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Water Resources Division
Geological Survey

Caribbean District
Open-File Report

WATER AND COPPER-MINE TAILINGS IN KARST TERRANE OF RIO TANAMA BASIN, PUERTO RICO

UNITED STATES DEPARTMENT OF THE INTERIOR
in cooperation with the
COMMONWEALTH OF PUERTO RICO

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by
Donald G.eorge Jordan, 1926-
U.S. Geological Survey

Prepared in cooperation with
COMMONWEALTH OF PUERTO RICO

October 1970

71-163

PRINCIPAL FINDINGS

The proposed disposal of copper-mine tailings in karst terrane of the Río Tanamá basin presents a number of unique problems about potential sediment and chemical pollution of Río Tanamá.

1. Estimates of water velocity in the subsurface from the vicinity of the tailings ponds to Río Tanamá range from 2.4 to 13.6 feet per minute. Actual velocity at places may be only one-tenth as fast or as much as 10 times faster.

2. The reported particle size of the tailings is small enough for the tailings to be transported by water at the velocities likely to be encountered in the subsurface. Once deposited, much higher velocities will be required to erode the tailings.

3. Although the tailings ponds are to be sealed, leakage may occur while the tailings still are in the slurry state. Attempts to seal reservoirs in karst rarely are completely successful. The still-fluid slurry also will exert hydrostatic pressure on the limestone sides and bottoms of the ponds that could cause collapse of a thin wall, allowing the tailings to enter a cavern system and so to reach Río Tanamá.

4. There can be chemical pollution by the tailings transport water if it escapes from the ponds. The water, which eventually would reach Río Tanamá, would have high dissolved solids, calcium sulfate, and hardness. The actual amount of these cannot be determined until operations start. Trace elements or minerals or both also will be present.

5. There is a potential for acid-water production from the oxidation of pyrite and other sulfide minerals in the tailings.

6. The small pyrite tailings particles in effect will be coated--that is, suspended in a mixture of water and essentially inert fines. Rainwater or other water highly charged with oxigen will percolate slowly (if at all) through the tailings. The protective coating on these pyritic particles will be disturbed only slightly, so little oxidation is expected.

7. A small amount of acid may be produced by rainfall on dry tailings at the surface, but since a byproduct of oxidation is a ferric-hydroxide gel, the reaction in all probability will be self-limiting, for the gel will act as a sealant.

8. Acid production, if any, likely would be neutralized by the alkaline water of the tailings slurry and by the naturally alkaline water in the subsurface and streams.

CONCLUSIONES

El método propuesto para disponer de los desperdicios ("colas") de las minas de cobre en el terreno kárstico de la cuenca del Río Tanamá, presenta un número de problemas peculiares relacionados con la posible contaminación química y por sedimentos en dicho afluente.

1. Los estimados de la velocidad del agua subterránea desde la vecindad de las lagunas de desperdicios hasta el Río Tanamá fluctúan desde 2.4 hasta 13.6 pies por minuto. La velocidad actual en algunos sitios puede variar de una décima parte a diez veces la velocidad estimada.

2. Los informes disponibles indican que el tamaño de las partículas en suspensión ("colas") es lo bastante pequeño para permitir que sean transportadas a las velocidades que pueden ocurrir en el subsuelo. Se requieren velocidades mucho más altas para desgastar los desperdicios que se hayan depositado.

3. Aunque las lagunas de desperdicios serán selladas, es posible que ocurran filtraciones mientras los desperdicios estén en estado líquido. Los intentos de sellar embalses en terreno kárstico raramente tienen éxito total. La presión hidrostática sobre la piedra caliza que formará los lados y el fondo de los embalses, podría causar el derrumbamiento de paredes finas en áreas cavernosas. Esto permitiría que las "colas" penetraran el sistema de cavernas y eventualmente llegaran al Río Tanamá.

4. Existe la posibilidad de contaminación química en caso de que la fase líquida de las "colas" escapase de las lagunas. El agua que eventualmente llegaría hasta el Río Tanamá, tendría un alto contenido de sólidos en solución, fosfato de calcio, y dureza. La cantidad actual de éstos no podrá ser determinada hasta el comienzo de las operaciones. También habrá presentes trazas de otros elementos o minerales, o de ambos.

5. Existe la posibilidad de que se produzca agua ácida de la oxidación de pirita y otros minerales sulfurosos en los desperdicios ("colas").

6. Las pequeñas partículas de pirita esencialmente estarán cubiertas, esto es, suspendidas en una mezcla de agua y materia fina básicamente inerte. El agua de lluvia y otra agua con alto contenido de oxígeno pasará (si acaso) lentamente a través de los desperdicios. La capa protectora en estas partículas de pirita será movida solo levemente, así que se espera poca oxidación.

7. Una pequeña cantidad de ácido puede ser producida por la lluvia al reaccionar con las "colas" secas en la superficie, pero como el hidróxido férrico gelatinoso es un producto secundario de la oxidación, la reacción será autolimitante, pues esta gelatina actuará como un sellador.

8. De ocurrir alguna producción de ácido, éste probablemente sería neutralizado por el agua alcalina de los desperdicios en suspensión y por el agua de naturaleza alcalina en el subsuelo y las corrientes.

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WATER AND COPPER-MINE TAILINGS IN KARST TERRANE OF RIO TANAMA BASIN, PUERTO RICO

by

Donald G. Jordan

HISTORY

An industrial firm is proposing to mine a diorite porphyry copper deposit in the Río Tanamá basin in west central Puerto Rico. The deposit is estimated to contain about 177 million tons of ore averaging 0.64 percent copper. Processing this ore will result in nearly the same amount of tailings. One proposal has been to dispose of the tailings, amounting to 20,000 tons of finely crushed rock mixed with 4.6 million gallons of water per day, in the karst terrane northeast of the mine (fig. 1).

In 1966 the Puerto Rico Mining Commission requested the United States Geological Survey to make a study of the proposed tailings area to determine the direction of subsurface flow in the karst terrane. Three injections of Rhodamine WT dye as a tracer were made in October and November 1966, one in a stream that has an underground course, and two in sinkholes in the tailings area. Río Tanamá and Río Grande de Arecibo, and several springs along them, were monitored for reappearance of the dye. The tests indicated that subsurface flow in the near vicinity of the tailings area is to Río Tanamá. A brief administrative report on the direction and velocity of the dyed water in the subsurface was given to the Mining Commission in January 1967.

The purpose of this report is to take a second look at the data collected in the earlier study, in the hope of obtaining further insight on the direction and velocity of subsurface flow in the limestone. A detailed study of topographic maps of the area resulted in strengthening hypotheses on the geomorphology made by others and in selecting possible routes of underground flow. Comments are made on the impact of the tailings disposal on potential pollution of the Río Tanamá basin. It must be emphasized that the report presents possibilities, not probabilities.

The proposed tailings area lies on the southern edge of the karst terrane of northern Puerto Rico where younger sedimentary rocks feather out against the hard rock central core of the Island (fig. 2, in pocket). The rocks of the central core and those exposed as inliers in the limestone mostly are of volcanic origin, consisting principally of indurated breccias and tuffs. The younger sedimentary rocks consist principally of a basal clayey conglomerate and sandstone, and overlying limestone.

In the practical sense, the volcanic rocks and the clayey conglomerates and sandstones are impermeable, where as the overlying limestone is highly permeable as a unit because of numerous well-developed solution channels.

The rocks are described briefly in the following text. The sedimentary rocks are referenced by name solely for the convenience of the reader and for reference later in the text. The names of the formations are unimportant. The critical factor lies in the rocks being permeable or impermeable.

Volcanic Rocks

No fewer than five volcanic formations, ranging from Cretaceous to Tertiary in age, are represented in the vicinity of the disposal area. Breccias and tuffs are the predominant rock type, with lava and volcanic sandstone as generally minor constituents. All these volcanic rocks are well indurated (hardened by heat) and exhibit secondary permeability only along fractures and joints.

Sedimentary Rocks

The younger sedimentary rocks of Tertiary age are represented by three formations.

