

Environmental Geology

Volume 2, Number 4

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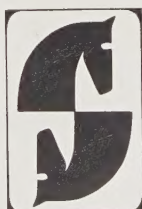
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Arsenic in Streams, Stream Sediments, and Ground Water, Fairbanks Area, Alaska

F. H. Wilson* and D. B. Hawkins

Geology Department and Institute of Water Resources
University of Alaska

ABSTRACT / Arsenic concentrations of less than 5 ppb to as large as 1,260 ppb in stream waters and from 5 ppm to 4,000 ppm in stream sediments were found in the Pedro Dome–Cleary Summit area, Alaska. Waters from three of 20 wells sampled had arsenic concentrations exceeding the U.S. Public Health Service recommended limit of 50 ppb. The high arsenic levels are a consequence of arsenic enrichment in the rocks of the area. Placer and lode-gold mining may increase the arsenic content of the waters by exposing arsenic-containing rocks to surface waters and by increasing the load of arsenic-rich sediments in the streams. Finding these disturbingly large concentrations of arsenic in the waters of the Fairbanks area was the major result of this work, inasmuch as a subsequent study (to be published) revealed arsenic concentrations as large as 10 ppm in domestic wells and prompted an extensive study by Federal and State agencies of the health hazard posed by these arsenic-rich waters.

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Introduction

This study was initiated to evaluate the arsenic content of streams and ground waters of the Pedro Dome–Cleary Summit area approximately 30 km north of Fairbanks, Alaska, in the heart of the historic Fairbanks Mining District (Fig. 1). Arsenic is associated with gold mineralization here and is believed to reach the waters of the area through weathering of arsenic-containing rocks.

Arsenic in a 70 mg dose is toxic to humans and at low concentrations is a carcinogen (Luh and others 1973). Arsenic also has been linked to cardiovascular ailments and to skin cancers (Bloom and Lewis 1973). These potential hazards in an area of increasing population prompted this study. Additionally, information was desired on the behavior of arsenic in the environment.

Setting

The study area is underlain by a metamorphic terrain of green schist facies metasediments (Yukon–Tanana Complex). More highly metamorphosed rocks occur around intrusives. Quartz-muscovite and calcareous schists with scattered gneisses are common. Into these were intruded small felsic plutons that are responsible for the sulfide and gold mineralization. The area lies within the Yukon–Tanana upland, a geomorphologically mature region mantled by loess derived from outwash fans which extend northward from the Alaska Range. The elevation of the area is about 600 m and ranges from 200 to 800 m above sea level. Three drainage systems, the Chatanika River, Goldstream Creek, and Fish Creek, divide the area into convenient sections for study (Fig. 1). In each of these drainages, parts of the major creek are floored with dredge tailings. In addition to placer mining, lode-gold mining took place in both the Fish Creek and Chatanika River drainages and, to a lesser extent, in the Goldstream drainage.

The economic mineralization in the Fairbanks district was classified into three categories by Brown (1962):

1. Gold, stibnite, and quartz
2. Sulfide (galena and jamesonite)
3. Scheelite

The mineralization is confined to a northeast-trending belt through the center of the area. The mineralization occurs as fissure fillings in the schist, although some veins also occur in the small plutons of Pedro Dome. Arsenic is primarily associated with the gold mineralization and secondarily with the sulfide mineralization.

Gold was discovered in the area in 1902. Subsequently, placer-gold operations were established in many of the creeks of the region with dredging beginning in 1911. The first lode-gold claim was established in 1903. Peak gold production for the district was in 1909. By the summer of 1974, only a few small placer operations remained active.

The Fairbanks area is becoming increasingly populated. The major development within the study area has been in the Goldstream Valley, where many homes are built on dredge tailings. The remainder of the study area is sparsely populated, with a total population of perhaps 400 people.

Methods

Sampling

Samples of water, suspended load, and bottom sediments were taken at approximately 85 localities, including 20 wells and springs (Fig. 1). During the summer of 1974, three collections were made at each locality, except where streams had dried up or where access to some of the wells was not possible. Collections were made in late May and early June, late June and early July, and late July and early August.

Prior to sampling, all sample bottles were soaked overnight in 70% HNO_3 , rinsed in fresh 70% HNO_3 , and then rinsed in deionized water. The bottles were then sealed for use in the field. At the time of sample collection, the pH and temperature of the water were measured and the sample was acidified with 10% HNO_3 to a pH of about 2. Bottom sediment samples were collected whenever possible, with the finer size fractions being preferred. Filtration of the samples in the field was a problem. After the first collection, samples were filtered in the laboratory although the samples were acidified in the field.

Analytical

An atomic absorption method, modified from that of Fernandez and Manning (1971), was used, employing the graphite furnace accessory. A Perkin Elmer model 303 atomic absorption spectrophotometer (A.A. unit) equipped with the HGA-2000 graphite furnace gave rapid and consistent results even at low concentrations. This apparatus allowed detection of $2 \times 10^{-4} \mu\text{g}$ of arsenic. However, the unit must be in near perfect adjustment to reach this sensitivity. To achieve this, the unit was adjusted to experimentally determined optimum conditions following the procedure given in the Perkin-Elmer manual for the graphite furnace. Standards and samples were compositionally matched, although it was found that the response of the instrument was independent of the bulk composition of the samples analyzed. Acids having small arsenic content were used in the digestions and were selected to reduce the level of arsenic contamination arising from the digestion procedure. All glassware was washed in 70% HNO_3 before use.

Results

The results of this study are summarized in the histograms in Fig. 2(a–d). The relationships among the arsenic concentrations of the water, suspended sediment, and bottom sediment for those

samples with analytical values greater than the detection limit for all three phases are shown in Fig. 3. Because unfiltered samples were acidified, the arsenic concentration of the water was somewhat higher than the natural value because of dissolution of arsenic from the suspended load. Therefore, Fig. 3 provides only an estimate of the true distribution of arsenic between the water and suspended sediment. The arsenic concentrations of the combined water and suspended sediment samples and the bottom sediment samples are not subject to this constraint. A complete set of data is available from the authors upon request.

Discussion

Stream samples

As shown in Fig. 2a, the arsenic concentration of 188 stream water samples ranged from less than 5 ppb to as large as 1,260 ppb. About 60% of the samples had concentrations less than 20 ppb and 90% of the samples contained less than 60 ppb arsenic. The extreme value of 1,260 ppb was from a stream heavily laden with sediment arising from active placer mining upstream.

The arsenic concentration of 182 suspended-sediment samples (Fig. 2b) ranged from less than 5 ppb to as large as 17,700 ppb. About 90% of the samples contained less than 20 ppb arsenic. The extreme value of 17,700 ppb arsenic was from a stream laden with sediment from placer mining.

The arsenic concentration of 178 bottom sediment samples (Fig. 2c) ranged from 5 ppm to as large as 4,114 ppm. About 70% of the samples contained less than 100 ppm arsenic and 90% of the samples contained less than 400 ppm. Samples containing greater than 1,000 ppm were from streams on which placer mining was occurring.

The arsenic concentrations in 53 water samples from wells and springs (Fig. 2d) ranged from less than 5 ppb to 70 ppb. Eighty percent of the samples contained less than 10 ppb and 95% of the samples contained less than 50 ppb. No unequivocal causal relationship is evident between the arsenic content of the ground water and mining activity.

As shown in Fig. 2a, b, and c, the arsenic concentration data are positively skewed. Cumulative probability plots of these data showed that these data could be approximated by a log-normal distribution. Therefore, a log transformation of the arsenic concentrations was done before other statistical analyses of the data were made.

For the data shown in Fig. 3, the correlation between the logarithm of the arsenic concentration of the water and the logarithm of the arsenic concentration of the bottom sediment is 0.469, which for the 55 data points is significant at the 99% confidence level. A linear regression of the log As(water) on log As(sed) yielded the equation shown in Fig. 3. An r^2 value of 0.22 was obtained for this regression, indicating that 22% of the variance of the log As(water) values is associated with increasing values of the independent variable log As(sed). From Fig. 3 it is

Figure 1. Simplified bedrock geologic map showing the location of the study area, drainages, and sampling sites of the Pedro Dome–Cleary Summit area of the Fairbanks district, Alaska.

