cohansey Sand of the New Jersey Coastal Plain (fig. 1) and the lack of well-defined point sources has led some in the New Jersey Department of Environmental Protection and Energy (Steve Spayd, written communication, 1990; Robert Richards, oral communication, 1990) to conclude that this represents a natural lithogenic contaminant source. Determining whether mercury in the Kirkwood-Cohansey aquifer system principally results from lithogenic (natural) or anthropogenic (man-made) inputs has a significant bearing on the course of action to be implemented by the State.

Geochemical and lithologic factors affecting aqueous mercury concentrations in the surficial Kirkwood-Cohansey aquifer system are briefly discussed herein. Owing to the complexity of natural systems and scientific and technical constraints, a complete description of the mercury chemistry in the natural environment is not feasible at this time.

Acknowledgments

I thank Drs. Gary E. Glass (U.S. EPA), John Sorensen and George R. Rapp, Jr. (Univ. of Minnesota), Jay H. Lehr (Association of Ground Water Scientists and Engineers), Gary A. Gill (Univ. of Calif., Santa Cruz), Robert P. Gambrell (Louisiana State Univ.), and Julia Barringer (U.S. Geological Survey) for their thorough and very constructive review of the initial manuscript. I. G. (Butch) Grossman (NJ. Geological Survey, NJGS) made editorial improvements. Appreciation is extended to Doreen Hogan (NJGS) for formatting the tables. Dr. Karl W. Muessig (NJGS) encouraged and supervised this study.

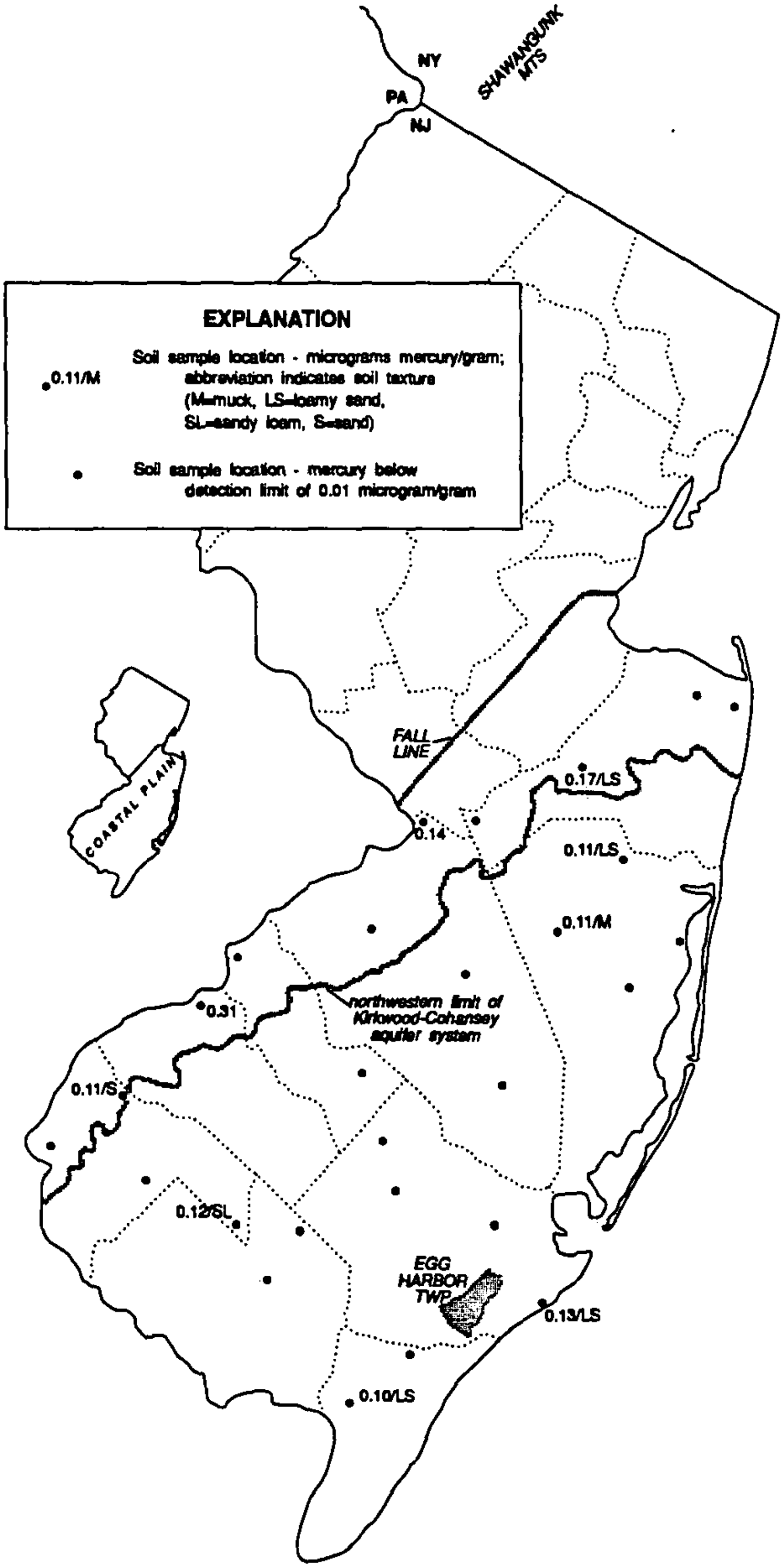

Figure 1. - Location of the New Jersey Coastal Plain, outcrop area of the Kirkwood-Cohansey aquifer system, and soil-sample sites.

GEOLOGY AND MINERALOGY OF MERCURY

Geochemically, mercury is a chalcophile element; that is, it tends to concentrate in sulfide minerals and ores (table 1). It is generally associated with syngenetic and epigenetic base-metal (for example lead, zinc, copper) sulfide/sulfosalt and noble metal (for example silver, gold, platinum) epithermal deposits. Epithermal deposits are hydrothermal mineral deposits formed in the temperature range of 50°-200° C near (that is within ~1 km of) the Earth's surface (Park and MacDiarmid, 1975, p. 215). Epigenetic deposits are emplaced during active tectonic events as late-phase products of igneous or metamorphic activities (Park and MacDiarmid, 1975; Varekamp and Buseck, 1984). Hydrothermal systems currently depositing epithermal mercury are the Sulphur Bank deposits in the Coast Ranges of northern California (White, 1981) and the Morgan Hot Springs, California (Varekamp and Buseck, 1983). Deposition of mercury ores from a hydrothermal system requires a) a source rock rich in mercury, b) high mercury solubility throughout a wide range of temperatures and fluid compositions, and c) low mercury solubility within a restricted range of conditions (Varekamp and Buseck, 1984).

Although mercury deposits occur in all types of rocks, the geologic environments that typically host mercury deposits are totally unlike those in the New Jersey Coastal Plain. Sedimentary rocks, particularly sandstone and limestone of Paleozoic to Recent age, host many of the larger economic deposits (Jonasson and Boyle, 1972). Ninety-five percent of the sedimentary-hosted mercury deposits are between Mesozoic and Recent in age (Moiseyev, 1971). Most mercury deposits occur in zones marked by deep faulting and shearing (Jonasson and Boyle, 1972). These active tectonic regimes are commonly distinguished by volcanic or geothermal activity. Additionally, because mercury deposits are largely confined to subduction and volcanic zones near convergent plate margins, some mercury mineralization occurs in or near serpentinites associated with ophiolites (Henderson, 1969; Barnes and others, 1973).

Extreme care should be exercised when interpreting mercury abundance data for geologic media. In addition to anthropogenic inputs of mercury, sampling, sample preservation and preparation, artifacts of sample analyses, and inherent limitations of the analytical instrumentation bias much of the data reported in the literature to the high side, because mercury contamination of samples and anthropogenic mercury typically are not differentiated from lithogenic mercury. Furthermore, elevated mercury concentration is an exploration tool for ore mineralization (Varekamp and Buseck, 1983; 1984) and reporting of elevated concentrations found in exploration inflates reported values for certain rock types and minerals.

Worldwide, sedimentary and metasedimentary rocks not mineralized with mercury-bearing fluids typically contain less than 100 ng Hg/g (table 2). Sandstones, which consist mainly of quartz, and limestones, which consist principally of calcite, have mean mercury concentrations of 2.5 to 110 ng/g (Mitra, 1986; Wedepohl, 1991) and 6 to 40 ng/g (Mitra, 1986; Jonasson and Boyle, 1972), respectively. "Normal range" mercury concentrations of quartz and calcite are 10 to 2,000 and 10 to 20,000 ng/g, respectively (table 1). Evidently the lower mercury concentrations in the quartz and calcite in table 1 typify normal background concentrations for sandstones and limestones (table 2) in regions not mineralized with mercury. Presence of minerals with mercury concentrations exceeding approximately 100 ng/g demonstrates direct influence by mercury-bearing fluids. Examples include the aforementioned sandstone- and limestone-hosted mercury deposits and the associated rock-alteration zones in these host rocks.