San Sebastián Formation

The San Sebastián Formation is the basal member of the sedimentary rocks and lies unconformably on the volcanic rocks. The formation consists of poorly consolidated sandstone, siltstone, shale, clay, and conglomerate, with some calcareous layers near the top of the formation. The sandstone and conglomerate commonly contain clay, filling the space between sand grains and pebbles, and in many places the clay is predominant. The upper surface of the formation is quite regular. It dips northward about 55 to 85 meters per kilometer (300 to 450 feet per mile), a slope of about 5°.

Lares Limestone

The Lares Limestone, conformably overlying the San Sebastián Formation, is the principal limestone cropping out in the area. The basal part of the Lares, 50 to 80 meters thick, is a thin-bedded to massive limestone with calcareous sandstone layers in the lower beds. This section appears to be the principal zone in which solution openings have been developed. Openings range in size from holes the size of a pencil to caverns having a floor area of several thousand square feet and a ceiling 30 feet high or more. Overlying the basal beds are 230 to 260 meters of hard, dense limestone that locally is somewhat chalky and crumbly. The upper beds form the prominent cliffs of the area.

Cibao Formation

The Cibao Formation is found only as small outliers capping the tops of the limestone hills in the northern part of the area. The rocks consist mostly of chalky fragmental limestone of the basal Montebello Limestone Member.

Unconsolidated Rocks

Scattered alluvial deposits of clay, silt, sand, and gravel are found in the river valleys and in the floor of a few sinkholes.

Along the contact of the sedimentary and volcanic rocks are extensive landslide deposits, consisting predominantly of rocks of the San Sebastián Formation. Some of the slides still are active, but with a velocity that cannot be detected by eye.

A group of volcanic inliers extends along the northern edge of the tailings area from Río Grande de Arecibo to Río Tanamá (fig. 2, in pocket). The inliers are the tops of hills of an erosional surface developed prior to the deposition of the sedimentary rocks. Although nearly buried, they form a barrier to the movement of water in the limestone, in the sense of the volcanic rocks being impermeable as compared with the permeability of the limestone.

In the southern part of the area a second group of volcanic inliers probably represents another range of hills also trending east-west. Drainage between the ranges of hills was westward before the limestone was deposited.

The clayey rocks of the San Sebastián Formation partly filled the valley and low areas of the old land surface, leaving the hills as islands isolated from the central core of the Island. The deposition of the Lares Limestone covered the San Sebastián Formation and completed the burying of the volcanic rock hills. Later erosion of the Lares exposed the San Sebastián and the volcanic rocks along the southern edge of the area and exhumed the tops of the two ranges of volcanic rock hills.

Deposition and erosion in the proposed tailings area thus left a bowl of mostly impervious rocks, open to the west and filled with limestone which developed as classic karst terrane.

The karst terrane is marked by numerous sinkholes and closed depressions showing a generally east-west lineation (fig. 3, in pocket). There also is a north-south lineation in individual sinkholes that is most evident in the larger closed depressions near the southern edge of the limestone and near Quebrada Jobos.

It is believed that two stages of solution activity are exhibited: the first stage, the result of downtilting of the Island to the west; and the second stage, the result of uptilting of the Island to the west with the hinge line somewhere to the east of Río Grande de Arecibo. In both stages the buried volcanic ridges and the impervious sedimentary rocks affected the development of solution features.

The first stage caused the development of east-west trending sinkholes. Drainage was toward Río Tanamá, which at the time may have been an underground stream, but at a higher base level. Figure 4 (in pocket) is a contour map based upon the lowest land surface altitude identified in each square of a 1,000-foot grid superimposed on 1:20,000 scale topographic maps. It might be construed to be a generalized ground-water contour map of the area during first-stage activity. An east-to-west drainage pattern in the subsurface was developed, probably following the general trend shown in figure 5.

The second stage of solution channels and drainage followed the uptilt of the Island to the west. The initial effect of the uptilt likely was the rapid downcutting of Río Tanamá and, if it had not already occurred, the collapse of the roof of the subsurface stream in most reaches. The downcutting was rapid, for if it had proceeded at a slow rate, the already developed first-stage solution channels east of Río Tanamá probably would have kept pace. Instead, the second-stage solution channels developed in response to a new, more northerly direction of the ground-water gradient, leaving the first stage sinkholes as a network of dry caves and passageways. The surface expression of the second-stage solution channels is best shown along the southern edge of the area, where the limestone is thin and collapse of the second-stage solution channels has occurred.

The bottoms of the first-stage sinkholes near Río Tanamá are as much as 60 meters above the river and there are no springs at that level; whereas springs of the second-stage solution channels discharge at or a few meters above present stream level. The lack of data on ground-water levels prevents making a satisfactory ground-water contour map that would define the present-day subsurface drainage pattern. The theoretical pattern of present-day subsurface drainage is shown in figure 6, based on intensive study of topographic maps supported by personal field observation.

Quebrada Jobos, which drains to Río Grande de Arecibo, probably headed on the east flank of the buried volcanic ridge during first-stage development. Following uptilt, Quebrada Jobos had rapid headward erosion. It cut through the volcanic ridge and captured the headwaters of a subsurface system draining to Río Tanamá that subsequently collapsed.

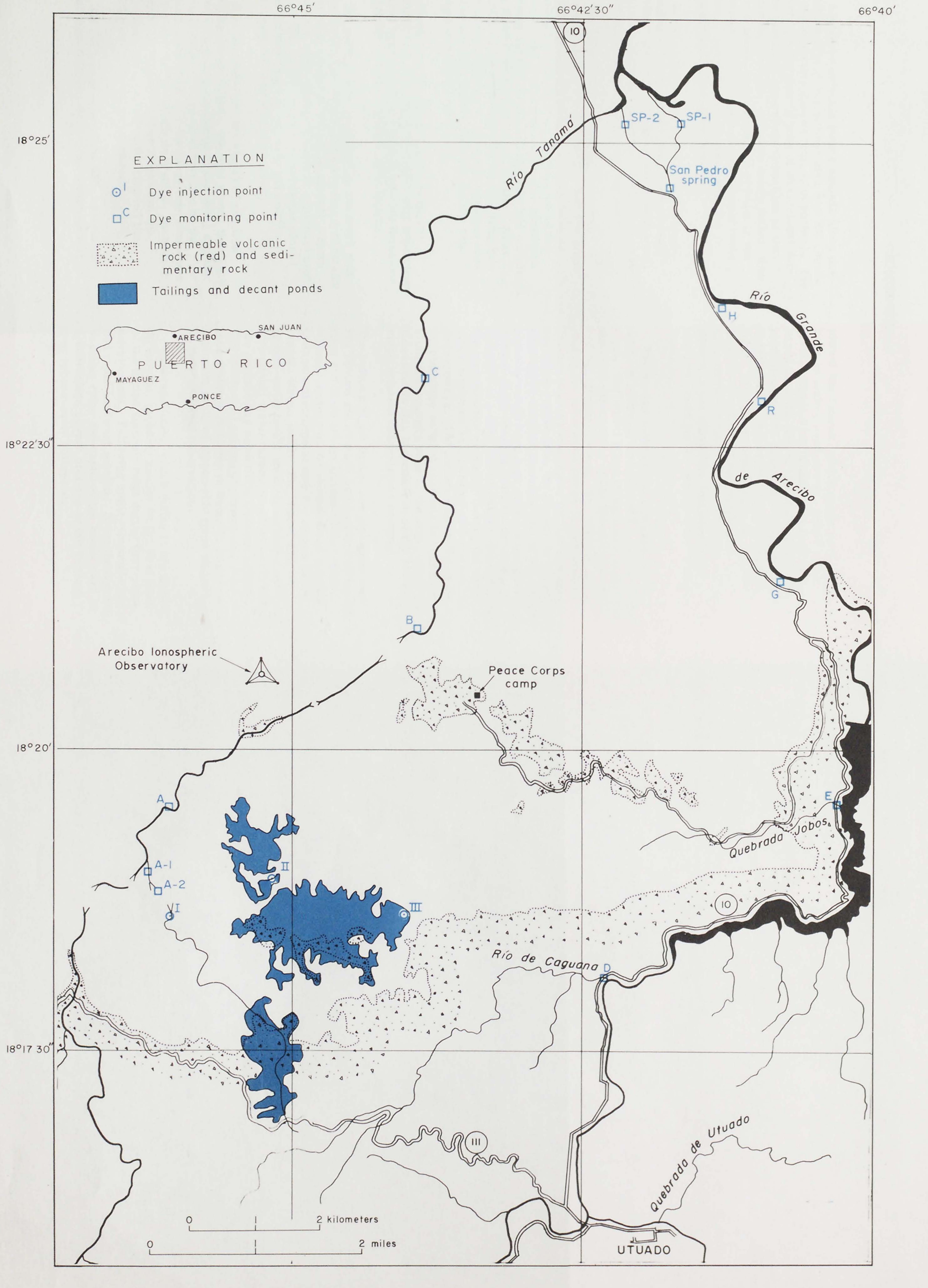


Figure 1.--Tailings disposal area, dye-injection points, and sampling station in lower Río Tanamá and Río Grande de Arecibo basins.