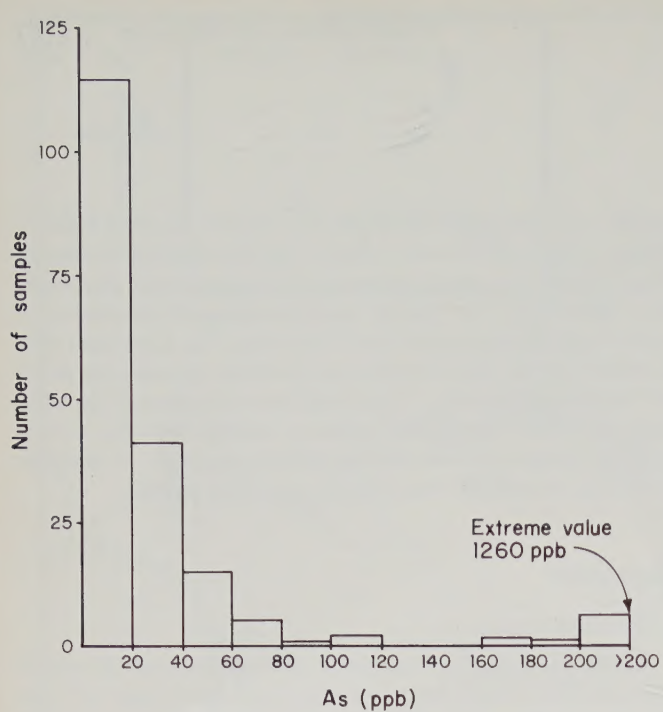


Figure 2a. Surface water, As in water (ppb), 188 samples.

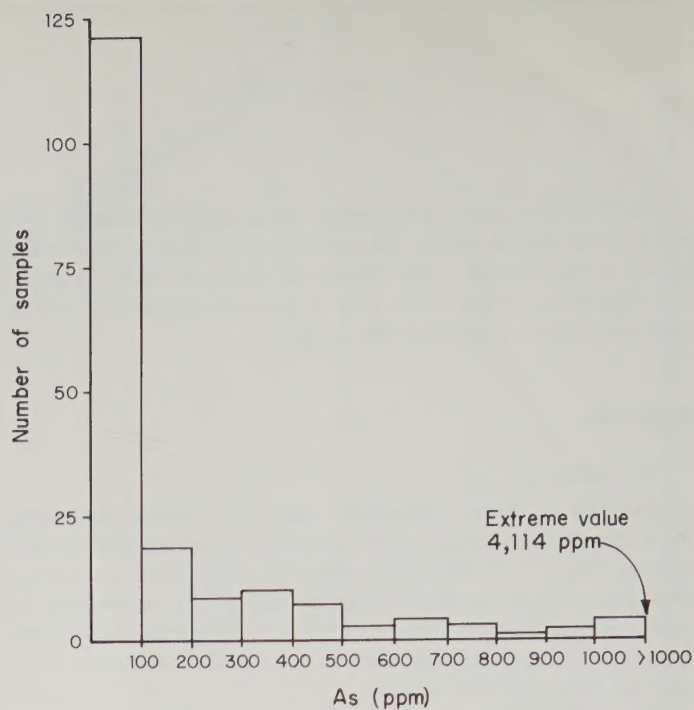


Figure 2c. Surface water, As in bottom sediments (ppm), 178 samples.

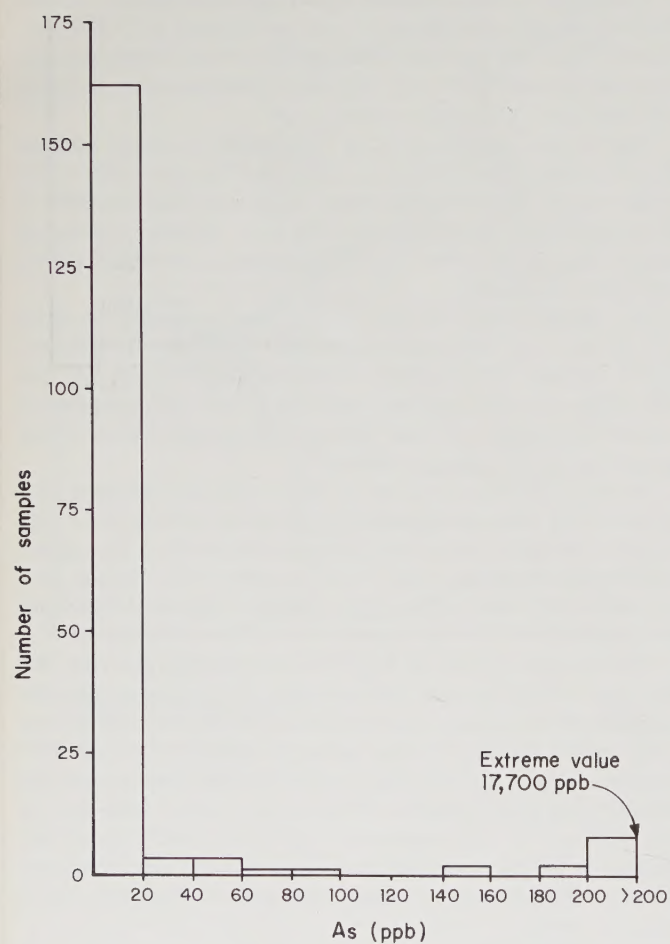


Figure 2b. Surface water, As in suspended sediments (ppb), 182 samples.

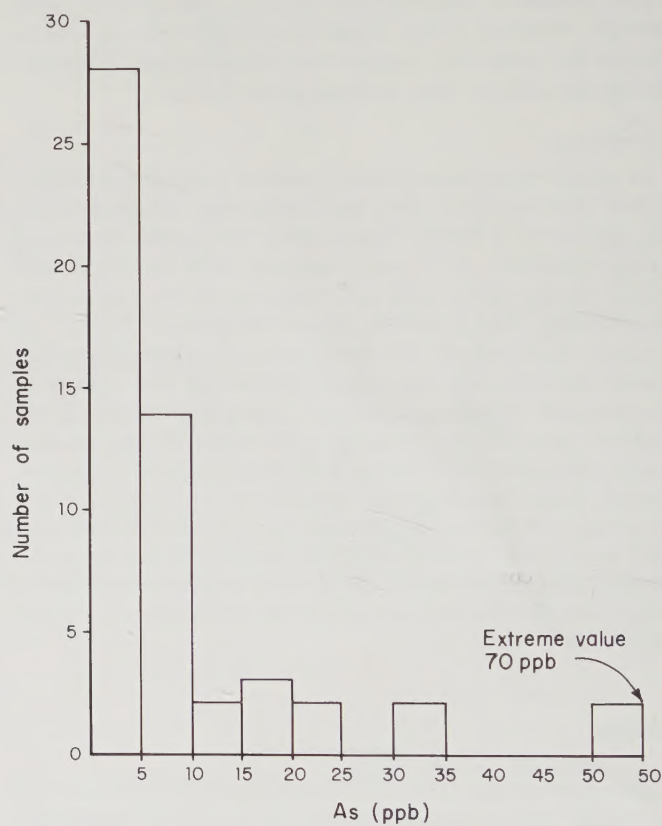


Figure 2d. Springs and wells, As in water (ppb), 53 samples.