The New Jersey Coastal Plain (fig. 1) consists of a wedge of Cretaceous to Quaternary siliciclastic sediments deposited on a passive continental margin after the Triassic rifting of the Atlantic Ocean. Although basaltic volcanics are found in the underlying rift zone, no volcanism is known in the Coastal Plain sedimentary wedge. With regard to the rifting, Jonasson and Boyle (1972) pointed out that after "a very thorough search of the literature ... there simply is no published data available for mercury in geological materials from anywhere in the Rift zones." No published data show elevated mercury in the Triassic-Jurassic rift basins of the Middle Atlantic States or in the basalt and diabase of this rift system (table 3). The worldwide mean for basic intrusive rocks (such as diabase) is 28 ng Hg/g. The range is from 5 to 84 ng Hg/g. For basic extrusive rocks (such as basalt) the mean is 20 ng Hg/g, and the range from 5 to 40 ng Hg/g (table 2, Jonasson and Boyle, 1972).

Mineralogically, most mercury deposits are simple. They consist of cinnabar or metacinnabar (both HgS) or both, along with one or more of the following: native mercury, pyrite, stibnite, real-

Table 1. - Mercury Concentration of Some Common Ore and Gangue Minerals in the World

Mineral	Composition	*Normal Range (ppm) Limits	**Highest Reported Content (%)
tetrahedrite	$Cu_{12}Sb_4S_{13}$	10 - 1,000	17.6; 21
grey copper ores	$(Cu,As,Sb)_xS_y$	5.0 - 500	14
sphalerite	ZnS	0.1 - 200	1
wurtzite	ZnS	0.1 - 200	0.03
stibnite	Sb_2S_3	0.1 - 150	1.3
realgar	AsS	0.2 - 150	2.2
pyrite	FeS_2	0.1 - 100	2
galena	PbS	0.04 - 70	0.02
chalcopyrite	$CuFeS_2$	0.1 - 40	—
bornite	Cu_5FeS_4	0.1 - 30	—
bournonite	$PbCuSbS_3$	0.1 - 25	—
chalcocite	Cu_2S	0.1 - 25	—
marcasite	FeS_2	0.1 - 20	0.07
pyrrhotite	$Fe_{1-x}S$	0.1 - 5	—
molybdenite	MoS_2	0.1 - 5	—
arsenopyrite	$FeAsS$	0.1 - 3	—
orpiment	As_2S_3	0.1 - 3	—
native gold	Au	1.0 - 100	60
native silver	Ag	1.0 - 100	30
barite	$BaSO_4$	0.2 - 200	0.5
cerussite	$PbCO_3$	0.1 - 200	0.1
dolomite	$CaMg(CO_3)_2$	0.1 - 50	—
fluorite	CaF_2	0.01 - 50	0.01
calcite	$CaCO_3$	0.01 - 20	0.03
aragonite	$CaCO_3$	0.01 - 20	3.7
siderite	$FeCO_3$	0.01 - 10	0.01
chalcedony and opaline silicas	$SiO_2.nH_2O$	0.01 - 10	—
quartz	SiO_2	0.01 - 2	—
pyrolusite	MnO_2	1.0 - 1,000	2
hydrated iron oxides	$Fe_2O_3.nH_2O$	0.10 - 500	0.2
graphite	carbon	0.5 - 10	0.01
coal	—	0.05 - 10	2
gypsum	$CaSO_4.2H_2O$	0.01 - 4	—

* "Normal range of mercury content" recorded in this column has been selected after assessment of the world literature and represents the most often reported data for mercury content of these minerals from deposits of all types.

** "Highest reported content", given in percentage mercury, is not necessarily the highest possible as may be defined by principles of isomorphous substitution or of solid solution formation, but is the highest figure reported in the literature available to the authors. In general, these levels are only achieved when the mineral in question co-exists in a deposit with cinnabar, metacinnabar or other mercury minerals. Highest reported contents of less than 0.01 percent are not recorded.

(From Jonasson and Boyle, 1972.)

Table 2. - Mercury in rocks of the world in ng/g (ppb).

Joensuu (1971), Jonasson and Boyle (1972), and McNeal and Rose (1974) express data as arithmetic means; Connor and Shacklette (1975) use geometric means; National Academy of Sciences (1978), Mitra (1986) and Wedepohl (1991) report averages. Mitra (1986) cites data on mercury in rocks from Sweden listed in Ferm and Larsson (1973). Last reference (in Swedish) was unavailable for this study.

Facies	Mean or Average	Range	Reference
		IGNEOUS	
Ultramafic (kimberlites, dunite)	—	5-20[a]	U.S. Geological Survey, 1970
	168	7-250	Jonasson and Boyle, 1972
	100[b]	4-500	National Academy of Sciences, 1978
Mafic (basaltic, gabbroic)	28/20[c]	5-84	Jonasson and Boyle, 1972
	50	2-500	National Academy of Sciences, 1978
	3.9	0.2-17.7	Mitra, 1986
	20[b]	—	Wedepohl, 1991
Intermediate (andesite, diorite)	38/66[c]	13-200	Jonasson and Boyle, 1972
	5.0	0.4-19.7	Mitra, 1986
Granitic, rhyolitic	—	15-100[d]	U.S. Geological Survey, 1970
	62	2-200	Jonasson and Boyle, 1972
	14	< 10-740	Connor and Shacklette, 1975
	60	5-400	National Academy of Sciences, 1978
	3.5	1.4-281	Mitra, 1986
	30	—	Wedepohl, 1991
Alkali-rich rocks	450	40-1400	Jonasson and Boyle, 1972
		METAMORPHIC	
Granulites	20[b]	—	Wedepohl, 1991
Amphibolites	50	30-90	Jonasson and Boyle, 1972
Quartzite	53	10-100	Jonasson and Boyle, 1972
Gneisses	—	20-200[e]	U.S. Geological Survey, 1970
	50	25-100	Jonasson and Boyle, 1972
	28[f]	2-250[f]	McNeal and Rose, 1974
Schists	100	10-1000	Jonasson and Boyle, 1972
Hornfels	225	35-400	Jonasson and Boyle, 1972
Marble/dolomite	50	10-100	Jonasson and Boyle, 1972
		SEDIMENTARY	
Shales	—	100-1000[g]	U.S. Geological Survey, 1970
	67	5-300	Jonasson and Boyle, 1972
	23	0.4-53	McNeal and Rose, 1974
	45	< 10-190	Connor and Shacklette, 1975
	90	5-510	National Academy of Sciences, 1978
	5.9	0.9-33.5	Mitra, 1986
	450[b]	—	Wedepohl, 1991
Black shale	437	100-3250	Jonasson and Boyle, 1972
	340	< 40-1500	Connor and Shacklette, 1975
	500	30-2800	National Academy of Sciences, 1978
	234	31.9-340	Mitra, 1986
Sandstones, arkose, graywacke	—	20-75	U.S. Geological Survey, 1970
	55	< 10-300	Jonasson and Boyle, 1972
	7	0.7-18	McNeal and Rose, 1974
	16	< 10-150	Connor and Shacklette, 1975
	50	1-300	National Academy of Sciences, 1978
	2.5	0.8-6.0	Mitra, 1986
	110	—	Wedepohl, 1991
Limestones	—	15-50	U.S. Geological Survey, 1970
	40	< 10-220	Jonasson and Boyle, 1972
	9	4-14	McNeal and Rose, 1974
	28	< 10-170	Connor and Shacklette, 1975
	40	10-220	National Academy of Sciences, 1978
	6.0	0.8-31.2	Mitra, 1986
	30	—	Wedepohl, 1991
Phosphorites	120[b]	—	Jonasson and Boyle, 1972
	50	1-500	National Academy of Sciences, 1978
Evaporites	25[i]	< 10-60	Jonasson and Boyle, 1972
	30[j]	20-200	Jonasson and Boyle, 1972
Coals	—	10-1000	U.S. Geological Survey, 1970
	—	10-3000	Fleischer, 1970
	3300	70-33000	Joensuu, 1971
	—	10-300000[k]	Ruch and others, 1971
	—	20-1600	Jonasson and Boyle, 1972
	300[l]	50-13300[l]	National Academy of Sciences, 1978

a. Includes basalts.
b. Estimated.
c. First number represents intrusives, the second, extrusives.
d. Includes andesite.
e. Mercury in metamorphic rocks as a whole.
f. Values represent a suite of 23 samples of Precambrian gneisses and schists from the Reading Prong (Pa.). Values in table 2 are estimated from figure 3, page 1775 in McNeal and Rose, 1974.
g. Presumed to include black shales.
h. Composite samples.
i. Anhydrite and gypsum.
j. Halite, sylvite, etc.
k. 300,000 ppb mercury in coal from mercuriferous zone.
l. Ash.