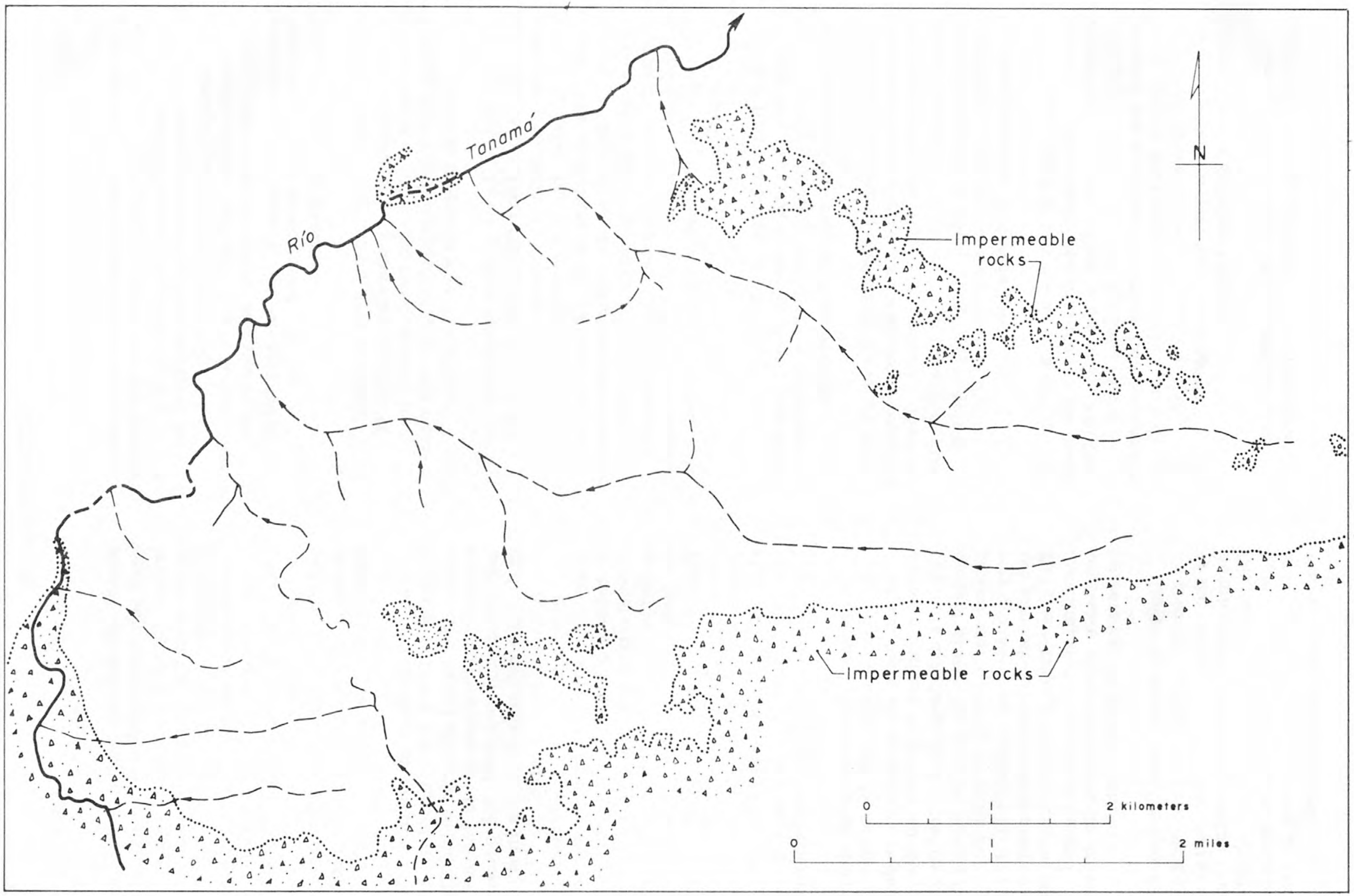


Figure 5.--Hypothetical subsurface pattern at end of first-stage development of karst terrane.

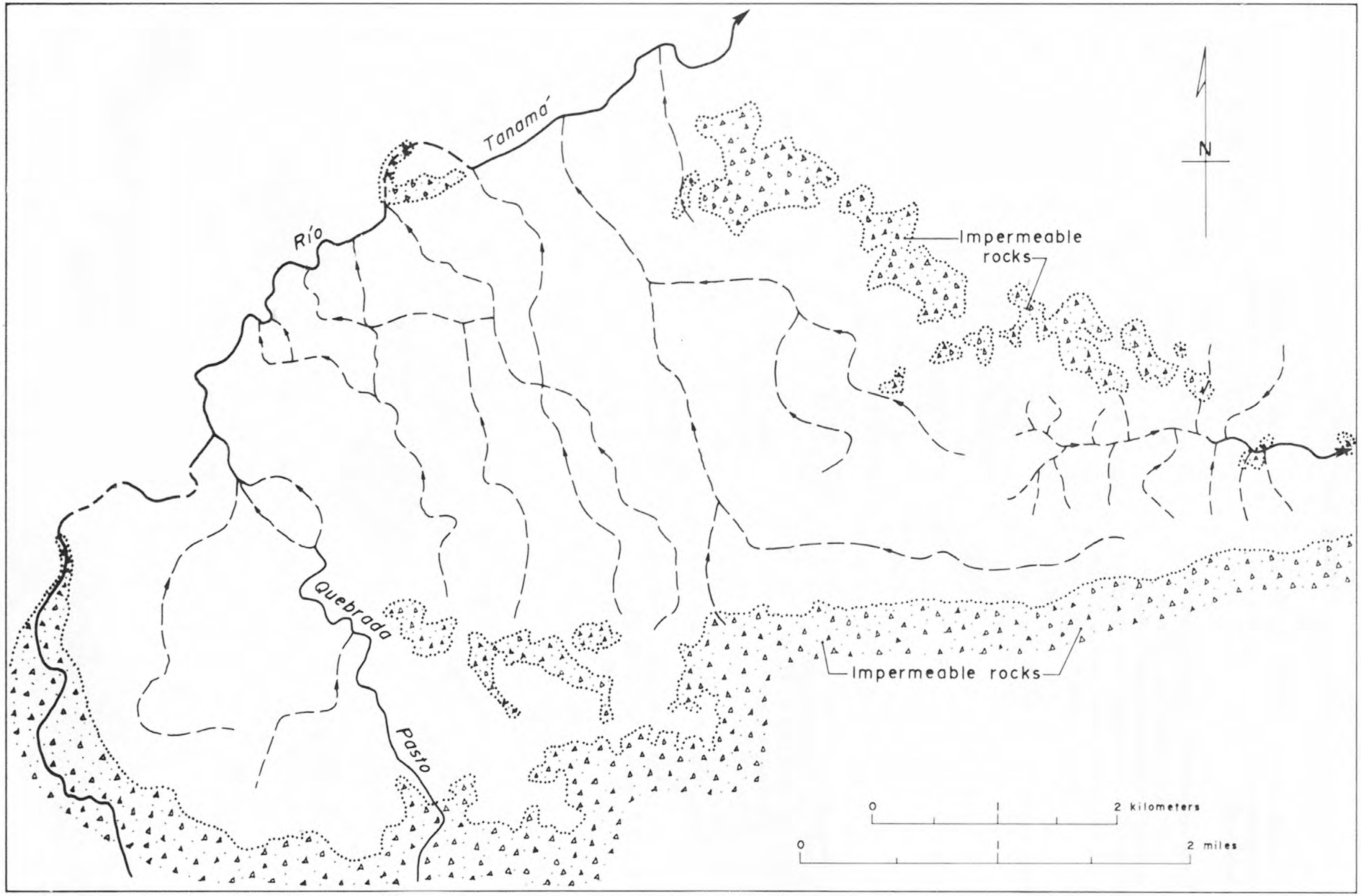


Figure 6.--Hypothetical subsurface drainage pattern of present-day karst terrane.