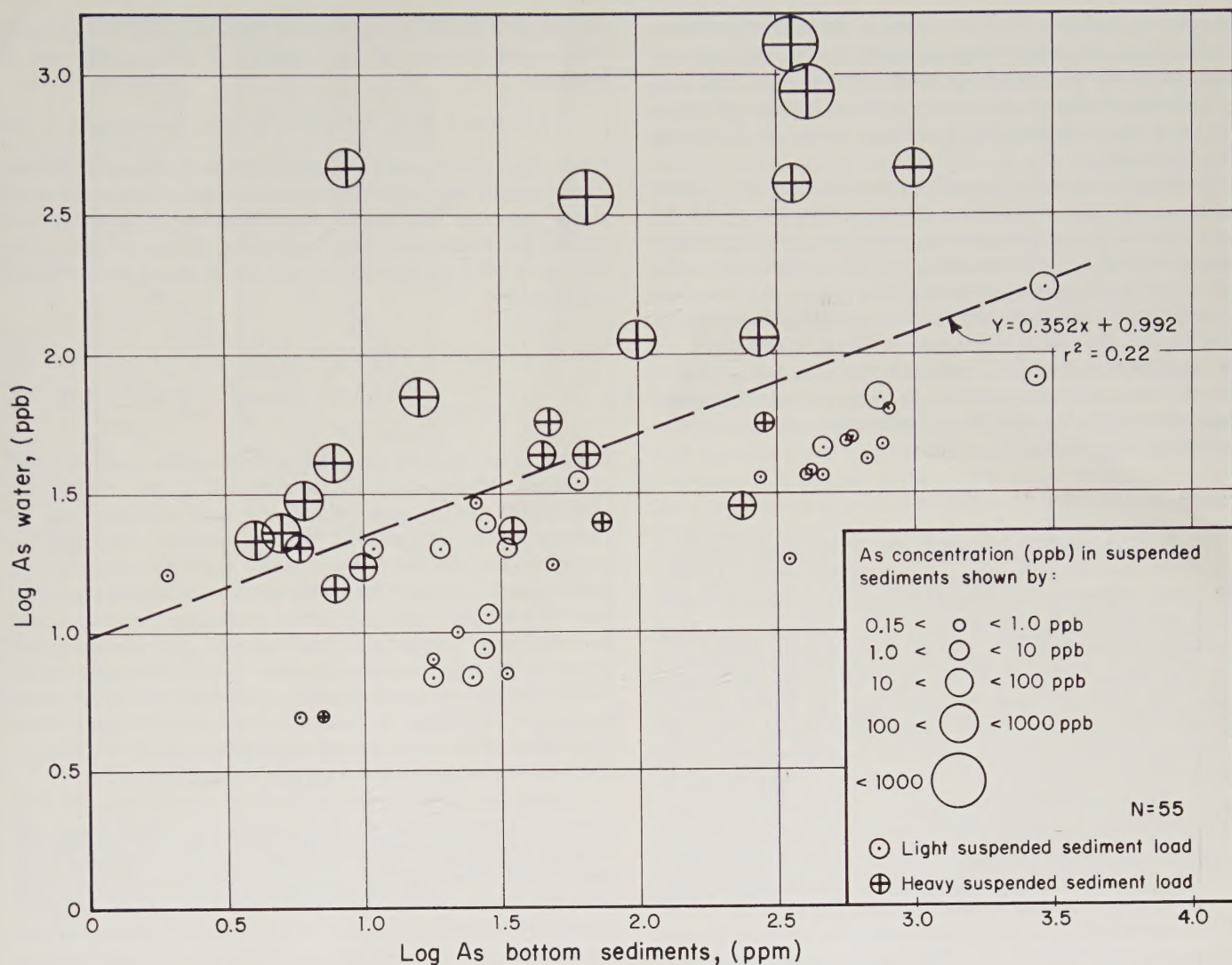


Figure 3. Log As concentration (ppb) in water versus log As concentration (ppm) in bottom sediments.

evident that larger concentrations of arsenic in water are associated with larger concentrations of arsenic in bottom and suspended sediments. Furthermore, the larger concentrations of arsenic in water are found in samples having larger sediment loads. Although this is not evident from Fig. 3, these large sediment loads result from placer mining. The relationships shown in Fig. 3 imply that the higher the concentration of arsenic in the bottom and suspended sediments and the larger the suspended-sediment load, the greater the concentration of dissolved arsenic in the water. Although this apparent relationship makes sense for the natural system, the relationship may be an artifact of the sample treatment, i.e., acidification prior to filtration. We think, but cannot prove from these data, that the suggested relationship is valid for the natural system. The regression equation shown in Fig. 3 can be used to estimate the dissolved arsenic concentration

(ppb) in stream water, given the arsenic concentration (ppm) of the bottom sediments. For the natural (unacidified) system, these estimated values of dissolved arsenic should be larger than the true value.

Analysis of variance (ANOVA) for combined water and suspended-sediment samples and for bottom-sediment analyses were used to determine the sources of variability in the arsenic concentrations with respect to time of collection, drainage area, and the amount of sediment load. The BIO MED program BMDO64x (Dixon 1973) was used for these ANOVA's. The ANOVA's supported the relationships among the arsenic concentrations of water and suspended and bottom sediments previously discussed and showed that the arsenic concentration of the samples from different drainage areas differed significantly. Most of the arsenic-rich samples were from the Fish Creek and Cha-

tanika River drainages. Variance owing to the time of collection was less than that attributable to other factors and was not significant at the 95% confidence level. Nevertheless, there may be a tendency for the arsenic concentration to increase with time over the summer, particularly in the Fish Creek and Chatanika River drainages.

Results of a correlation analysis were ambiguous and suggested that no clear-cut relationship existed among the pH of the water, the arsenic concentration in the water, and the arsenic concentration in the bottom sediments. The correlation coefficient between the arsenic content of the water and the water temperature for a series of eight samples taken from three sample localities over the summer was not significant in two cases but was significant at the 95% confidence level for the third. We interpret these ambiguous results to mean that no significant relationship exists between water temperature and the arsenic concentration in the water.

Wells and springs

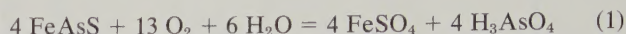
The 20 wells sampled were split into three groups based on their arsenic content (Fig. 2d). The three groups were: (1) wells with arsenic concentrations consistently less than the U.S. Public Health Service (1962) recommended limit of 10 ppb, (2) wells consistently above this limit, and (3) wells varying around this limit over time. Fifteen wells fell in group 1, the low-arsenic wells. Two wells belonged to group 3, those having arsenic concentrations equal to or slightly greater than 10 ppb. The wells in both groups were from a variety of locations, had depths ranging from 9.5 to 130 m, and were completed in bedrock and in gravels. Three wells were in group 2, the consistently high-arsenic concentration wells. These wells were drilled through dredge tailings to depths between 45 and 75 m and were completed in bedrock. As is true of most wells in the Fairbanks area, these do not have casings cemented in place, which may allow arsenic-contaminated surface-water to enter the wellbore thereby contaminating the water supply. This may be a source of arsenic contamination in domestic wells. A subsequent study by Wilcox, (in preparation) revealed arsenic concentrations as large as 10 ppm in domestic wells not associated with dredging. It seems that the association of arsenic-rich ground water and dredging noted in this study is probably fortuitous and not causal.

Owners of all wells sampled were informed of the arsenic concentrations found. The Alaska Department of Environmental Conservation and the Alaska State Department of Health and Social Services received copies of these letters. It was recommended to these agencies that the arsenic-rich wells be monitored periodically to see whether the arsenic concentrations were increasing or whether they posed a health hazard.