Table 3. - Geologic and hydrogeologic units of Triassic to Quaternary age in New Jersey (from New Jersey Geological Survey, 1990).

Era	System	Series	Stratigraphic unit			Predominant lithology	Aquifer name or hydrogeologic characteristics
CENOZOIC	Quaternary	Holocene	alluvial, coastal, marsh, and eolian deposits			sand, gravel, silt, mud, and peat	Under water-table conditions at most locations
		Pleistocene	COASTAL AREAS Wisconsinan alluvium, Cape May Formation, colluvium	INLAND, NORTHERN NEW JERSEY Wisconsinan and pre-Wisconsinan alluvial, colluvial, glacial, lacustrine, and eolian deposits		sand, gravel, silt, clay (statewide), till and till-like deposits (northern New Jersey)	Includes glacial buried-valley aquifers and Cape May aquifer system/Holly Beach aquifer
	Tertiary	Miocene	Pensauken Formation			sand, clayey silt	Under water-table conditions at most locations
			Bridgeton Formation				
			Beacon Hill Gravel			gravel, sand	
			Cohansey Sand			sand, some clayey silt	Kirkwood-Cohansey aquifer system
			Kirkwood Formation			sand, gravel, clayey silt	confining unit Rio Grande water-bearing zone confining unit Atlantic City 800-foot sand
		Oligocene	ACGS beta unit			sand, some glauconitic sand	composite confining unit Piney Point aquifer
			Mays Landing unit				
		Eocene	Shark River Formation			clayey silt, fine quartz sand, glauconitic sand	
			Manasquan Formation				
		Paleocene	Vincentown Formation			sand, clayey silt, glauconite sand, calcarenite	Vincentown aquifer
			Hornerstown Formation			glauconitic sand	
MESOZOIC	Cretaceous	Upper Cretaceous	Tinton Sand			sand, glauconitic sand	
			Red Bank Sand			sand, clayey silt, some glauconite sand	Red Bank Sand
			Navesink Formation			glauconite sand	
			Mount Laurel Sand			sand	Wenonah-Mount Laurel aquifer
			Wenonah Formation			silty sand, some glauconite	Marshalltown-Wenonah confining unit
			Marshalltown Formation			clayey silt, glauconitic sand	
			Englishtown Formation			sand, clayey silt	Englishtown aquifer system
			Woodbury Clay			clayey silt	Merchantville-Woodbury confining unit
			Merchantville Formation			clayey silt, glauconitic sand	
			Magothy Formation			sand, clayey silt	Potomac-Raritan-Magothy aquifer system upper aquifer confining unit
			Raritan Formation				middle aquifer
		Lower Cretaceous	Potomac Group			gravel, sand, silt, clay	confining unit lower aquifer
	Jurassic	Lower Jurassic	Newark Supergroup	Brunswick Group	Boonton Formation	sandstone, siltstone, shale, conglomerate	Ground water occurs along bedding surfaces, joints, faults, intergranular spaces, and other openings
					Hook Mountain Basalt	basalt	
					Towaco Formation	sandstone, siltstone, shale, conglomerate	
					Preakness Basalt	basalt, intercalated sedimentary rock	
					Feltville Formation	sandstone, siltstone, shale, conglomerate, limestone	
					Orange Mountain Basalt diabase intrusives	basalt diabase	
	Triassic	Upper Triassic			Passaic Formation	sandstone, siltstone, shale, conglomerate	
				Lockatong Formation		siltstone, mudstone, sandstone, shale	
				Stockton Formation		arkosic sandstone, siltstone, shale, conglomerate	

gar, native sulfur, quartz, fluorite, and carbonates (Ozerova, 1962; Moiseyev, 1971). The mercury-mineralized zones are invariably veins, stockworks, impregnations or replacement lodes (Jonasson and Boyle, 1972).

Mercury is seldom incorporated into the crystal lattice of most common minerals. Theoretically, trace quantities can be incorporated into the crystal structures of the common minerals, either by isomorphous replacement (ionic substitution) of major (abundant) elements, or by random inclusion in the voids of a crystal lattice (Krauskopf, 1967). The amount of mercury accommodated in mineral structures depends on atomic characteristics of the mercurous (Hg^{+}) and mercuric (Hg^{+2}) ions. Electronegativity (which affects bonding character), valence, and the large ionic radius of the mercurous and mercuric ions contribute to mercury's incompatibility with common mineral lattices. Mercury, like beryllium, copper, and uranium, is capable neither of forming its own high-temperature minerals nor of substituting appreciably for common elements and many other trace elements in silicate structures. Instead it is concentrated in residual solutions that generate pegmatites and sulfide veins (Krauskopf, 1967). A detailed discussion of the distribution of elements in minerals is in Krauskopf (1967, p. 575-597).

LITHOGENIC (NATURAL) OCCURRENCE OF MERCURY

The Kirkwood-Cohansey aquifer system (table 3), from which elevated mercury concentrations have been reported (NJDEP, 1989), is a water-table and semi-confined aquifer system with an extremely low acid-buffering capacity. Quartz sand makes up more than 95 percent of the Cohansey Sand; muscovite, plagioclase, potash feldspar, perthite, and chert total another 1 to 2 percent. A very fine to fine sand-size suite of heavy minerals consisting of abundant aluminosilicates (sillimanite, kyanite, andalusite, staurolite) and ilmenite along with lesser amounts of zircon, rutile, leucoxene, magnetite and tourmaline make up another 1 to 2 percent (Markewicz, 1969; Carter, 1972; Owens and others, 1988). Local concentrations of these heavy minerals may be as high as 50 percent (Carter, 1972). Table 4 lists the heavy minerals and associated trace minerals in the Cohansey Sand, their general chemical composition, and the minor and trace elements commonly associated with them.

The various minerals that constitute the Cohansey Sand are not known to contain substantial quantities of mercury. Although certain heavy minerals may contain trace amounts, crystal lattices of the minerals in table 4 do not easily accommodate mercury ions. Mercury in minerals with lattice structures that are incompatible with substitution may be surficially complexed, occupy fluid inclusions, occupy exsolution lamellae, or be incorporated into imperfections in the lattice by diffusion or precipitation. Therefore, if the minerals of the Kirkwood-Cohansey aquifer system contain lattice-bound mercury, it would be expected only in ultra-trace to trace amounts. Even if traces of lattice-bound or incorporated mercury are present, they would not likely have been released into the environment. Carter (1972, p. 160) observed that the heavy minerals of the Kirkwood Formation and Cohansey Sand "appear very fresh and unaltered, without corroded borders or ragged, irregular ends" and that most of the aluminosilicates (that is sillimanite and kyanite) are unaltered by chemical weathering. There is no preferential leaching or incongruent dissolution which would release covalently bonded, lattice-bound mercury or mercury in fluid inclusions, exsolution lamellae, or lattice imperfections from these resistates. These observations, confirmed by ongoing studies of the New Jersey Geological Survey, suggest that the heavy minerals are not a potential source of the mercury.

The only mineral reported to contain mercury in the New Jersey Coastal Plain is glauconite, a hydrous aluminosilicate containing ferric iron (Fe^{+3}) and potassium (table 4). Glauconite is virtually absent from the Kirkwood-Cohansey aquifer system, but abundant in several underlying formations (table 3). Trace-element analyses of glauconite (commonly called greensand) from the Navesink and Hornerstown Formations show mercury concentrations of 0.02 ppm (Navesink Formation) and 0.05 ppm (Hornerstown Formation) (analyzed in 1984 by Skyline Labs, Inc.; written communication, Inversand Company, Clayton, New Jersey, 1985). The absence of glauconite in the sediments of the Kirkwood-Cohansey aquifer system is largely a result of the deposition of these sediments in a paralic to marginal marine sedimentary environment which differs from the marine

Table 4. - Heavy minerals in the sand/silt fraction of the Cohansey Sand.

(Markewicz, 1969; Carter, 1972; Owens and others, 1988; Uptegrove and others, 1991; F.L. Muller, New Jersey Geological Survey, oral communication, 1991). Mineral formulas and associated trace elements listed for glauconite are from Deer and others, 1979. Trace elements listed for glauconite are from analyses of glauconites from the New Jersey Coastal Plain supplied by the Inversand. Company (written communication, 1985).