TAILINGS PONDS

The proposed tailings disposal ponds cover about 800 acres of the karst terrane east of Río Tanamá, as shown in figure 2 (in pocket). Two ponds with a reported total storage capacity of 134 million tons of tailings and a decant pond are proposed. (It may be noted that the capacity of the tailings ponds appears to be about 40 million tons less than the proposed amount of ore to be milled.)

The smaller of the ponds, formed by damming Quebrada Pasto, will be used principally for standby when pipeline repairs or other repairs are required in the larger pond. It will have an area of about 200 acres at a spillway elevation of about 425 meters. The floor of the pond will be in essentially impervious rock of the San Sebastián Formation. The contact between the San Sebastián Formation and the overlying Lares Limestone is at an altitude of 425 meters in the headwaters of the pond and 370 meters at the dam across Quebrada Pasto.

The larger tailings pond lies east and north of Quebrada Pasto in a major depression composed of many sinkholes. This pond will have an area of about 400 acres at an altitude of about 400 meters. Several small dams will be required in saddles between the principal ridges forming the boundary of the pond. The pond is floored in part with volcanic rocks and rocks of the San Sebastián Formation. The lowest contact between these impervious rocks and the overlying limestone is at an altitude of 360 meters.

The decant pond: The decant pond lies north of the larger tailings pond. Maps supplied by the Puerto Rico Mining Commission indicate the altitude of the pond will be about 350 meters and the area about 200 acres. No outcrops of impervious rocks are evident in the bottoms of the two prominent sinkholes in the pond area. The floors of the sink appear to be blanketed by residual material derived from the surrounding limestone.

Cross sections have been made through the tailings area, showing the approximate contact of the impervious rock and the overlying limestone--see figure 7.

Although the floor of two of the ponds in part will be impervious rock, the greater part of the ponds will lie in the permeable solutioned limestone. This involves two risks of leakage of the tailings slurry or the decant water: 1) by possible existing openings into underground passages; and 2) by blowout into underground passages covered by a thin shell of weak rock, as hydrostatic head builds in the ponds. Attempts to seal reservoirs in karst rarely are completely successful.

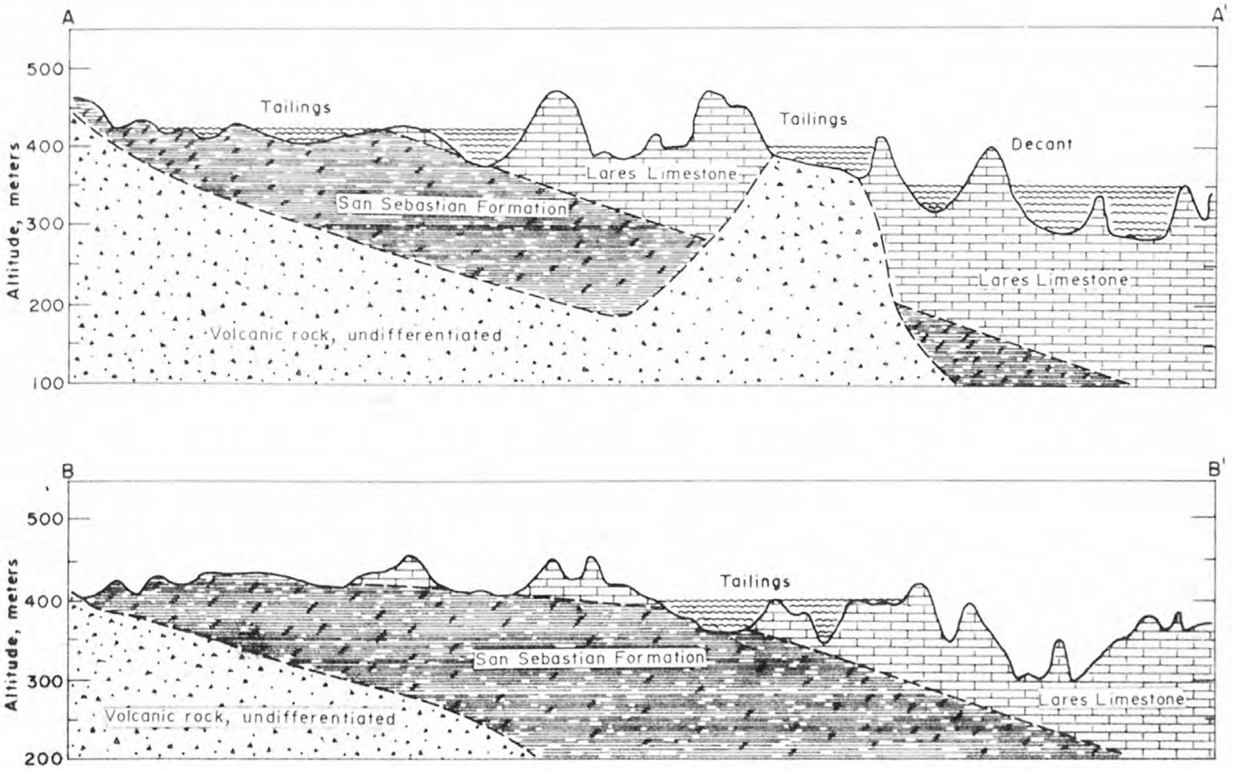


Figure 7.--Cross sections through tailings and decant ponds. See figure 2 for location.

Table 1.--Time of travel of dye injected in karst terrane of Río Tanamá basin.

Phase	Injection sites		Dye injected		Dye detected at point						Route traveled - subsurface					Route travel - surface					
					A		B		C		Injection site to river	Time of travel, min.	Distance, feet	Velocity		Upstream site	Downstream site	Time of travel, min.	Distance, feet	Velocity ft/min.	
	Latitude	Longitude	Time	Date 1966	Time	Date 1966	Time	Date 1966	Time	Date 1966				ft/min	cm/sec						
I	18°18'49"	66°45'45"	0930	Oct. 19	1455	Oct. 19			1915	Oct. 19						A	C	275	36,800	134	
											I A_2	293	2,800	9.6	4.1	A_2	A	28	3,800	134	1/, 2/
											I A_2	293	4,000	13.6	5.8						
II	18°18'55"	66°45'06"	0745	Oct. 25	not detected		0500	Oct. 27	1000	Oct. 27						B	C	300	18,800	62.7	
											II' e_1	2,465	9,100	3.7	1.6	e_1	B	250	15,700	62.7	3/
											II e_2	2,471	7,200	2.9	1.2	e_2	B	244	15,300	62.7	3/
											II e_3	2,503	9,600	3.8	1.6	e_3	B	212	13,300	62.7	3/
											II e_4	2,540	8,900	3.5	1.5	e_4	B	175	11,000	62.7	3/
III	18°18'08"	66°44'01"	1130	Nov. 7	not detected		0330	Nov. 11	0820	Nov. 11						B	C	290	18,800	64.8	3/
											III IIIa	1,230	4,600	3.7	1.6						4/
											III e_3	5,795	15,500	2.7	1.1	e_3	B	205	13,300	64.8	3/
											III e_4	5,830	16,100	2.8	1.2	e_4	B	170	11,000	64.8	3/
											III e_5	5,844	14,200	2.4	1.0	e_5	B	156	10,100	64.8	3/
											III e_6	5,003	14,100	2.8	1.2	e_6	B	97	6,300	64.8	3/

1/ Time of travel of surface flow calculated from time of travel site A to site C.
2/ Dye observed visually at site A, at some time after 1230 and before 1455.
3/ Time of travel of surface flow calculated from time of travel site B to site C.
4/ Dye observed visually upon arrival at site IIIa at 0800 November 8.