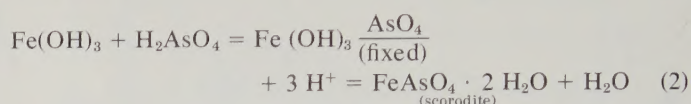
Geochemistry of arsenic

The geochemistry of arsenic has been reviewed recently by Boyle and Jonasson (1973). According to Boyle and Jonasson, during weathering of minerals containing arsenic, arsenic enters the surficial (exogenic) cycle mainly as soluble arsenates in which the element is present in the pentavalent (V) state. The oxidation

of arsenic minerals is complex and involves a number of steps. The overall process for the oxidation of arsenopyrite can be written:



Under highly acid conditions, arsenic in this form is quite mobile. Under weakly acid to basic conditions, arsenic(V) becomes relatively immobile because of coprecipitation on hydrous iron oxides that form under these conditions. Therefore, arsenic(V) ultimately will form the mineral scorodite as shown by the following equation:



Arsenic in the trivalent state (III) is not common under surficial conditions. Where the oxidation potential is low, As(III) can exist as $[\text{As}(\text{OH})_2]^+$ and H_3AsO_3 in acid solutions and as H_2AsO_3^- , AsO_2^- , or $[\text{As}(\text{OH})_4]^-$ in basic solutions. Arsenic(III) in these forms will be mobile because like As(V) it exists in natural waters mainly in anionic form. Inasmuch as the mineral constituents of soils and rocks are cation exchangers, arsenic is not immobilized by contact with these minerals. This was confirmed in our study when samples of water were taken immediately before and after it passed through a standard household cation exchanger. No change in the arsenic concentration was evident as a result of the water having passed through this exchanger. The behavior of As(V) and As(III) is summarized in Fig. 4.

Arsenic precipitated (reaction 2) in soils, sediments, and bogs may be released again to the environment by bacteria, fungi, and other microorganisms (Boyle and Jonasson 1973). Little is known about such processes but bacterial production of arsenates, arsenites, arsine (AsH_3), dimethylarsine $[(\text{CH}_3)_2\text{HAs}]$, trimethylarsine $[(\text{CH}_3)_3\text{As}]$, and other volatile arsenic compounds has been observed (Boyle and Jonasson 1973). Braman and Foreback (1973) also indicated that arsenic should occur in natural waters as methyl arsenic acid.

From the above discussion, primary arsenic present in the Fairbanks district as arsenopyrite and arseniferous pyrite (Chapman and Foster 1969) should be released to the waters of the area by weathering. In well-oxygenated waters, arsenic should be present in the (V) state as HAsO_4^{2-} , which form is quite mobile. However, it will coexist and ultimately coprecipitate with ferric hydroxide as shown in Fig. 4. Bottom sediments rich in ferric oxide and hydroxide should also be enriched in arsenic. Our data show that most of the arsenic burden of streams is in the sediments. Arsenopyrite is not evident in these sediments. It seems on the basis of this observation and the known geochemistry of arsenic that most of the arsenic is transported in streams by sorption on and transport of ferruginous sediments. The low dissolved arsenic concentrations ultimately observed even for streams draining arsenic-rich areas arise from an approach to equilibrium with this scorodite-like phase rather than with arsenopyrite.

With the exception of the three wells previously discussed,

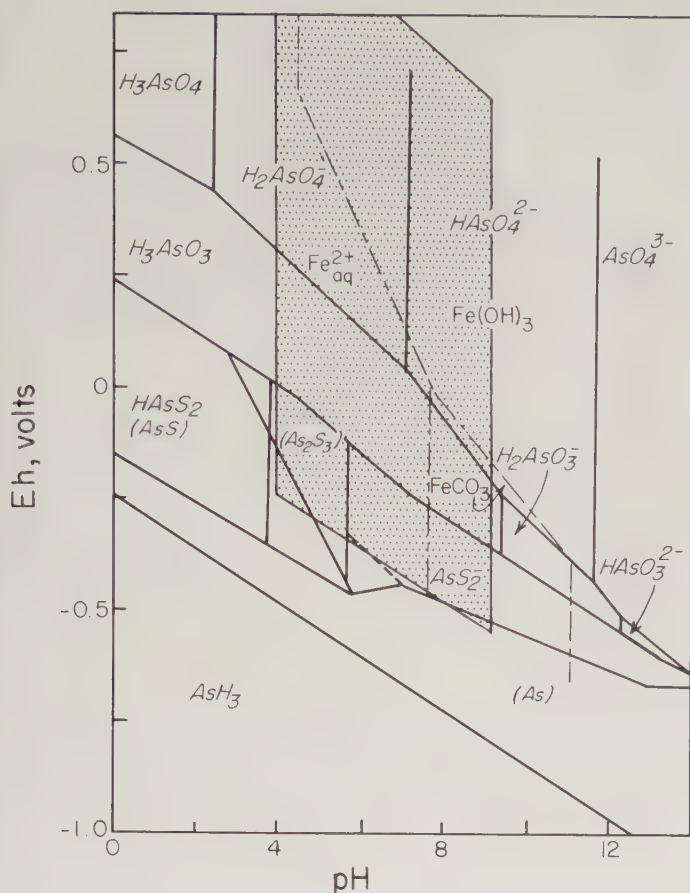


Figure 4. E_h versus pH diagram, showing various arsenic ionic species and iron minerals. Data compiled from Ferguson and Gaves (1973), Krauskopf (1967), and Garrels and Christ (1964).

the arsenic content of the ground waters sampled is small. Wilcox (in preparation) shows this to be a result of sample distribution, because wells in the Ester Dome area (southwest of the study area) contain as much as 10 ppm arsenic. Ground waters for which a source of arsenic is present and that are enriched in iron and therefore necessarily oxygen poor should also be enriched in As(III) (see Fig. 4). The ground waters of the study area range in pH from 6.5 to 8.5; in arsenic- and iron-rich, poorly oxygenated waters, therefore, As(III) as H_3AsO_3 should coexist with Fe^{2+}_{aq} . Upon aeration of these waters, the arsenic will be oxidized to As(V) as $HAsO_4^{2-}$ and the iron to Fe(III), ultimately to be precipitated as $Fe(OH)_3$ which should carry down the As(V) as shown in reaction (2). The relative rates of these oxidation reactions are not known. It may be possible for the iron to be oxidized before the arsenic and still coprecipitate arsenic in the (III) state following which the arsenic is oxidized. We can only speculate on this at present. It seems clear, however, that the geochemical behavior of arsenic in the waters of the Fairbanks district is closely tied to that of iron.

Effect of mining

The effect of gold mining operations on the arsenic content of streams in the area is not clear because of the difficulty of separating the effects of mining arsenic-enriched rocks from the natural effects of the rocks themselves. Both placer mining, by sluicing and dredging, and lode mining have been carried out in the study area. The effect of these activities is to accelerate the natural erosion and weathering processes. In lode mining, particularly during the milling stage, crushing increases the surface area of the rock and hence accelerates solution of the contained arsenic. As a result of the mining and milling operations, large quantities of tailings enriched in arsenic are exposed to weathering. In several streams studied here, high concentrations of arsenic in the sediments were the result of the dumping of mill tailings directly into the streams in the past.

Our data show that sluicing results in the addition of arsenic-rich sediment to the streams. This material may partially dissolve and contribute arsenic to the stream water. Because almost all the arsenic in the stream is present on the sediments, the quantity of mobile arsenic can be decreased markedly by allowing the sediments to settle out of the water used in placer mining before this water is discharged to the streams.

No dredge is currently operating in the Fairbanks district. Because of the depth and extent of dredge workings relative to sluicing, and because of the large quantities of frozen, fine-grained sediment that must be removed to expose the gold-bearing gravels, the effect of dredging should be similar to sluicing but it involves much larger volumes of sediments. At Engineer's Creek (Fig. 1), dredging has exposed deeply buried arsenopyrite-bearing cobbles to present-day stream waters. Although this is a unique situation, dredging in this instance has created a condition similar to that arising from lode mining, and at this locality it may be responsible for the arsenic content of poorly cased wells in these dredge tailings.

Conclusions

Surface waters and ground waters in parts of the Fairbanks Mining District are enriched in arsenic. There is a significant positive correlation between the dissolved arsenic concentration of stream water and the arsenic content of the suspended and bottom sediments. Placer mining operations, by adding large quantities of arsenic-rich sediments to stream waters, contribute significantly to the total arsenic burden of the stream. The mobility of arsenic in surface waters and ground waters is closely tied to the behavior of iron in these waters. Because of the mobility of arsenic and the numerous sources of arsenic available within the Fairbanks district, public and private water supplies in the mineralized zone should be examined for arsenic contamination. The most important result of this work is that it has provided impetus for a subsequent study that has revealed hazardous concentrations of arsenic in domestic water supplies elsewhere in the district. The presence of arsenic in wells in dredged areas and the desirability of these areas as building sites suggests that more care be taken in completing wells in dredge tailings. It seems

desirable to develop treatment techniques suitable for home use to remove arsenic and other metal pollutants.