Mineral	Formula	Trace Elements
Actinolite	$Ca_2(Mg,Fe^{+2})_5\,[Si_8O_{22}](OH, F)_2$	—
Andalusite	$Al_2O[SiO_4]$	Ti, Fe, Mn, Mg, Ca, Na
ChloriteGroup	$(Mg, Al, Fe)_{12}[(Si, Al)_8O_{20}](OH)_{16}$	Mn, Cr, Ni, Ti
Diopside	$Ca, Mg[Si_2O_6]$	Ti, Al, Cr, Ni, Zn
Enstatite (pyroxene)	$Fe, Mg(SiO_3)$	Al, Ca, Mn, Fe^{+3}, Ti, Cr, Ni
Epidote Group	$X_2Y_3Z_3(O,OH,F)_{13}$ where: $X = Ca, Ce^{+3}, La, Y, Th, Fe^{+2}, Mn^{+2}, Mn^{+3}$ $Y = Al, Fe^{+3}, Mn^{+3}, Fe^{+2}, Mn^{+2}, Ti$ $Z = Si, Be$	Pb, Sr, Cr
Garnets	$(Ca, Mg, Mn, Fe^{+2})_3(Al, Cr\,[Fe^{+3}, Ti])_2Si_3O_{12}$	Y, Na, K, Sc
Hornblende Group	$(Ca, Na, K)_{2\text{-}3}(Mg, Fe^{+2}, Fe^{+3}, Al)_5[Si_6(Si, Al)_2O_{22}](OH,F)_2$	Ti, Cr
Ilmenite	$(Fe^{+2}, Mg, Mn)TiO_3$	Cr, Ni, U
Kyanite	$Al_2O[SiO_4]$	Ti, Fe, Mn, Mg, Ca, Na, Cr
Magnetite	$Fe^{+2}Fe^{+3}{}_2O_4$	Ti, Al, Mg, Ca, Mn, Ni, Co, Zn
Monazite	$(Ce, La, Th)PO_4$	U, Al, Fe, REEs*(Nd), Pb, Zr, Be, Sn, Ca, Mg, Mn
Rutile	TiO_2	Nb, Ta, Fe^{+2}, Cr, U
Sillimanite	$Al_2O[SiO_4]$	Ti, Mg, Ca, Fe
Sphene	$CaTiSiO_5$	Na, REEs*, Al, Nb, F, Cr, Sn, Zr, Pb, Sr, U, Cu, Ga, Ta, Ba, Mn, Mg
Staurolite	$(Fe^{+2}, Mg)_2(Al, Fe^{+3})_9O_6[SiO_4]_4(O,OH)_2$	Zn, Co, Ni
Tourmaline Group	$Na, (Mg, Fe, Mn, Li, Al)_3Al_6[Si_6O_{18}](BO_3)_3(OH, F)_4$	Cr, Ti, U
Zircon	$Zr[SiO_4]$	Hf, Th, U, P, Na, Al, K, Mg, Mn, Ca, REEs*, Fe, Sn, Nb, Y, Ti, Ga, Ag, Cu, U, Ba, Sr, B, Pb
Associated Minerals in the Cohansey Sand		
Chert	SiO_2	Li, Na
Feldspar Group	$Na, K[AlSi_3O_8]\text{-}Ca[Al_2Si_2O_8]$	Ti, Fe^{+3}, Fe^{+2}, Mn, Mg, Ba, Sr
Glauconite	$(K, Na, Ca)_{1.2\text{-}2.0}(Fe^{+3}, Al, Fe^{+2}, Mg)_{4.0}$ $[Si_{7\text{-}7.6}Al_{1\text{-}0.4}O_{20}](OH)_4\cdot n(H_2O)$	Ti, Cu, Pb, Cd, Co, Ni, Cr, Mo, F, Hg, U
Muscovite	$K_2Al_4[Si_6Al_2O_{20}](OH,F)_4$	Na, Rb, Cs, Ca, Ba, Mg, Fe^{+2}, Fe^{+3}, Mn, Li, Cr, Ti, U

* REE = rare earth elements (lanthanide series)

environment in which the Navesink and Hornerstown Formations were deposited.

Where glauconite occurs in the Coastal Plain sediments, it could directly affect their aqueous mercury content. In an investigation of the contaminant-removing capabilities of glauconite, Spoljaric and Crawford (1978; 1979) filtered a sample of Pigeon Point landfill leachate (pH 7.65) containing 8.7 ug Hg/L to achieve a reduction to below the 0.04 ug Hg/L method detection limit (MDL). Many other aqueous heavy metals were removed as well. The effectiveness of glauconite in removing aqueous heavy metal cations suggests that glauconite strongly and effectively adsorbs ionic mercury species throughout a wide range in pH from 3.0 to 10.5 (Spoljaric and Crawford, 1978; 1979). Therefore glauconite should act as a sink for mercury and other heavy metals, maintaining the naturally low levels of mercury in the glauconite-rich aquifers underlying the Kirkwood-Cohansey aquifer system.

A hydrogeologic investigation of aqueous mercury contamination in the Pleasant Wood section of Egg Harbor Township, Atlantic County (fig. 1) revealed 69 ng Hg/g in clay from a lens occurring 76 to 78 feet below land surface (NJDEP, 1989, p. 6). This concentration is exceptional; 11 other sediment samples from various depths in five monitor wells were reported as "non detect" (NJDEP, 1989, Table 1). No method detection limit (MDL), analytical methodology and protocol, and quality assurance/quality control (QA/QC) data are described in the report so that these data cannot be adequately evaluated. Table 2 shows that the 69 ng Hg/g in the clay is close to the arithmetic mean of 67 ng Hg/g for shales, falls within the range of <10 to 190 ng Hg/g for United States shales, and is high compared to the arithmetic mean of 23 ng Hg/g and range of 0.4 to 53 ng Hg/g for Pennsylvania shales. The 69 ng Hg/g from Pleasant Woods may represent a glauconite grain that contains both natural, lattice-bound and anthropogenic (complexed) mercury.

The mineralogy of the Cohansey sediments suggests that the sediments of the Coastal Plain were derived from deeply weathered igneous and metamorphic rocks of granitic composition. The ancestral Delaware and Schuylkill Rivers eroded crystalline rocks of the Piedmont, igneous and metamorphic rocks of the New Jersey Highlands, Triassic and Jurassic red beds, diabase and basalt, and sedimentary rocks of the Appalachians. The resulting sediments were subsequently deposited as the Cohansey Sand (Markewicz, 1969). Carter (1972) presents strong evidence that the ancestral Hudson River was a principal source of the Cohansey sediments.

Unfortunately, no site-specific data on the mercury content of the Cohansey minerals are known. A study of the geochemistry of mercury in sedimentary rocks of Pennsylvania (McNeal and Rose, 1974) showed that the mean mercury concentrations of 11 sandstone samples and 10 shale samples were 7 ng/g and 23 ng/g, respectively. The 7 ng Hg/g is close to the 5 ng Hg/g for sandy (presumably quartz) sediments from the Lake Superior side of Minnesota Point, Minnesota (Glass and others, 1990). It is highly probable that the natural background (mineralogic) concentration of mercury in the Cohansey Sand averages less than 10 ng/g.

Fields and others (1991), reporting on selected soil constituents and contaminants at more than 2 dozen sites in central and southern New Jersey (fig. 1) provide data that support the conclusion that the natural mercury concentration in the New Jersey Coastal Plain is very low. Of 17 homogenized 12-inch core samples of soils overlying the Kirkwood-Cohansey aquifer system or derived from the Kirkwood Formation and Cohansey Sand, 12 had less than 10 ng Hg/g (the method detection limit). The remaining 5 soil samples ranged from 100 to 130 ng/g total mercury (fig. 1). Two of the 5 soil samples, that is, the 110 ng Hg/g loamy sand from northern Ocean County and the 130 ng Hg/g loamy sand from Atlantic City in Atlantic County are "disturbed soil" (Fields and others, 1991). They define disturbed soil as one that "indicates that the native soil profile was not present" and "... does not necessarily imply that contamination has occurred." Linear regression analysis for the 5 soils with measurable mercury concentration versus moisture, percent organic carbon, soil pH, cation exchange capacity (CEC), and sand/silt/clay content only yields a strong correlation ($r = 0.79$ and $r^2 = 0.61$) with soil pH. No significant correlation between soil mercury and soil pH was found when all 17 soil samples were used in the calculation.

Why are these 5 soils enriched in mercury relative to the other 12 soils? The data in Fields and others (1991) are inadequate to answer this question. Mercury in selected soils from New Jersey (Fields and others, 1991) was analyzed employing an aqua regia (3 volumes of 12M HCl and 1 volume of 16M HNO_3) extraction/cold-vapor atomic-absorption-spectrometry (CVAAS) protocol (U.S. EPA, 1979). Dr. Wen Yuan, analytical chemist at Rutgers University, who made the analyses, reported that very poor and variable recovery of mercury spikes, and unspecified interferents adversely affected data quality (oral commun., 1991). Interferences from some volatile organics, chlorine, and sulfur compounds are an inherent limitation of the standard CVAAS procedure. Therefore the 110 ng Hg/g average for the five soil samples from the Coastal Plain (Fields and others, 1991) may be due in part to errors associated with the analytical methodology and mineralogical differences which affect the effi-

Table 5. - Mercury concentration in soils of the world in ng/g (ppb)

Jonasson and Boyle (1972), World Health Organization (1976), Frank and others (1979), McKeague and Wolynetz (1980), and Phelps and Buseck (1980) express data as arithmetic means whereas Connor and Shacklette (1975), Ebens and Shacklette (1982), and Shacklette and Boerngen (1984) report geometric means. Fields and others (1991) use arithmetic and geometric means.