Studies were made by the Geological Survey in the fall of 1966 to determine the direction of possible subsurface flow from the tailings area. Time of travel in the subsurface was not considered to be important at the time. Rhodamine WT, a fluorescent dye detectable in quantities as small as 0.2 ug/l (micrograms per liter), was used. Three injections of the dye were made: at the swallow hole where Quebrada Pasto goes underground; in the reach of a subsurface stream exposed in a sinkhole in the decant pond area; and in a pool in the bottom of a sinkhole in the area encompassed by the tailings pond. The injection sites are shown in figures 1 and 2. The dates of injection were far enough apart to preclude interference between the three dye clouds.

In the first two injection phases, observation sites were monitored only on Río Tanamá. In the third phase, all the observation sites shown in figure 1 in the Río Tanamá and Río Grande de Arecibo basins were monitored.

The time of travel and velocity of the dye in its underground movement was calculated by total elapsed time of the leading edge of the dye cloud from injection point to observation point. Time of travel as streamflow from actual or estimated points of emergence was subtracted from the total elapsed time, giving subsurface time. The length of the possible subsurface courses was scaled from a 1:20,000 scale map. Velocity of flow from point of injection to the probable points of emergence at the surface then was computed.

Several aspects of the dye tests must be emphasized:

1. The leading edge of the dye cloud was used in determining the time of travel. Mean concentration of the dye lagged the leading edge by about 1 hour in Phase I, but by about 24 hours in Phases II and III. The computed velocity, therefore, is higher than it would be if the mean concentration of the dye cloud were used.
2. The subsurface paths of the dye cloud were determined on the basis of surface features and assumed solution channels. The paths therefore are the most probable paths and not necessarily the actual courses of the dye cloud in the subsurface.
3. The velocity computed is average velocity. Flow may have been in quiet pools, over falls and cascades, or through water-filled tubes. Velocity in any reach thus may have ranged from less than one-tenth the computed velocity to 10 times that velocity.
4. Water flow in the subsurface may be either laminar or turbulent, which greatly affects the deposition, erosion, and transportation of particles.

Table 1 summarizes the observations made during the three injection phases.

Phase I

Dye was injected into Quebrada Pasto where it disappeared into a swallow hole, on October 19, 1966. About 5 hours after injection, the leading edge of the dye cloud was detected by fluorometer at site A_1 (fig. 8). Later in the passage of the cloud, the dye was visible to the eye. The dye also was visible in the series of springs at site A_2 where Quebrada Pasto emerges from the underground, but the time of observance was not recorded at either site.

Two possible subsurface paths for the dye are shown in figure 8, which was derived from figures 3 and 4 (both in pocket). One, an almost straight-line passage from the injection site to the emergent springs at A_2; the second, a more roundabout path under a series of sinks. The movement of the dye was rapid, and depending upon the path chosen, the edge of the dye cloud had an indicated velocity of 9.6 or 13.6 feet per minute.

Heavy rainfall immediately after injection caused a rise in Quebrada Pasto and Río Tanamá. Velocity of dye movement in Río Tanamá itself was about 2 feet per second, more than twice that measured during the two following phases as the result of the increased discharge. The velocity of subsurface flow in Quebrada Pasto likely increased as well.

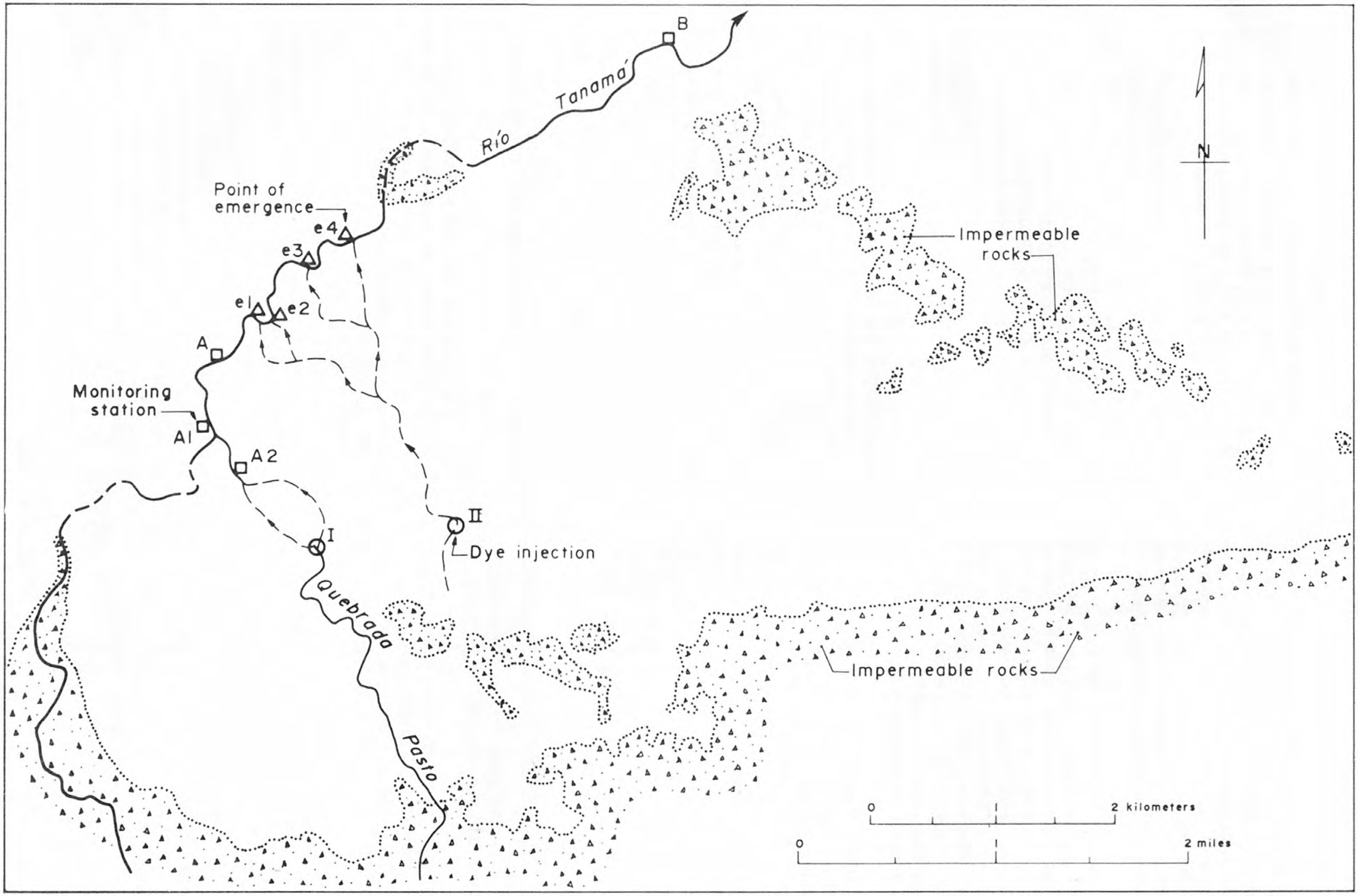


Figure 8.--Hypothetical subsurface paths of dyed water from injection sites of Phase I and Phase II to possible emergent points along Río Tanamá.

Phase II

The second dye injection was made October 25 in a sinkhole in the decant pond. The dye was placed in a small stream emerging in one side of the sink and disappearing in a swallow hole on the opposite side--a distance of perhaps 75 feet. Mixing of the dye with the flow was rapid and all visible traces of dye disappeared within 30 minutes. First appearance of the leading edge of the dye cloud was at observation site B on Río Tanamá 2 days later.

Four possible subsurface paths for the dye were selected. The paths and their estimated points of emergence are shown in figure 8. Velocity of subsurface flow by different paths ranged from 2.9 to 3.8 feet per minute.