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Landslides are a recognized geologic hazard responsible for both economic and personal losses. These losses could increase as urbanization, energy development, and similar land utilization expand over areas with high hazard potential. Studies of landslides on natural slopes help to identify specific factors or geologic conditions resulting in slope failure. Identification of specific, measurable factors is important to the development of regional landslide-susceptibility evaluations.

Sharpe (1938) outlined an extensive set of conditions contributing to landsliding. This list was divided into groups under the headings of passive or basic conditions and active or initiating conditions. Active conditions included such factors as removal of support by natural or human agencies, reduction of cohesion, earth vibrations, and similar circumstances. Passive conditions favoring landslides are lithologic, stratigraphic, structural, and topographic (Sharpe 1938). A fifth passive condition, termed organic, includes overgrazing, cultivation, and similar conditions commonly related to human activities.

Some regional landslide evaluations use factors derived from passive conditions as a basis for analysis (Brabb and others 1972, Nilsen and Brabb 1973, 1975, Lessing 1976, DeGraff 1977). Data can be collected on the bedrock and slope inclination at landslide locations. Within an area, some bedrock units are assumed to be more susceptible to landsliding than others. This stems from their physical and chemical characteristics, as well as the types and thicknesses of regolith derived from them (Nilsen and Brabb 1975). Two passive conditions noted by Sharpe (1938) are defined by lithology and stratigraphy, respectively, as conditions resulting in inherent weakness in a bedrock unit and circumstances involving weaker bedrock interlayered with stronger bedrock. Use of the relative susceptibility of different bedrock units for regional evaluation is assumed to incorporate both lithologic and stratigraphic conditions. Slope inclination is equivalent to the topographic passive condition (Sharpe 1938). It identifies inclinations of the land surface conducive to landsliding. Slope is employed as a measurable parameter regardless of the geologic factors responsible for the measured inclination. Slope orientation or aspect also can be used to evaluate regional landsliding. It can identify any significant slope orientation that may coincide with structural or climatic factors enhancing slope failure (Bailey 1971, Leighton 1976, DeGraff 1976). Structural condition refers to bedding planes, fault planes, and similar attributes noted under passive conditions by Sharpe (1938). An organic passive condition is sometimes included by using climatic factors. Climatic factors include rainfall distribution or slope drying characteristics (Beatty 1954).

Regional evaluations using bedrock units, slope, and aspect (slope inclination) incorporate Sharpe's (1938) passive categories of lithologic, stratigraphic, structural, and topographic conditions. Exclusion of active conditions tends to imply that passive

Regional Landslide Evaluation: Two Utah Examples

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ABSTRACT / Landslide-susceptibility evaluations based on bedrock units, slope inclination, and aspect (slope orientation) incorporate the lithologic, stratigraphic, structural, and topographic passive conditions contributing to landsliding as outlined by Sharpe (1938). Generalized results based on passive condition analyses may define potential for failure over entire states or large parts of states, establishing an approximate landslide susceptibility for specific areas that are still in need of detailed study. This provides a preliminary susceptibility for use in land management and identifies high-priority areas for future detailed investigations.

Landslides in the Bear River Range, north-central Utah, and the northern Wasatch Plateau, central Utah, illustrate application of these factors to regional landslide-susceptibility evaluation. The greatest landslide potential exists on slopes of between 10 and 40%, with a westerly aspect, underlain by Wasatch or Salt Lake formations in the Bear River Range and on slopes of from 20 to 60% that are underlain by either North Horn or Price River formations in the northern Wasatch Plateau. Results from the two study areas are compared to a statewide landslide evaluation (Schroder 1971) in terms of passive conditions. Lithologic and stratigraphic conditions of the state and of the two study areas are nearly identical. Aspect data detect the presence or absence of structural conditions favoring failure in the two study areas rather than climatic factors as concluded in the statewide analysis. Topographic condition is more precisely stated in quantitative as opposed to qualitative terms to define failure-prone slopes in the two study areas.

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conditions control stability. Regional evaluation of past landslide activity assumes that the slopes most susceptible to active factors are ones with passive conditions most conducive to failure. Although this is not always the case, difficulty in evaluating the past influence of active conditions precludes their explicit use on a regional basis. Additionally, some workers conclude that conditions other than bedrock and slope exert minimal influence, on a regional basis, appearing to be averaged temporally and spatially (Nilsen and Brabb 1973). This conclusion is supported with one exception. Structural conditions are suggested to be more influential in some instances and amenable to regional evaluation by use of slope orientation data.

Methodology

Landslides in the Bear River Range were identified and investigated as part of a geomorphic study of the range (DeGraff 1976). A similar study of landslides resulted from field investigations that were part of a land-management research project (DeGraff 1977). In both studies, all possible landslides were identified initially on vertical, black and white aerial photography at a scale of 1:15,840. Each potential landslide location was investigated in the field. Data were collected on all correctly identified landslides that were 1 ha or larger in size. Except for five landslides and one rockslide in the Bear River Range identified by previous workers (E. J. Williams 1964, Mullins and Izett 1964, Mendenhall 1975), all landslides cited were compiled as part of these two studies.

At each landslide, data were collected on the bedrock unit involved, slope, and aspect. The bedrock unit used was the formation. Slope is expressed in percent and grouped in 10% class intervals for evaluation. Aspect is the compass direction a slope faces. It is expressed as one of eight compass directions and defined by degrees of azimuth.

To assess the relative importance of different bedrock formations or slope percent classes, it is necessary to compare the percentage of the bedrock formation exposed or slope percent class present in the study area, to the percentage of total landslide terrain involving that same element. These two percentage values can be compared visually. If the percentage values are the same or the landslide terrain percentage less, the chance for that element to be involved in landsliding is considered to be normal. It exhibits no tendency toward failure except compared to elements that have no involvement in landslide terrain. If the percentage for involvement in landslide terrain is greater than the percentage of total area, that element has more than a random chance of being involved in landsliding. Such an element is considered to be landslide prone. Unless the percentage of landsliding on a particular bedrock formation or slope class is compared to the percentage available for failure, it is impossible to assess whether a commonly involved formation or class is really prone to failure or just has more opportunity to fail owing to a greater availability.

A different assessment strategy is employed to evaluate aspect data. These data are collected on a circular rather than a linear scale. An analysis must be made to determine whether a

preferential orientation exists. A rose diagram of the measured azimuth values provides, by inspection, a preliminary estimate of preferred orientation. Using aspect values for all landslides in an area, a resultant vector, radial standard deviation, and z value are computed. The z value is used in the Rayleigh test for uniform distribution of circular data (Batschelet 1965). Rejection of the hypothesis that the data are uniformly distributed statistically supports the significance of a preferred orientation.

Bear River Range

The north-central Utah study area includes most of the southern half of the Bear River Range and the extreme eastern margin of Cache Valley (Fig. 1). This area is on the boundary between the Basin and Range and Middle Rocky Mountain physiographic provinces. Elevations range from about 1525 m in Cache Valley to nearly 3050 m in the range. The Bear River Range consists mainly of carbonate bedrock of early Paleozoic age (Table 1). Some quartzite and shale are present. Tertiary conglomerate and mudstone bedrock are widely distributed within upland basins of the range and as pediments along the eastern margin of Cache Valley (J. S. Williams 1948). The East Cache fault zone is at the base of the mountain front along the eastern edge of Cache Valley. Movement on the fault zone has uplifted the mountains relative to the valley. Structurally, the Bear River Range is broadly folded into a syncline on the west and an anticline on the east. These folds trend north-northeast and are subparallel to the northerly trend of Cache Valley and the Bear River Range (J. S. Williams 1958). Erosion, predominantly by fluvial and glacial processes, has sculptured the Bear River Range into steep, sharp ridges and canyons with narrow bottoms in the unglaciated segments.