Soil	Mean	Range	Reference
Background surface soils	70	20-150	Jonasson and Boyle, 1972
	60	10-700	Frank and others, 1979
	60[a]	5-100	McKeague and Wolynetz, 1980
	20[b]	----	Phelps and Buseck, 1980
	58/89[c]	< 10-4600	Shacklette and Boerngen, 1984
	20/70[d]	< 10-260	Fields and others, 1991
	180[e]	< 10-2710[f]	Fields and others, 1991
Tills, glacial clays and sand	50	20-100	Jonasson and Boyle, 1972
BACKGROUND SOIL HORIZONS			
A horizon	161[g]	60-200	Jonasson and Boyle, 1972
	21[h]	10-70	Ebens and Shacklette, 1982
	20[i]	10-60	Ebens and Shacklette, 1982
B horizon	89[g]	30-140	Jonasson and Boyle, 1972
	96/55[j]	< 10-4600	Connor and Shacklette, 1975
	22[h]	< 10-90	Ebens and Shacklette, 1982
C horizon	96[g]	25-150	Jonasson and Boyle, 1972
	25[h]	10-160	Ebens and Shacklette, 1982
	20[i]	< 10-60	Ebens and Shacklette, 1982
SOIL HORIZONS NEAR MERCURY DEPOSITS			
A horizon	480	200-1860	Jonasson and Boyle, 1972
	---	< 1- > 10000	Phelps and Buseck, 1980
B horizon	275	140-605	Jonasson and Boyle, 1972
C horizon	262	150-554	Jonasson and Boyle, 1972
SOILS IN MUNICIPALITIES			
Pittsburgh, Pa.			
urban ----------	640	110-2100	World Health Organization, 1976
rural ----------	90	0-740	World Health Organization, 1976
Washington, D.C.			
urban ----------	480	70-7800	World Health Organization, 1976
rural ----------	160	30-1100	World Health Organization, 1976
Pittsfield, Ma.			
urban ----------	330	110-2500	World Health Organization, 1976
rural ----------	170	70-270	World Health Organization, 1976

a. Whole-soil profiles for podzols and sandy soils of Canada.

b. Mean background concentration of mercury more than 1 km from known thermal features in Yellowstone National Park, Wyoming.

c. First value is the geometric mean, the second is an estimated arithmetic mean for 1267 soil samples from the conterminous United States.

d. First value is the geometric mean, the second is the arithmetic mean for suburban (n = 20) and rural (n = 33) soils throughout New Jersey.

e. Arithmetic mean for soil samples (n = 72) from top 12 inches of soils in New Jersey.

f. 2170 ppb mercury is from a "disturbed soil" which Fields and others (1991) state "does not necessarily imply that contamination has occurred." "Disturbed soil" indicates that the native soil profile was not present (Fields and others, 1991).

g. Examples from Clyde Forks area, Ontario, Canada.

h. Powder River Basin, Wyoming and Montana (n = 64).

i. San Juan Basin, New Mexico (n = 47).

j. First value is the geometric mean (n = 420) for the eastern United States, the second for the western United States (n = 492).

ciencies of the aqua regia extractions (Belzile and others, 1989). The aqua regia extractable mercury may be anthropogenically enriched due to sorption and precipitation phenomena rather than natural.

Table 5 is a compilation of means and ranges of mercury concentrations in soils of the world. Note that the mean concentrations are 2 to 7 times higher in urban areas than in rural ones, illustrating the significant effects of anthropogenic inputs. Composite soil samples from 55 rural and suburban sites in New Jersey yield a 20 ng Hg/g geometric mean and a 70 ng Hg/g arithmetic mean (Fields and others, 1991), consistent with mercury concentrations in background surface soil reported by others.

The United States Geological Survey maintains a surface-water monitoring network for New Jersey which provides records of various surface-water and stream-sediment characteristics. Mercury data for suspended and bottom sediments are reported as "total recoverable" and "recoverable from bottom material," respectively, and as "dissolved" in water (Bauersfeld and others, 1990a; 1990b). Bauersfeld and others (1990a) define these terms as:

1. **total recoverable** is the amount of a given constituent that is in solution after a representative water-suspended sediment sample has been digested by a method (usually using a dilute acid solution) that results in dissolution of only readily soluble substances. Complete dissolution of all particulate matter is not achieved by the digestion treatment, and thus the determination represents something less than the "total" amount (that is, less than 95 percent) of the constituent present in the dissolved and suspended phases of the sample.
2. **recoverable from bottom material** is the amount of a given constituent that is in solution after a representative sample of bottom material has been digested by a method (usually using an acid or mixture of acids) that results in dissolution of readily soluble substances. Complete digestion of all bottom material is not achieved by the digestion treatment.
3. **dissolved** refers to that material in a representative water sample which passes through a 0.45-um membrane filter. Determinations of "dissolved" constituents are made on subsamples of the filtrate.

For that part of the New Jersey Coastal Plain occupied by the Kirkwood-Cohansey aquifer system, the total recoverable mercury from water-suspended sediments ranges from <0.1 to 0.2 ng/g. In fact, the mercury concentrations of the suspended sediments in 3 of 5 river systems of the Coastal Plain are below the 0.1 ng Hg/g MDL. Water-suspended sediments in the other 2 river systems, the Cohansey River at Sealy and the Shark River near Neptune City, contain 0.1 and 0.2 ng Hg/g, respectively. Mercury concentrations from the "recoverable from bottom material" fraction are 20 ng/g for Marsh Bog Brook at Squankum and Great Egg Harbor River near Blue Anchor, and 40 ng/g for Hammonton Creek at Wescoatville. The corresponding concentration in water-suspended sediments for these particular river systems is less than the 0.1 ng Hg/g MDL. The dissolved mercury concentrations in three river systems of the New Jersey Coastal Plain typically are less than the 0.1 ug Hg/L MDL. A 1.0 ug Hg/L maximum for the river systems sampled was reported for Toms River near Toms River (Bauersfeld and others, 1990b).

These data on mineralogy, soil, and stream sediment support the interpretation that lithologic (natural) sources in the Coastal Plain contribute insignificant quantities of mercury to the Kirkwood-Cohansey aquifer system.

MERCURY CONCENTRATION IN GROUND WATER

Natural fresh water generally contains only ultra-trace levels of mercury (table 6). Recent environmental studies, employing improved in analytical techniques and sample-collection methodologies, demonstrate that background mercury concentrations in unpolluted, natural, fresh, surface water are in the range of 1 to 5 ng Hg/L, that is, 1-5 parts per trillion (ppt) (Fitzgerald and Watras, 1989; Gill and Bruland, 1990; Glass and others, 1990). Accurate quantitative data on the background mercury concentrations of pristine ground water are scarce. Bloom (1989) reports that laboratory tap water from an on-site deep well in Washington State contains an extremely low and constant concentration of 0.3 ng/L total mercury. Empirically pristine, fresh ground water likely has mercury concentrations lower than that of unpolluted surface water in streams, rivers and lakes. This is due, in part, to the high solid-to-liquid ratio in aquifers (Mills and others, 1985).

Elemental mercury and its mercurous and mercuric species are hydrophobic; in other words, mercury is very particle-reactive. Factors influenc-

Table 6. - Mercury concentration in aquatic systems of the world in ng/L (ppt)

Water type	Mean	Range	Reference
Fresh water (lakes, streams, rivers)	30	10-100	Jonasson and Boyle, 1972
	----	1-6	Lindqvist and Rodhe, 1985
	8.2^{a}	5.6-15.6	Robertson and others, 1987
	6.79^{b}	3.3-8.8	Lee and others, 1989
	1.45^{c}	1.15-1.73	Haraldsson and others, 1989
	2.72^{d}	2.34-3.08	Haraldsson and others, 1989
	----	1-3	World Health Organization, 1989
	----	$0.5\text{-}100^{e}$	Gill and Bruland, 1990
	----	$0.9\text{-}3.6^{f}$	Gill and Bruland, 1990
Ground water	----	10-100	Jonasson and Boyle, 1972
	$< 100^{g}$	----	U.S. Environmental Protection Agency, 1980
	0.3^{h}	----	Bloom, 1989
Hydrothermal	2000^{i}	----	White and others, 1970
	----	$< 100\text{-}30000^{j}$	Ohta and Terai, 1971
	1500^{k}	-----	Barnes and others, 1973
	----	$26000\text{-}28000^{l}$	Davey and Van Moort, 1974
	----	$< 10\text{-}26000^{m}$	Nakagawa, 1974
	2600^{n}	----	Weissberg, 1975