Phase III

The third injection of dye was made November 7 in a pool in a sinkhole in the eastern part of the large tailing pond. There was very little movement of water in the pool and the dye did not disappear visually until 2 hours after injection. The following morning dye was observed visually in a sinkhole (site IIIa, fig. 9) north of the injection site. No further observation of the dye was made until its appearance at site B nearly 4 days after injection.

Four possible paths to Río Tanamá are shown in figure 9, of which the downstream part of two overlap those selected for Phase II. The velocity of the dye from the injection point to the sink at IIa is computed to be about 3.7 feet per minute. Velocity of subsurface flow for the total length of the four paths, however, ranged from 2.4 to 2.8 feet per minute. The higher velocity in the segment III to IIIa indicates either a steeper gradient or a relatively open channel, either of which would allow for more rapid movement.

Traces of dye were observed in San Pedro Spring (fig. 1) during Phase III, indicating subsurface movement of water from Río Tanamá. The dye first was detected at 1215 November 13, but the edge of the dye cloud is estimated to have reached the spring from 12 to 18 hours earlier. No traces of dye were observed in Quebrada Jobos during Phase III, nor would it be expected because Quebrada Jobos lies beyond a ground-water divide.

The peak dye concentration observed at San Pedro Spring and the estimated discharge, 15 µg/l and 10 cfs (cubic feet per second), respectively, were about one-tenth of that observed at Site C on Río Tanamá. A rough computation on the basis of dye concentration and discharge indicates a loss of about 1 cfs from Río Tanamá to the Spring--about one-hundredth of the discharge of Río Tanamá at the time.

The water loss from Río Tanamá probably occurred somewhere between Site C and Charco Hondo (fig. 1). One possible area is about 0.8 mile downstream of Site C, and a second is about 0.2 mile upstream of the old hydroelectric plant at Charco Hondo. A subsurface velocity of about 6 feet per minute from the first site and about 3 feet per minute from the second would be required for dyed water to move from river to spring.

Inherent in the results of this experiment is that Río Tanamá not only receives water from some of the limestone area, but also distributes it. Data are not available to state how much water is distributed at times or whether it occurs in some degree all the time.

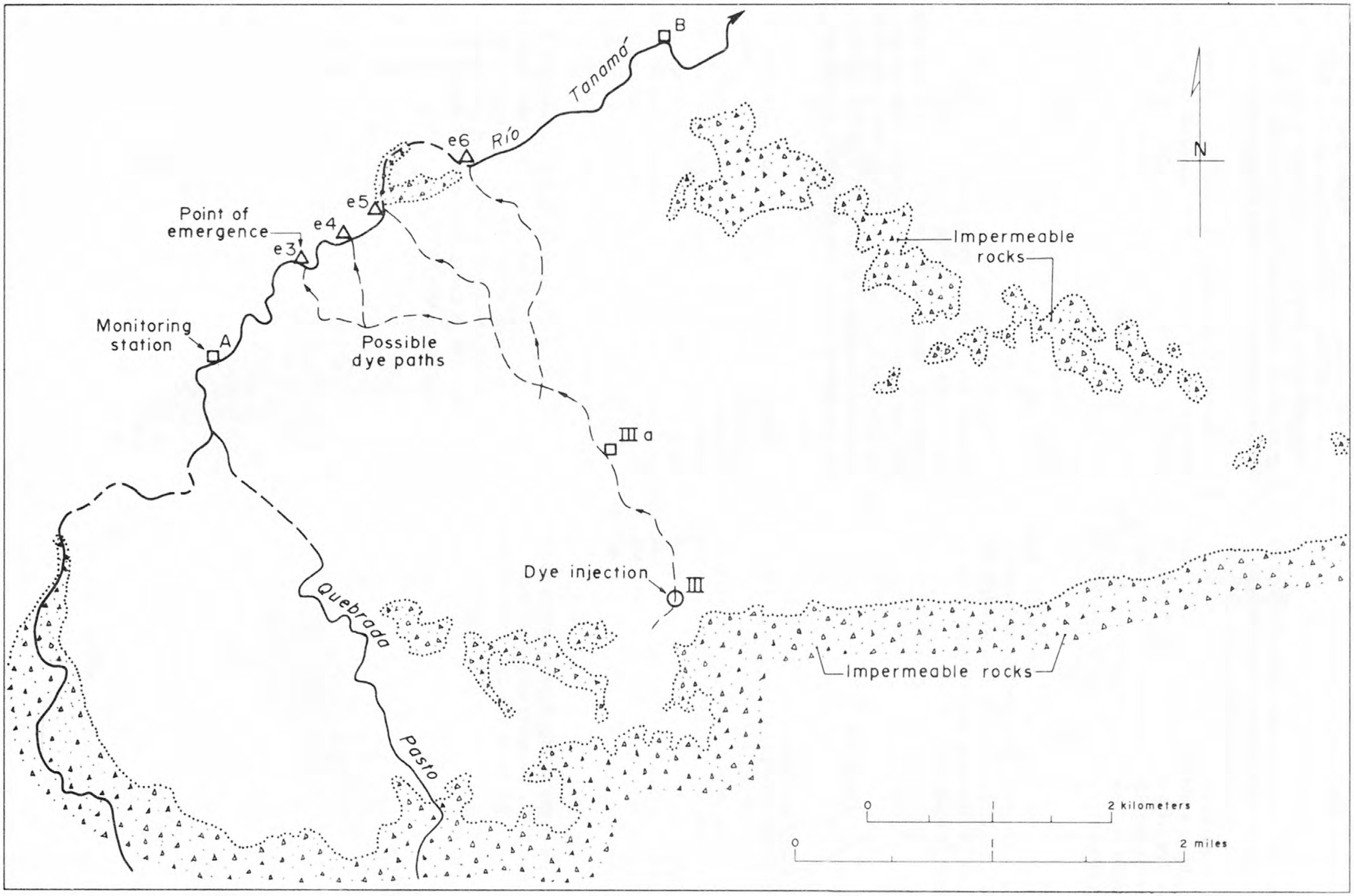


Figure 9.--Hypothetical subsurface paths of dyed water from injection site of Phase III to possible emergent points along Río Tanamá.

A copper-bearing concentrate will be produced by an industrial firm from the ore by a flotation process, which requires that the rock be ground to an almost flour-like size in order to release the copper-bearing minerals. The Tanamá ore reportedly will be reduced by grinding preparatory to flotation, until about 88 percent of the material will pass a 400-mesh screen. After flotation and the removal of most of the copper-bearing minerals, the residue will be disposed of as tailings. The bulk of the tailings, therefore, will be less than 37 microns in diameter, falling in the clay to silt size of the Wentworth particle-size classification.

Because of the large difference in the size of the crushed mineral-bearing rock from two similar ore bodies, an attempt was made to obtain representative samples of tailings from operating mines. Tailings from test milling of rock of the Tanamá ore was unavailable, but a sample of tailings from a mine in Utah was obtained from the Puerto Rico Industrial Development Laboratory. The particle size of the Utah tailings reportedly is similar to that to be produced in the Tanamá operation, but it was found that although 100 percent of Tanamá particles will be 625 microns or smaller, 76 percent of Utah particles were between 625 and 1,000 microns in size. The size analysis is given in table 2.

Table 2.--Particle size of tailings from Utah mine and Tanamá mine.

Size, mm	Cumulative percent finer	
	Utah 1/	Tanamá 2/
1.0	100	
.50	65	
.25	42	
.125	9	
.0625	9	100
.0312	6	79
.0156	4	49
.0078	3	32
.0039	1	14
.00195	1	7

1/ Analysis by sieve and bottom withdrawal tube in Río Pellejas water.

2/ Size distribution of Tanamá tailings is partly theoretical, being based on 88 percent of particles passing a 400-mesh screen and on the cumulative curve of Utah sample.

Since there is such a large variation in size between the Utah tailings and the reported size of the Tanamá tailings, a comparison of the two in regard to erosion transport and deposition was made.

Of primary concern is the possible escape of tailings from the ponds in the karst terrane to Río Tanamá. Whether the tailings would reach Río Tanamá if leakage from the ponds occurred depends in part upon the sediment transport capability of the subsurface flow. This in turn depends in part upon the size of the sediment.