Thirty-six landslides of probable late Pleistocene to Holocene age are identified and mapped in the Bear River Range (Table 2; DeGraff 1976). These features are widely distributed within the study area (Fig. 1). Landslides range from 2 to 75 ha with a mean size of 15 ha. The slides are a mixture of rock and earthy material, except for two composed of rock debris. The rate of movement interpreted from the morphology of the features ranged from slow to very rapid. Following the classification outlined by Schroder (1971), landslides composed of rock and earthy material are debris slides. The two composed of rock debris are rockslides.

In Fig. 2 are shown three bedrock units that clearly have been subject to landsliding in greater amount than expected for the available bedrock. These units are the Salt Lake and Wasatch formations, of Tertiary age, and the Bloomington formation, of Cambrian age.

Failure of the Wasatch Formation generally results where weathering causes loss of shear strength in mudstone beds within the formation. Sliding usually involves conglomerates overlying the mudstones at failure locations (Fig. 3). Loss of competence caused by weathering of the clayey matrix may contribute to sliding in the conglomeratic beds.

Similarly, failure in the Salt Lake formation follows a nearly

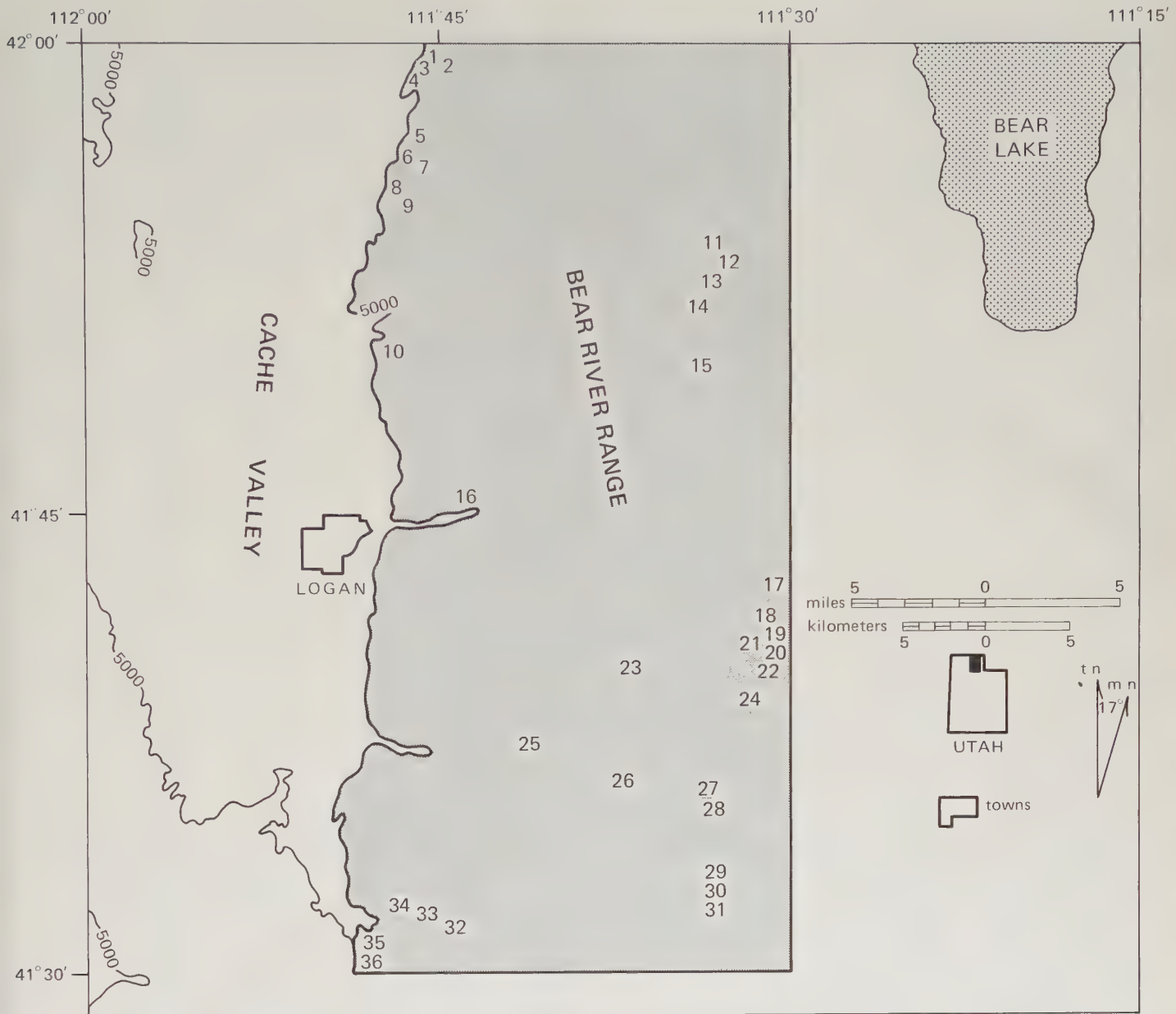


Figure 1. Index map locating the Bear River Range study area in north-central Utah. Major valley and mountain areas are delineated along the 5000-ft contour line. The location of each landslide is indicated by a number corresponding to its description in Table 2.

identical pattern. Loss of shear strength caused by weathering appears to occur in tuffaceous beds. Failure in these beds causes the overlying conglomeratic beds to slide.

The Bloomington formation has a higher susceptibility to landsliding than other bedrock in the Bear River Range, with the exception of the Salt Lake and Wasatch formations. This formation is not considered significant to regional landsliding for two

reasons. First, it is represented by a single large landslide. Second, it seems to be a product of a special set of circumstances. A fault is adjacent to the western margin of this landslide. The dip slope of this formation is in the same direction, but at a gentler angle, than the canyon slope. The Bloomington formation consists of interbedded massive limestone and shale. It is suggested that instability caused by the coincidence of dip slope and canyon

Table 1 Generalized Stratigraphic Section in the Bear River Range*

Unit	Description	Landslides?
Quaternary System		
Postlake deposits	Alluvial deposits	Absent
Lake Bonneville Group	Lacustrine deposits	Absent
Tertiary System		
Salt Lake Formation**	Sandstone, conglomerate, and limestone	Present
Wasatch Formation	Conglomerate, mudstone, sandstone, and limestone	Present
Permian–Pennsylvanian Systems		
Oquirrh Formation	Sandstone, limestone, and shale	Absent
Mississippian System		
Brazer Formation†	Limestone and sandstone	Present
Lodgepole Formation	Limestone	Absent
Mississippian–Devonian Systems		
Leatham Formation	Siltstone and dolostone	Absent
Devonian System		
Jefferson Formation‡	Dolostone and sandstone	Present
Ordovician–Silurian Systems		
Laketown Formation	Dolostone	Absent
Ordovician System		
Fish Haven Formation	Dolostone	Absent
Swan Peak Formation	Quartzite and shale	Absent
Garden City Formation	Limestone and dolostone	Absent
Cambrian System		
St. Charles Formation	Dolostone and quartzite	Present
Nounan Formation	Dolostone	Absent
Bloomington Formation	Limestone and shale	Present
Blacksmith Formation	Dolostone	Absent
Ute Formation	Limestone and shale	Absent
Langston Formation	Dolostone, limestone, shale, and siltstone	Present
Brigham Formation	Quartzite and shale	Present
Precambrian System		
Mutual Formation	Quartzite, purple and white	Absent
Precambrian Quartzite	Quartzite and shale	Absent

*From DeGraff (1976).

**Designation of Salt Lake unit as a formation follows previous U.S. Geological Survey usage (J. S. Williams 1962). Some other publications refer to the same unit as the Salt Lake group in this area.