All data expressed as a mean are an arithmetic mean.

a. Onondaga Lake, New York.

b. Vertical profile of Lake Soyang, Soyang, Korea with seven depths sampled and analyses performed in duplicate.

c. Lake Vanern, Sweden (n = 6).

d. Lidan (n = 2) and Klaralven (n = 2) Rivers in Sweden.

e. Gill and Bruland studied California freshwater systems ranging from a pristine alpine lake to a system with mercury-contaminated sediments.

f. Great Lakes.

g. 100 ng mercury/L is the method detection limit (MDL) for the cold vapor atomic absorption methodology used in the study.

h. Value represents an unspecified number of mercury determinations
on tap water from an on-site deep well in Sequin, Washington.

i. Amedee Springs, Idaho.

j. Shirane volcano, Gunma Prefecture, Japan in 10 hot springs.

k. Sulfur Bank and Wilbur Springs, California.

l. Ngawha, New Zealand.

m. 55 Japanese hot springs.

n. Champagne Pool, New Zealand.

ing the adsorption of metals are pH, the species (anionic/cationic/neutral) and concentration of adsorbent (for example iron/manganese/aluminum oxides and oxyhydroxides) and competing adsorbates, concentration of complexing ligands, and the concentration and type of organic matter associated with the solid and aqueous phases (Mills and others, 1985). The concept of particle reactivity of a solute is described in terms of the distribution coefficient (K_d) or partitioning coefficient (K_p). The distribution coefficient (K_d) is defined as the ratio of the mass of the solute species adsorbed or precipitated on solids per unit bulk dry mass (S) to the solute concentration in solution (C) (Freeze and Cherry, 1979, p. 403). Therefore:

$$K_d = S/C$$

represents the partitioning of the solute (mercury) between the solid and solution phases and is applicable to equilibrium reactions, such as ion exchange. A detailed discussion of the constraints on, and deficiencies of, the K_d is beyond the scope of this paper.

Little information has been published on K_d values for mercury. The published K_d values range over 7 orders of magnitude. Studies on mercury distribution coefficients for various soil-water systems list K_d ranges of 10.2 to 115.3 (Buchter and others, 1989) and 0.41 to 408 (Rai and Zachara, 1984). Moore and Ramamoorthy (1984, p. 131) report that K_d values for mercury in natural water-suspended solids (< 20 um - 0.45 um) systems are 1.34×10^5 to 1.88×10^5. Calculation of a regional K_d for mercury based on data for mercury in solution and suspended solids (table 2 of Glass and others, 1990) yields 1.18×10^5 ($r^2 = 0.82$). Similarly, Robinson and Shuman (1989) provide data on dissolved mercury and particulate-associated mercury in six streams and rivers in central North Carolina which yield K_d values of 8.68×10^4 and 1.13×10^5 for polluted and background levels of mercury, respectively. Diamond and others (1990), studying the movement of radioisotopes added to lake enclosures, report mean K_p values for Hg^{203} of 3.6×10^5 and 1.3×10^5 for suspended particles and sediment trap, respectively. Partitioning coefficients (K_p) for mercury as a function of suspended solids concentrations in streams are 3 x 10^6 and 2 x 10^5 for 1 and 10 mg/L suspended solids, respectively (Mills and others, 1985, part 1, p. 537).

Apparently the range of mercury K_d values for soil-water systems, $K_d \sim 0.41 - 408$, differs significantly from that for water-suspended solids systems, $K_d \sim 10^5$. William Fitzgerald (University of Connecticut, oral communication, 1990) states that the K_d for mercury probably is closer to 10^6, based on problems associated with the quantification of mercury in various media. To a large extent the physicochemical state in the quartz of the Cohansey Sand is analogous to the water-suspended-solids systems in which the mercury K_d is $\sim 10^5 - 10^6$. The close similarity in quality between ground water of the Cohansey Sand and surface water of the Coastal Plain in such characteristics as total dissolved solids, pH, specific conductance, and some major ions supports this view.

Review of the literature on distribution coefficients shows inconsistency in the expected values of K_d for mercury in the natural environment. The use of distribution coefficients to describe mercury behavior in the environment has not been particularly successful owing to the ease and rate at which mercury interconverts between different chemical forms (Gary Glass, USEPA, written communication, 1991). Based on the fact that mercury speciates and each species exhibits different adsorption behavior, errors associated with the predicted distribution coefficients are possible, severely limiting predictive ability. The large variability in distribution coefficients emphasizes the need to use site-specific K_d values.

A mercury K_d of 10^5 and a mean of 10 ug Hg/L detected in water from the Cohansey Sand suggest that the Kirkwood-Cohansey sediments should contain approximately 1 mg Hg/g (part per thousand mercury). Actual mercury levels for the Coastal Plain for New Jersey, eastern Pennsylvania and southern New York are several orders of magnitude lower. Alternatively, a mean of 10 ng/g total mercury for the sediments of the Kirkwood-Cohansey aquifer system should yield an aqueous mercury concentration of 0.1 ng Hg/L, which is not unrealistic. The study by Gill and Bruland (1990) of the speciation of mercury in surface freshwater systems illustrates this. They studied freshwater systems with more widely varying geochemical and geological characteristics, such as pH, dissolved organic carbon concentration and composition, alkalinity and mineralogy than those in water of the Kirkwood-Cohansey aquifer system.

Silver Lake, a pristine high-alpine lake in California, contains 0.6-ng/L total mercury (Gill and Bruland, 1990), presumably because it occupies a geologic environment low in mercury. Davis Creek, which flows through a mineralized area in California high in cinnabar and metacinnabar, contains 2.8-ng/L total mercury upstream of a mine and 34-ng/L total mercury downstream of it. The highest total mercury concentration in the freshwater systems studied in California is 104 ng/L, which results from the resuspension of mercury-laden bottom sediments. Gill and Bruland (1990) state, "the source of Hg in these sediments is most likely Hg-contaminated mine tailings from the Sulfur Bank mine." Based on physicochemical considerations of the environmental chemistry of mercury, aqueous mercury contamination resulting from chemical weathering of mercury-bearing minerals or areas of substantial mercury mineralization does not exceed the 2 ug-Hg/L MCL.

A study by Buller (1972) of the lakes and streams of the Adirondack region of New York State indicates that the natural background concentration of total mercury (dissolved and adsorbed on suspended sediments) is less than the method detection limit of 0.5 ug/L. Based on these data, Buller (1972) concluded that "concentrations higher than 0.5 ug/L could be considered an indication of pollution." Furthermore, water samples from streams draining the Balmat-Edwards zinc district have total mercury concentrations of less than 0.5 ug/L (Buller, 1972). The sulfide minerals of this mining district contain enough mercury to make its recovery profitable (Richard Dalton, NJGS, oral communication, 1991).

The Shawangunk Mountains of southeastern New York, immediately north of the New Jersey/New York border (fig. 1), contain veins of zinc, lead, and copper sulfides. Sphalerite (ZnS) from these veins has exceptionally high mercury concentrations (48-240 ug/g) (Wilbur and others, 1990). Ranges of mercury concentrations in other sulfide minerals associated with the sphalerite are: 0.12-15.0 ug/g in galena (PbS), 1.00-3.30 ug/g in chalcopyrite ($CuFeS_2$), and 0.035-1.40 ug/g in pyrite (FeS) (Wilbur and others, 1990). Mercury concentrations in nearby streams, Rondout Creek and Wallkill River, apparently are lower than the 0.4 ug/L MDL (Rohmann and others, 1987, p. 62-63). Also mercury in the stream sediments is not excessively high. Although mercury data in Rohmann and others (1987) are not clear enough to derive an unequivocal interpretation, all these data from the Shawangunk Mountains demonstrate that low aqueous mercury concentrations occur even where the minerals are enriched in mercury.

The Water Resources Division of the United States Geological Survey generously provided mercury data for water from the Kirkwood-Cohansey aquifer system from approximately 100 wells from a study of the relationship between land use and contamination (Eric Vowinkel, USGS, written communication, 1991). Mercury data were expressed as "dissolved" mercury in ug/L. The dissolved mercury concentration ranges from < 0.1, the MDL, to 0.5 ug/L; most values are reported as < 0.1 ug/L. The highest aqueous mercury values (0.6 and 1.0 ug/L) were from a well used by a large paper company in Atlantic County, presumably reflecting past or current uses of mercurial biocides. The 0.1-ug Hg/L MDL for cold-vapor atomic-absorption spectroscopy (CVAAS), the standard protocol used for mercury determinations, does not provide a suitable measure of the background aqueous mercury concentration in most natural ground water. Therefore the only valid conclusion regarding natural background aqueous mercury concentrations in the New Jersey Coastal Plain is that the ground water of the Kirkwood-Cohansey aquifer system typically contains less than 100 ng/L aqueous mercury. A 100-ng/L background aqueous mercury concentration is 20 times less than the current 2-ug Hg/L MCL, 400 times less than the values in some Coastal Plain domestic wells, and approximately 10 times greater than the pristine background.