The size of the tailings particles is critical to the degree of transport the tailings might undergo once deposited in the tailings ponds. Hjulstrom (Krumbein and Sloss, 1951) formalized the hydrodynamic relations of particle movement in running water, demonstrating that at certain critical velocities particles will be eroded, transported, or deposited. A comparison of particle size of the Utah tailings and the theoretical particle size of the Tanamá tailings is shown in figure 10.

The size distribution of the Tanamá tailings has been plotted as a bar graph on the Hjulstrom diagram in figure 11. The base of the bar graph is at 1.3 cm per sec velocity (same as 3.5 feet per minute computed for Phases II and III of dye tests), which shows that the entire range of tailings is in the "transportation" zone.

In a similar manner, the size distribution of the Utah tailings has been plotted as a bar graph on the Hjulstrom diagram in figure 12. The base of the bar graph also is at 1.3 cm per sec velocity. Only part of the tailings falls in the "transportation" zone. The larger part would be deposited.

At the minimum velocity of 4.1 cm per sec (9.6 ft per min) obtained in Phase I, all but the coarsest part of the Utah tailings and all of the Tanamá tailings fall in the "transportation" zone.

It must be emphasized that the velocities computed for the dye tests may be from one-tenth to ten times as much in any reach of the subsurface path. The higher velocities are critical with respect to transportation and erosion of sediments; but the lower velocities probably will control because the sediments will drop out and tend to clog the passageways.

Figure 10.--Cumulative curve of particle size of tailings, Tanamá ore body and Utah mine.

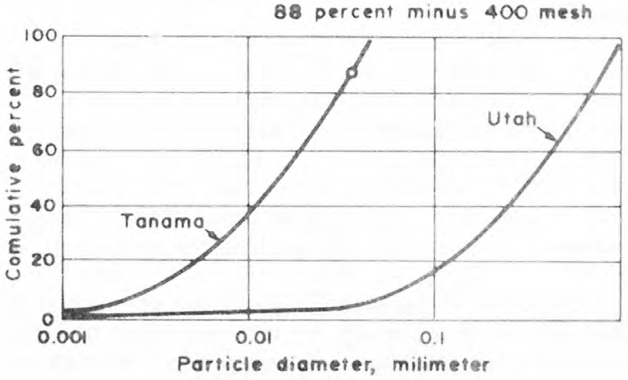


Figure 11.--Relation of erosión, transportation, and deposition of Tanamá tailings to water velocity.

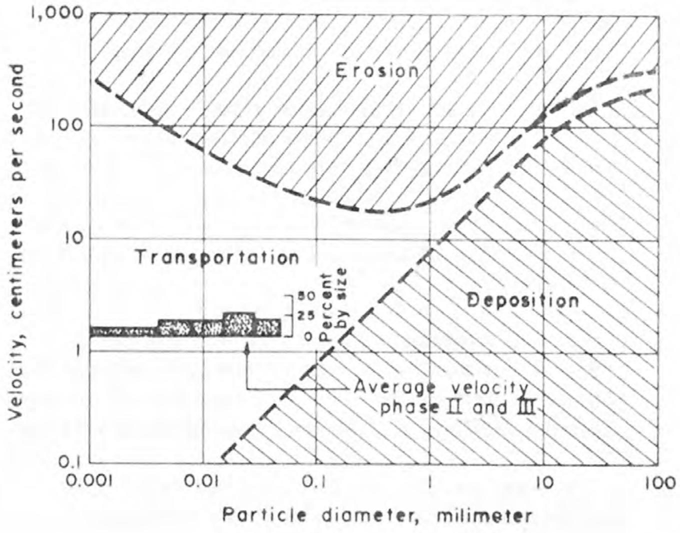
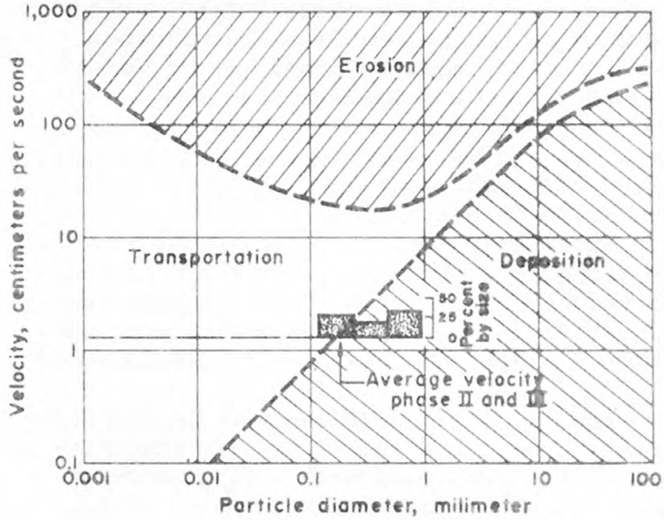


Figure 12.--Relation of erosion, transportation, and deposition of Utah tailings to water velocity.



Due to the small particle size of the proposed tailings, water velocity of less than 1 cm per sec will keep the finer particles in suspension and movement. The large percentage of the tailings particles in the clay range will result in a very slow settling rate of this fine fraction even in quiescent ponds. The smaller clay particles 0.001 mm in diameter will settle at about 0.0001 cm per sec (1 foot in 3 days). Silt 0.02 mm in diameter will settle at a rate of about 0.04 cm per sec (1 foot in 10 minutes) (Krumbein and Sloss, 1952). One-half to two-thirds of the tailings likely would settle out in a matter of minutes, whereas the remainder may take days. Once deposited, however, erosion of the particles would require a velocity as much as 100 times greater than that necessary for transportation.

Tailings as a Sediment Hazard

A major hazard that may be encountered is the possible escape of tailings from the ponds while the tailings are in a slurry or highly saturated, still mobile state.

The most probable means of escape would be through unplugged solution openings in both the sides and bottoms of the ponds. The greater part of the ponds lie in the lower part of the Lares Limestone, in which solution is extensive. Even though it is proposed to seal the ponds with a clay blanket, it is possible that some openings not be sealed permanently and new openings will develop. Constant surveillance would be required to detect leaks of this nature.

A massive blowout would be a serious problem. The tailings while in a saturated state will exert considerable hydrostatic head on the sides and floors of the ponds. It is conceivable that in places only thin walls of rock exist between the ponds and extensive cavern systems. Sufficient pressure could cause collapse of the walls or floors and consequent escape of large volumes of tailings toward Río Tanamá.

It is possible that tailings escaping from the ponds would deposit in caverns and solution openings and eventually seal them. There always is the possibility of a head of water building up behind any such plug, creating pressure sufficient to blow out the plug. The resulting water velocity could be high, erosion of deposited tailings could take place, and a slug of tailings could enter Río Tanamá.

If tailings did create a permanent seal in the lower part of the cavern system it would mean that the water that presently flows through the system would of necessity have to find a new outlet to Río Tanamá. The outlet undoubtedly would be at a higher level. Ground-water levels in the limestone then would become higher and could conceivably turn some of the deeper sinkholes in the area into small lakes.

If an effective sealing by escaping tailings occurred in the immediate vicinity of the tailings ponds, excess water from the tailings ponds then would go to the decant pond, as now planned, from which it would be recycled to the concentration plant. However, any tailings fluid leaked directly to the subsurface or spilled over a saddle between the hills confining the pond would eventually reach Río Tanamá.

The transportation or deposition of the tailings, particularly those in the clay range, can be affected by the kinematic viscosity, temperature, pH, and mineral composition of the tailings water and also of the natural ground water with which the tailings and tailings water would mix in the subsurface. Flocculation and possible rapid settling of the clay-size particles is related to these variables. Much depends upon the physical and chemical parameters of the waters. This applies to both retention of the tailings in the ponds and their possible escape from the ponds.

Tailings as a Water-Quality Hazard

Chemical reactions will occur within and between the tailings, tailings water, limestone, and native water of the Río Tanamá basin. A major uncertainty is the effect of the tropical climate on these chemical changes, on which comparatively few data seem to be available.