†Brazer formation (J. S. Williams 1948) has been subdivided into the Great Blue and Little Flat formations.

‡Jefferson formation (J. S. Williams 1948) has been subdivided into the Beirdneau, Hyrum, and Water Canyon formations.

slope angles was accentuated at this location by past faulting. Failure resulted in movement of massive limestone beds on shale beds acting as shear planes.

Three slope classes are especially susceptible to sliding (Fig. 4). This results in a predominance of landslides on slopes of between 10 and 40%, which is probably related to the character of the landslide-prone bedrock. Neither the Salt Lake formation nor the Wasatch formation forms steep slopes. Therefore, this range of slopes would include the optimum unstable slope for these Tertiary rock units. Oversteepening by fluvial, glacial, and lacustrine action has contributed to the availability of failure-

Table 2 Characteristics of Landslides in the Bear River Range

Landslide	Size (ha)	Slope (%)	Aspect (°)	Bedrock (formation)
1	2	36	275	Salt Lake
2	4	34	336	Salt Lake
3	38	33	309	Salt Lake
4	17	44	296	Salt Lake
5	2	44	303	Salt Lake
6	12	21	309	Salt Lake
7	18	23	265	Salt Lake
8	25	28	269	Salt Lake
9	32	22	234	Salt Lake
10	8	51	207	Salt Lake
11	18	36	277	Wasatch
12	2	25	265	Wasatch
13	5	23	312	Wasatch
14	8	36	278	Wasatch
15	11	21	229	Wasatch
16	3	27	133	Jefferson
17*	75	23	301	Wasatch
18	5	34	269	Brigham
19	2	31	256	Brigham
20	5	32	240	Brigham
21	2	16	4	Wasatch
22	2	27	351	Brigham
23	49	19	298	Bloomington
24	18	21	224	Langston
25	2	53	313	St. Charles
26	2	58	10	Brigham
27	2	21	271	Wasatch
28	5	34	288	Wasatch
29	49	19	310	Wasatch
30	8	32	281	Wasatch
31	39	27	276	Wasatch
32	8	11	110	Wasatch
33	5	27	136	Brazer (Great Blue?)
34	18	36	231	Brazer (Great Blue?)
35	38	16	344	Salt Lake
36	26	17	325	Salt Lake

*This feature is a landslide-prone zone composed of several landslides that are not readily distinguished from each other.

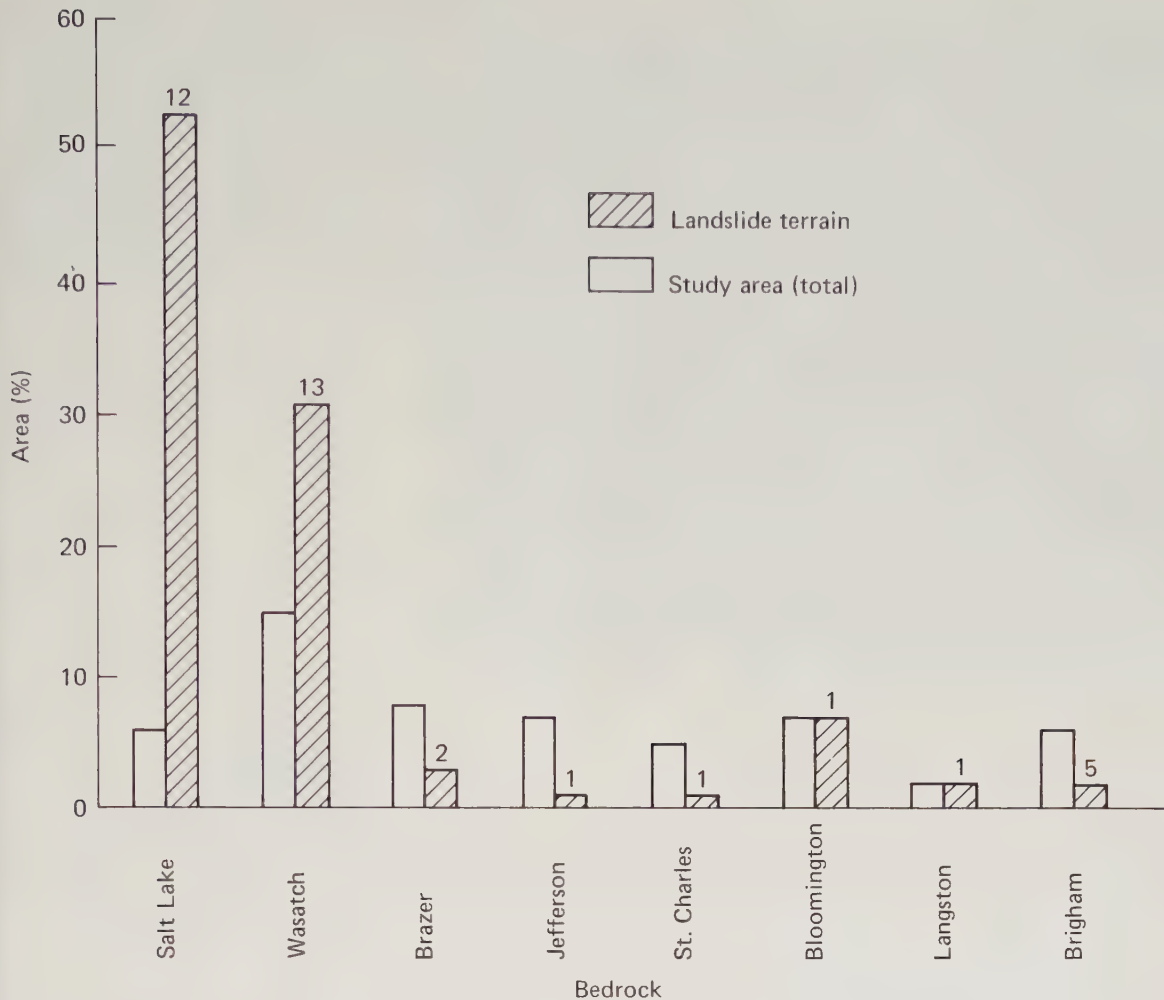


Figure 2. Graph comparing percentage of landslide terrain to percentage of total study area for bedrock formations involved in failures located in the Bear River Range, north-central Utah. Numerals over each landslide terrain bar indicate the number of landslides on that unit.

prone slopes. Most landslides are near actively eroding streams or on adjacent canyon slopes. Therefore, fluvial erosion is the major process responsible for oversteepened slopes. In upper Logan Canyon, glacial erosion oversteepened slopes in some areas underlain by the landslide-prone Wasatch formation. This oversteepening was enhanced by subsequent fluvial action in several locations. The Salt Lake formation is exposed along the western front of the Bear River Range at the margin of Cache Valley. A number of landslides exist where Pleistocene Lake Bonneville shorelines intersect exposures of Salt Lake formation. Lacustrine erosion appears to have oversteepened these locations underlain by failure-susceptible bedrock. Other landslides involving the Salt Lake formation are adjacent to actively eroding canyon streams.

Aspect distribution of Bear River Range landslides is not uniform and a significant, preferred direction exists (Table 3). A rose diagram illustrates the aspect distribution and the preferred orientation toward the west (255°) of the resultant vector (Fig. 5).

This preferential direction is clearly related to a structural factor. Exposures of Salt Lake formation are concentrated along the west-facing mountain front. The Salt Lake formation dips toward the west at angles of between 17 and 31° (Galloway 1970). Bedrock dipping in the same direction as the slope of the land increases the chance for failure (Cooke and Doornkamp 1974). Consequently, a significant number of landslides exists on these west-facing slopes. In contrast, the generally flat-lying beds of the Wasatch formation appear to have no affect on the distribution of slope orientation.



Figure 3. Two landslides on the north-facing slope of Logan Canyon in the Bear River Range, north-central Utah (landslides 11 and 12, Table 2). Arrows point out the scarp areas for the large primary and smaller secondary landslides. Both failures involve sliding of Wasatch formation. Scale is shown by 100-ft-long building adjacent to the slides.