CONCLUSION

The preponderance of evidence suggests that geologic sources in the New Jersey Coastal Plain contribute only minor amounts of mercury (probably less than 10 ng/L) to the Kirkwood-Cohansey aquifer system. The locally elevated (>10 ng/L) mercury concentrations in ground water of the New Jersey Coastal Plain are presumably attributable to multiple past and current anthropogenic inputs of mercury into the poorly acid-buffered Kirkwood-Cohansey aquifer system.

REFERENCES

Barnes, Ivan, and Hem, J. D., 1973, Chemistry of subsurface waters, in Donath, F. A., ed., Annual review of earth and planetary sciences, v. 1: Palo Alto, Calif., Annual Reviews, p. 157-181.

Barnes, Ivan, Hinkle, M. E., Rapp, J. B., and White, D. E., 1973, Chemical composition of naturally occurring fluids in relation to mercury deposits in part of north-central California: U.S. Geological Survey Bulletin 1382-A, p. 1-19.

Bates, R. L., and Jackson, J. A., eds., 1987, Glossary of geology, 3rd ed.: Alexandra, Va., American Geological Institute, 788 p.

Bauersfeld, W. R., Moshinsky, E. W., Pustay, E. A., and Jones, W. D., 1990a, Water resources data - New Jersey, water year 1989; v. 1, Atlantic Slope Basins, Hudson River to Cape May: U.S. Geological Survey Water-Data Report NJ-89-1, 345 p.

---------- 1990b, Water resources data - New Jersey, water year 1989; v. 2, Delaware River Basin and tributaries to Delaware Bay: U.S. Geological Survey Water-Data Report NJ-89-2, 215 p.

Belzile, N., Lecomte, P., and Tessier, A., 1989, Testing readsorption of trace elements during partial chemical extractions of bottom sediments: Environmental Science and Technology, v. 23, p. 1015-1020.

Bloom, Nicolas, 1989, Determination of picogram levels of methyl-mercury by aqueous phase ethylation, followed by cryogenic gas chromatography with cold vapour atomic fluorescence detection: Canadian Journal of Fisheries and Aquatic Sciences, v. 46, p. 1131-1140.

Buchter, B., Davidoff, B., Amacher, M. C., Hinz, C., Iskandar, I. K., and Selim, H. M., 1989, Correlation of Freundlich K_d and retention parameters with soils and elements: Soil Science, v. 148, no. 5, p. 370-379.

Buller, William, 1972, Natural background concentration of mercury in surface water of the Adirondack region, New York: U.S. Geological Survey Professional Paper 800-C, p. C233-C238.

Carter, C. H., 1972, Miocene-Pliocene beach and tidal flat sedimentation, southern New Jersey: Baltimore, Maryland, The Johns Hopkins University, Ph.D. dissertation, 186 p.

Connor, J. J., and Shacklette, H. T., 1975, Background geochemistry of some rocks, soils, plants, and vegetables in the conterminous United States, with sections on Field studies, by Richard J. Ebens and others: U.S. Geological Survey Professional Paper 574-F, p. F99-F101.

Davey, H. A., and Van Moort, J. C., 1974, Current mercury deposition at Ngawha Springs, New Zealand: Search, v. 5, p. 154-156.

Deer, W. A., Howie, R. A., and Zussman, J., 1979, An introduction to the rock forming minerals: London, England, Longman Group, 528 p.

Diamond, M. L., Mackay, Donald, Cornett, R. J., and Chant, L. A., 1990, A model of the exchange of inorganic chemicals between water and sediments: Environmental Science and Technology, v. 24, no. 5, p. 713-722.

Ebens, R. J., and Shacklette, H. T., 1982, Geochemistry of some rocks, mine spoils, stream sediments, soils, plants, and waters in the western energy region of the conterminous United States, with sections on field studies, by Barbara M. Anderson and others: U.S. Geological Survey Professional Paper 1237, p. 100-102.

Fields, T. W., Harkov, Ronald, McNevin, T. F., and Hunter, J. V., 1991, A summary of selected soil constituents and contaminants at background locations in New Jersey: unpublished preliminary draft, New Jersey Department of Environmental Protection and Energy, 64 p.

Fitzgerald, W. F., and Watras, C. J., 1989, Mercury in surficial waters of rural Wisconsin lakes: Science of The Total Environment, v. 87/88, p. 223-232.

Fleischer, Michael, 1970, Summary of the literature on the inorganic geochemistry of mercury, in Mercury in the environment: U.S. Geological Survey Professional Paper 713, p. 6-13.

Frank, R., Stonefield, K. I., and Suda, P., 1979, Metals in agricultural soils of Ontario: Canadian Journal of Soil Science, v. 59, p. 99-105.

Freeze, R. A., and Cherry, J. A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, 604 p.

Gill, G. A., and Bruland, K. W., 1990, Mercury speciation in surface freshwater systems in California and other areas: Environmental Science and Technology, v. 24, no. 9, p. 1392-1399.

Glass, G. E., Sorensen, J. A., Schmidt, K. W., and Rapp, G. R., Jr., 1990, New source identification of mercury contamination in the Great Lakes: Environmental Science and Technology, v. 24, no. 7, p. 1059-1069.

Haraldsson, Conny, Westerlund, Stig, and Ohman, Peder, 1989, Determination of mercury in natural samples at the sub-nanogram level using inductively coupled plasma/mass spectrometry after reduction to elemental mercury: Analytica Chimica Acta, v. 221, p. 77-84.

Henderson, F. B., III, 1969, Hydrothermal alteration and ore deposition in serpentine-type mercury deposits: Economic Geology, v. 64, p. 489-499.

Joensuu, O. I., 1971, Fossil fuels as a source of mercury pollution: Science, v. 172, p. 1027-1028.

Jonasson, I. R., and Boyle, R. W., 1972, Geochemistry of mercury and origins of natural contamination of the environment: Canadian Mining and Metallurgical Bulletin, v. 65, no. 717, p. 32-39.

Krauskopf, K. B., 1967, Introduction to geochemistry: New York, McGraw-Hill, 721 p.

Lee, S. H., Jung, K-H., and Lee, D. S., 1989, Determination of mercury in environmental samples by cold vapour generation and atomic-absorption spectrometry with a gold-coated graphite furnace: Talanta, v. 36, no. 10, p. 999-1003.

Lindqvist, Oliver, and Rodhe, Henning, 1985, Atmospheric mercury – a review: Tellus, v. 37B, p. 136-159.

Markewicz, F. J., 1969, Ilmenite deposits of the New Jersey Coastal Plain, in Subitzky, Seymour, ed., Geology of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions: New Brunswick, N.J., Rutgers University Press, p. 363-382.

McKeague, J. A., and Wolynetz, M. S., 1980, Background levels of minor elements in some Canadian soils: Geoderma, v. 24, p. 299.

McNeal, J. M., and Rose, A. W., 1974, The geochemistry of mercury in sedimentary rocks and soils in Pennsylvania: Geochimica et Cosmochimica Acta, v. 38, p. 1759-1784.

Mills, W. B., Porcella, D. B., Ungs, M. J., Gherini, S. A., Summers, K. V., Mok, Lingfung, Rupp, G. L., Bowie, G. L., and Haith, D. A., 1985, Water quality assessment: a screening procedure for toxic and conventional pollutants in surface and ground water - parts 1 and 2 (revised 1985): EPA/600/6-85/002a, U.S. Environmental Protection Agency, Office of Research and Development, Athens, Ga.

Mitra, S., 1986, Mercury in the ecosystem: its dispersion and pollution today: Switzerland, Trans Tech Publications, p. 19-50.

Moiseyev, A. N., 1971, A non-magmatic source for mercury ore deposits?: Economic Geology, v. 66, p. 591-601.

Moore, J. W., and Ramamoorthy, S., 1984, Heavy metal in natural waters - applied monitoring and impact assessment: New York, Springer-Verlag, 268 p.

Nakagawa, R., 1974, The mercury content in hot springs: Nippon [Japan] Kagaku Kaishi 1974, p. 71-74.

National Academy of Sciences, 1978, Geochemistry and the environment - distribution of trace elements related to the occurrence of certain cancers, cardiovascular diseases, and urolithiasia, v. 3: Washington, D. C., National Academy of Sciences, 200 p.

New Jersey Department of Environmental Protection, 1989, Hydro-geologic investigation of mercury in ground-water in the Pleasant Wood section of Egg Harbor Township, Atlantic County, New Jersey: Geraghty and Miller, Inc., Newtown, Pa., variously paginated.