Typical chemical analyses of native water from Río Tanamá prior to entering the limestone terrane and near the mouth of the river are given in table 3. Principal changes in the water between these two points are increases in calcium and bicarbonate, and an associated increase in hardness and dissolved solids--the effect of ground water discharging from the limestone aquifer into the river. Iron in solution is not evident either upstream in the volcanic rocks or downstream in the limestone. Sulfate, which is low at the upstream station, is even lower at the downstream station due to dilution by the inflow of ground water from the limestone.

Tailings Water

An analysis of tailings water from laboratory experiments is given in table 4, as furnished by the Puerto Rico Mining Commission. In addition to the mineral content of the water, there will be residue of pine oil and Dow-Z-200, ingredients added in the flotation process. These additives reportedly will decompose into harmless compounds within a few days. However, more information on their degredation is needed.

The high pH of the tailings water is attributed to lime added during flotation. It can be expected that a pH of about 10 will decrease rapidly in the tailings ponds to about pH 7, after precipitation of calcium carbonate and aluminum. Trace minerals will be expected to precipitate, possibly as carbonates, or be occluded (?). The tailings water, provided it is not strongly affected by chemical reaction with the tailings or local rock, probably will stabilize as a sulfate water with high hardness. If released to Río Tanamá, the quality of the native water will be degraded by the addition of the more mineralized tailings water. The degree of degradation will, of course, depend upon the volume of water from each source.

Table 3.--Typical analyses of Río Tanamá water.

Date of collection	Discharge, cfs	Milligrams per liter																	Specific conductance (micromhos at 25°C)	pH	Color	Temperature °C
		Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Orthophosphate (PO_4)	Dissolved solids, calculated	Hardness as $CaCO_3$					
																	Calcium, magnesium	Non-carbonate				
April 12, 1966 1/	20.7	25	0.00	0.00	16	7.3	6.2		74	--	12	6.6	0.0	1.0	--	110	70	9	166	7.2	5	24
April 18, 1966 2/	46.5	10	.00	.00	46	5.6	1.4		156	--	1.2	7.2	.0	2.8	--	171	138	10	280	7.7	5	25
April 2, 1969 1/	20.9	25	--	--	16	5.6	8.6	1.4	69	--	13	7.2	.0	.4	0.0	111	63	6	161	7.3	--	25
April 2, 1969 3/	48.9	5.5	--	--	47	3.7	6.8	.7	156	--	6.6	7.3	.3	.4	.0	155	133	5	285	8.2	--	24

1/ Río Tanamá at Highway 111.

2/ Río Tanamá at Highway 10.

3/ Río Tanamá at Charco Hondo.

Table 4.--Analysis of tailings water from laboratory experiments. (Data furnished by Puerto Rico Mining Commission.)

Constituent	Concentration	
pH	10.6	
TDS	250	mg/l
Alkalinity as $Ca(OH)_2$	118	"
Ca	85	"
Al	30	"
Fe	0.5	"
Na	4	"
SiO_2	5	"
As	0.05	"
Cu	0.05	"
Trace Minerals		
Ba	25	µg/l
Bi	< 2.5	"
Ga	2.0	"
Ge	1.8	"
Mn	12.5	"
Mo	800	"
Ni	< 2.5	"
Pb	< 7.5	"
Ti	25	"
V	5	"
Yt	< 2.5	"
Zr	2.5	"

Tailings Solids

The great uncertainty is that chemical reactions may take place in the tailings and exert control on the composition of the tailings water. This in turn would affect native water. An analysis of samples from the Tanamá ore body is given in table 5. The tailings can be expected to have much the same composition, less the copper extracted.

Dennis Cox (personal communication) makes a preliminary estimate that pyritic material averages about 3 percent in the ore body, but that it may range from none to 8 percent. It also is present in the waste rock that will be removed in mining the ore, but probably in somewhat lower concentration.

The pyritic material in the tailings undoubtedly will be a potential source of pollution, for pyrites will produce sulfuric acid and ferrous sulfate when exposed to air and water. The end result is an acid water and an iron oxide precipitate derived from the breakdown of the ferrous sulfate. Water quality may be degraded further by increases in hardness, sulfate, and heavy metals nor normally present in nearly neutral or basic water.

Table 5.--Mineral constituents of Tanamá ore body. (Data furnished by Puerto Rico Mining Commission.)

Mineral	Percent by weight
Quartz	40
Plagioclase feldspar	18
Chlorite	20
Magnetite	10
Pyrite	10
Carbonates	1
Kaolinite	Trace
Epidote	Trace

The rate at which the breakdown of pyritic material will take place is a function of the interaction of physical, chemical, and bio-chemical forces. The result may be either rapid and voluminous production of acid, or production of acid at a slow rate and in meager amount. The principal parameters are size and surface area of pyritic crystals exposed; presence of bacteria capable of catalytic action; temperature; duration of contact with air and water; dissolved oxygen content of the water; presence or absence of inorganic metals capable of catalytic action; presence or absence of organic material; and quite possibly photocatalytic effects.

Presumably the mineral composition of the tailings will approximate that shown in table 5, less the copper removed. The particles largely will be in the 37-micron range and will be suspended in a thick slurry with a pH about 9 to 10.

The question of chemical significance is whether acid water will be produced from this slurry. A minor amount of acid may be produced when local surface water or rainfall dilutes the slurry. This will be a surface effect only and one that should be controlled easily if significant, either by spreading lime or by diluting with native alkaline water. In the event that acid is produced on the surface of the tailings ponds, the runoff water after neutralization would be degraded by an increase in sulfate compounds, dissolved solids, and hardness. The effect of such water released to Río Tanamá would be minor in comparison with untreated acid-water release. Whether or not acid is produced, there may be deposition of yellow or brown iron oxide in the vicinity of the tailings ponds.

There is evidence to suggest that anaerobic oxidation of pyritic materials can take place underground, below the water table, but this phenomenon has been observed only in anthracite mines in Pennsylvania. The interior of the tailings deposits presents conditions radically different from those in coal mines.

In this study area, we are dealing with extremely small particles of pyritic material that in effect are coated--that is, they are suspended in a mixture of water and other, essentially inert fines. Very little chemical action is expected, at least as far as oxygen is concerned. Clumping of the pyritic particles within the mass of tailings is improbable, and rainfall or applied local water that may be highly charged with oxygen will not percolate downward and upset the coating effect because of the higher specific gravity of the tailings slurry.

Even after the mines cease operations, the tailings probably will retain a considerable amount of water that will not drain by gravity. Surface drying during dry periods could produce a powder, however, that might result in a small amount of acid being produced when rainfall contacts it. But since one of the by-products of oxidation is a ferric-hydroxide gel, the reaction in all probability will be self-limiting, for the gel will act as a sealant to vertical water movement.

It has been suggested that blankets of clay be spread on the tailings ponds at successively higher levels of the ponds, to provide barriers against percolation of water through the tailings. This is a technical refinement of limited value, because the tailings themselves will be in the clay particle size and percolation will be very slow to negligible once the tailings have settled and become compated by gravity. There also is the practical aspect of trafficability of the tailings. If they will sustain vehicles carrying and spreading clay, they already are compacted to the point of having low porosity.

The foregoing is not meant in any way to minimize the potential danger of acid pollution in the mining area, nor the effect of acid pollution that is a matter of deplorable record in coal-mining regions of the United States. Insofar as acid-water production from the tailings is concerned, perhaps the reader might dwell upon some of the opposite problems that a chemical engineer would face if he were given the assignment of producing and recovering sulfuric acid from tailings ponds like the ones planned for the mining area. It would be difficult.

It is not within the scope of this report to cover acid-water production from either waste rock or fresh cuts in the pit face. But it must be borne in mind that the same parameters that govern acid production from such sources will be vastly different in degree from those encountered in tailings storage.

ACKNOWLEDGMENTS

Data on mining operations given in this report were furnished by the Puerto Rico Mining Commission. The report draws heavily on the administrative report on water tracing prepared by the U.S. Geological Survey in cooperation with the Mining Commission, for which personnel of the Mining Commission and of Cobre Caribe participated in selecting dye-injection sites, helped inject the dye, and collected water samples.

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