New Jersey Geological Survey, 1990, Generalized stratigraphic table for New Jersey: N.J. Geological Survey Information Circular 1.

Ohta, N., and Terai, M., 1971, The mercury content of several acid springs in Japan: Bulletin of the Chemical Society of Japan, v. 44, p. 1153-1157.

Owens, J. P., Bybell, L. M., Paulachok, Gary, Ager, T. A., Gonzales, V. M., and Sugarman, P. J., 1988, Stratigraphy of the Tertiary sediments in a 945-foot-deep core hole near Mays Landing in the southeastern New Jersey Coastal Plain: U.S. Geological Survey Professional Paper 1484, 39 p.

Ozerova, N. A., 1962, Primary dispersion haloes of mercury: Proceedings of The Institute of Geology of Ore Deposits; Petrography, Mineralogy and Geochemistry, no. 72, Questions of Geochemistry [in Russian], Part 4, Moscow, Nauka Press, 136 p. [English translation in International Geology Review (American Geological Institute), v. 15, 1970.]

Park, C. F., Jr., and MacDiarmid, R. A., 1975, Ore deposits: San Francisco, Ca., W. H. Freeman & Co., 530 p.

Phelps, David, and Buseck, P. R., 1980, Distribution of soil mercury and the development of soil mercury anomalies in the Yellowstone geothermal area, Wyoming: Economic Geology, v. 75, p. 730-741.

Rai, D., and Zachara, J. M., 1984, Chemical attenuation rates, coefficients, and constants in leachate migration, v. 1, a critical review: Electric Power Research Institute EA-3356, v. 1, research project 2198-1, 2792 p. (Prepared by Battelle, Pacific Northwest Laboratories, reprinted with corrections 1986.)

Robertson, D. E., Sklarew, D. S., Olsen, K. B., Bloom, N. S., Crecelius, E. A., and Apts, C. W., 1987, Measurement of bioavailable mercury species in freshwater and sediments: Final Report for Project Rp-2020-3, Electric Power Research Institute, Palo Alto, Calif.

Robinson, K. G., and Shuman, M. S., 1989, Determination of mercury in surface waters using an optimized cold vapor spectrophotometric technique: International Journal of Environmental Analytical Chemistry, v. 36, p. 111-123.

Rohmann, S. O., Lilienthal, Nancy, Miller, R. L., Szwed, R. M., and Muir, W. R., 1987, Tracing a river's toxic pollution - a case study of the Hudson, phase 2: New York, New York, INFORM Inc., 209 p.

Ruch, R. R., Gluskoter, H. J., and Kennedy, E. J., 1971, Mercury content of Illinois coals: Environmental Geology Notes no. 43, Urbana, Illinois, Illinois State Geological Survey, 15 p.

Shacklette, H. T., and Boerngen, J. G., 1984, Element concentrations in soils and other surficial materials of the conterminous United States: U.S. Geological Survey Professional Paper 1270, 105 p.

Spoljaric, Nenad, and Crawford, W. A., 1978, Glauconitic greensand: a possible filter of heavy metal cations from polluted waters: Environmental Geology, v. 2, no. 4, p. 215-221.

---------------- 1979, Removal of contaminants from landfill leachates by filtration through glauconitic greensand: Environmental Geology, v. 2, no. 6, p. 359-363.

United States Environmental Protection Agency, 1979, Methods for chemical analysis of water and wastes: EPA-600 4-79-020, U.S. Environmental Protection Agency, Cincinnati, Ohio, variously paginated.

------------------ 1980, Ambient water quality criteria for mercury: EPA 440/5-80-058, U.S. Environmental Protection Agency, Office of Water Regulations and Standards, Washington, D. C., 217 p.

United States Geological Survey, 1970, Mercury in the environment: U.S. Geological Survey Professional Paper 713, 67 p.

Uptegrove, Jane, Grosz, A. E., Maharaj, S. V., Muller, F. L., Muessig, Karl, Farnsworth, John, Burbanck, G. P., and Cheung, T.-T., 1991, Preliminary textural and mineralogic analyses of vibracore samples collected between Absecon and Barnegat Inlets, New Jersey: New Jersey Geological Survey Open File Report OFR 91-3, 11 p.

Varekamp, J. C., and Buseck, P. R., 1983, Hg anomalies in soils: a geochemical exploration method for geothermal areas: Geothermics, v. 12, p. 29-47.

------------------ 1984, The speciation of mercury in hydrothermal systems, with applications to ore deposition: Geochimica et Cosmochimica Acta, v. 48, p. 177-185.

Wedepohl, K. H., 1991, The composition of the upper Earth's crust and the natural cycles of selected metals. Metals in natural raw materials. Natural resources, in Merian, Ernest, ed., Metals and their compounds in the environment - occurrence, analysis, and biological relevance: New York, VCH, p. 3-17.

Weissberg, B. G., 1975, Mercury in some New Zealand waters: New Zealand Journal of Science, v. 18, p. 195-203.

White, D. E., 1981, Active geothermal systems and hydrothermal ore deposits, in Skinner, B. J., ed., 75th anniversary volume of Economic Geology: El Paso, Texas, Economic Geology Publishing Company, p. 392-423.

White, D. E., Hinkle, M. E., and Barnes, Ivan, 1970, Mercury contents of natural thermal and mineral fluids, in Mercury in the environment: U.S. Geological Survey Professional Paper 713, p. 25-28.

Wilbur, J. S., Mutschler, F. E., Friedman, J. D., and Zartman, R. E., 1990, New chemical, isotopic, and fluid inclusion data from zinc-lead-copper veins, Shawangunk Mountains, New York: Economic Geology, v. 85, p. 182-196.

World Health Organization, 1976, Environmental health criteria I - mercury: Geneva, Switzerland, 131 p.

------------------ 1989, Environmental health criteria 86 - mercury - environmental aspects: Geneva, Switzerland, 115 p.

GLOSSARY

Definitions of technical and scientific terms in this report conform to those in Bates and Jackson (1987).

Crystal lattice - The three-dimensional regularly repeating set of points that represent the translational periodicity of a crystal structure.

Epigenetic - Said of a mineral deposit of origin later than that of the enclosing rocks.

Facies - The aspect, appearance, and characteristics of a rock unit, usually reflecting the conditions of its origin; especially as differentiating the unit from adjacent or associated units. Rocks of any origin formed within certain pressure-temperature conditions.

Gangue - The valueless rock or mineral aggregates in an ore; that part of an ore that is not economically desirable but cannot be avoided in mining.

Heavy mineral - A detrital mineral from a sedimentary rock, having a specific gravity higher than a standard (usually 2.85), and commonly forming as a minor constituent or accessory mineral of the rock (less than one percent in most sands); for example magnetite, ilmenite, zircon, rutile, kyanite, garnet, tourmaline, sphene, apatite, biotite.

Hydrothermal deposit - A mineral deposit formed by precipitation of ore and gangue minerals in fractures, faults, breccia openings, or other spaces, by replacement or open-space filling, from watery fluids ranging in temperature from 50° to 700°C but generally below 400°C, and ranging in pressure from 1 to 3 kilobars. The fluids are of diverse origin. Alteration of host rocks is common.

Incongruent solution - Dissolution accompanied by decomposition or by reaction with the liquid so that one solid phase is converted into another; dissolution to give dissolved material in different proportions from those in the original solid.

Ionic substitution - The replacement of one or more kinds of ions in a crystal structure by other kinds of generally similar size and charge.

Paralic - By the sea, but nonmarine; especially pertaining to intertongued marine and continental deposits laid down on the landward side of a coast or in shallow water subject to marine invasion, and to the environments (such as lagoonal or littoral) of the marine borders. Also said of basins, platforms, marshes, swamps, and other features marked by thick terrigenous deposits intimately associated with estuarine and continental deposits, such as deltas formed on the heavily alluviated continental shelves.

Pegmatite - An exceptionally coarse-grained igneous rock, with interlocking crystals, usually found as irregular dikes, lenses, or veins, especially at margins of batholiths. Although pegmatites having gross compositions similar to other rock types are known, their composition is generally that of granite; the composition may be simple or complex and may include rare minerals rich in such elements as lithium, boron, fluorine, niobium, tantalum, uranium, and rare earths. Pegmatites represent the last and most hydrous portion of a magma to crystallize and hence contain high concentrations of minerals present only in trace amounts in granitic rocks.

Resistates - Sediments composed of chemically resistant minerals, enriched in weathering residues; thus highly quartzose sediments characteristically rich also in zircon, ilmenite, rutile, and, more rarely, cassiterite, monazite, and gold.

Stockwork - A mineral deposit consisting of a three-dimensional network of planar to irregular veinlets closely enough spaced that the whole mass can be mined.

Syngenetic - Said of a mineral deposit formed contemporaneously with, and by essentially the same processes as, the enclosing rocks.

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