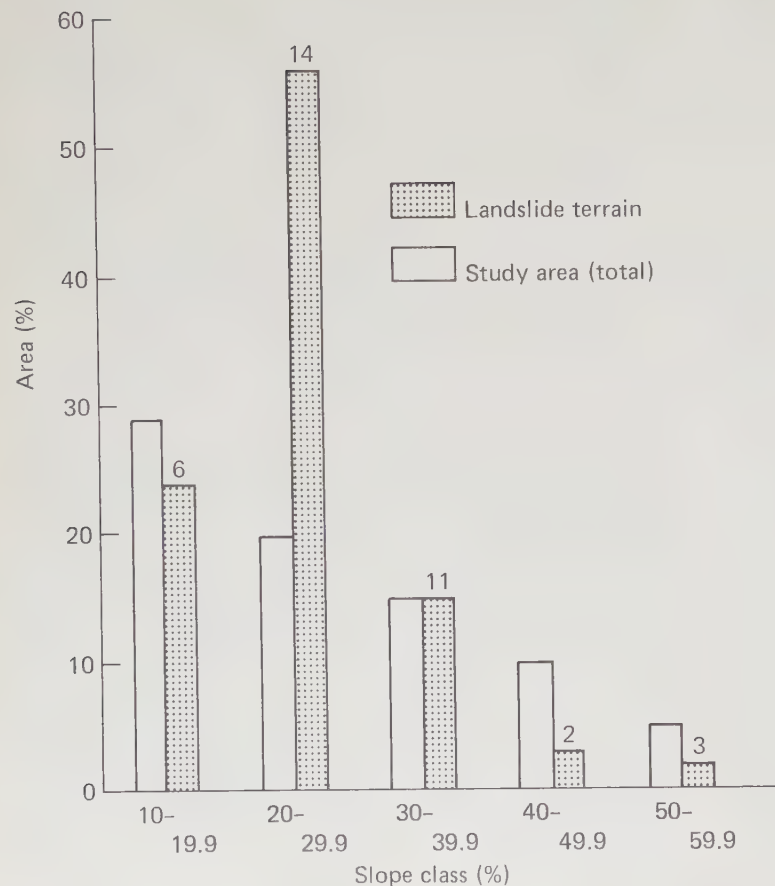


Figure 4. Graph comparing percentage of landslide terrain to percentage of total study area for each 10% slope class hosting landslide locations in the Bear River Range, north-central Utah. Numerals over each landslide terrain bar indicate the number of landslides on that unit.

Table 3 Rayleigh Test for Circular Distribution for Landslide Aspects

Landslide group	Sample <i>n</i>	Z statistic (calculated)*	H ₀ : uniform distribution
Bear River Range	36	14.7082	Reject
Wasatch Plateau	34	2.9185	Cannot reject

*Z statistic (table), 2.9957; $p = 5\%$, $24 < n < \infty$

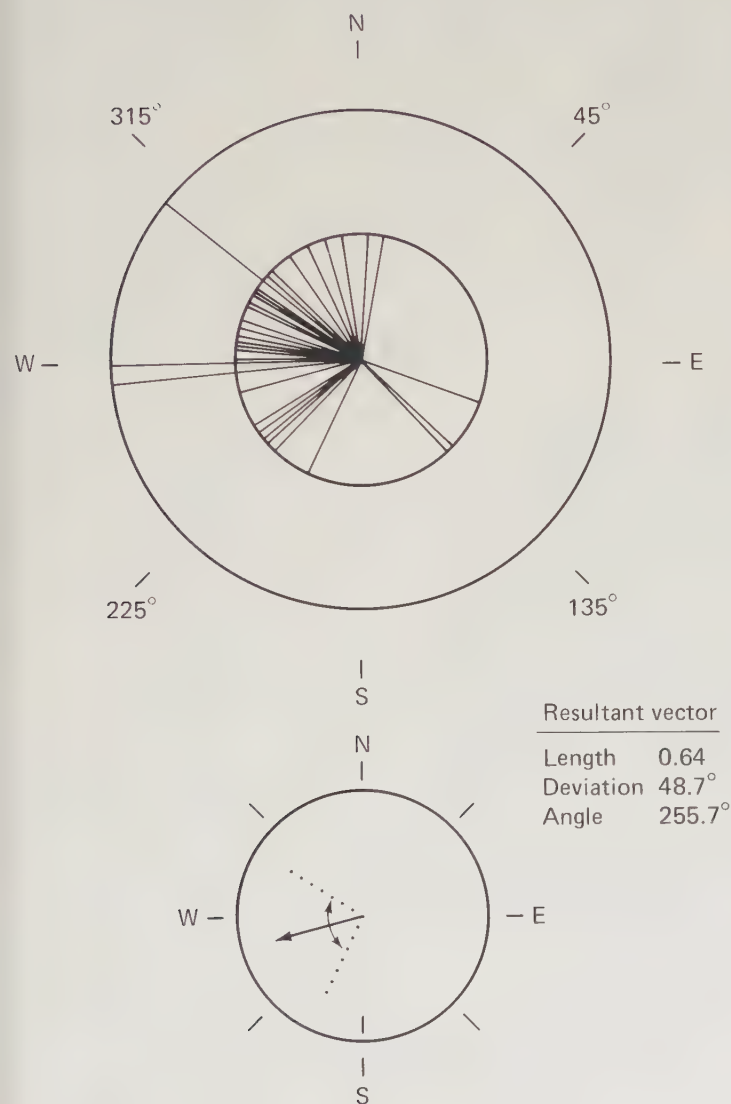


Figure 5. Rose diagram showing the orientations, in degrees, of Bear River Range landslides. The statistically significant resultant vector indicates the preferred aspect.

In summary, the greatest potential for landsliding in the Bear River Range exists where slopes of between 10 and 40%, with a westerly aspect are underlain by Wasatch or Salt Lake formations.

Wasatch Plateau Landslides

The central Utah study area includes the northern half of the Wasatch Plateau (Fig. 6), which is the northernmost member of the High Plateau section in the Colorado Plateau physiographic province. Elevations range from 1700 m to more than 3350 m in this part of the Plateau. The northern Wasatch Plateau consists mainly of late Cretaceous and early Tertiary sandstone (Table 4). Some bedrock units contain significant proportions of interbedded shale. Both coal and limestone beds may be present in some formations. Within the study area, the bedrock dips to the east at 0 to 5°. The northern end of the Upper Joe's Valley graben extends north into the study area (Spieker 1931). Glacial erosion has steepened the eastern slope of Skyline Drive Ridge along the western boundary of the study area (Spieker and Billings 1940). The plateau has high relief with steep, broad ridges and deep, narrow canyons. This dissection is the result of fluvial erosion.

Thirty-four landslides are identified and mapped in the northern Wasatch Plateau (Table 5; DeGraff 1977). Most of these features appear to be late Pleistocene to Recent in age. These features are widely distributed within the study area (Fig. 6). Landslides range from 1 to 33 ha with the mean size being 6 ha. Four slides are composed primarily of rock fragments. The remaining 30 slides consist of rock and earthy material. The rate of movement is inferred from field evidence to be from slow to very rapid. These features are classified as rockslides and debris slides, respectively (Schroder 1971).

The North Horn, Price River, Castlegate, and Blackhawk formations are involved in landsliding (Table 4). No landslide is detected on other formations in the northern Wasatch Plateau. A comparison between percentage of landsliding to percentage of bedrock formation exposed indicates that the North Horn and Price River formations are especially susceptible to landsliding (Fig. 7).

The Tertiary-Cretaceous North Horn formation is composed of interbedded sandstone and shale. The shale weathers to clay where exposed, resulting in loss of shear strength. Overlying sandstone layers are undermined and slide on the glide plane created in the weathered shale. In some instances, the slide mass rotates back during failure (Fig. 8). In the majority of landslides involving the North Horn formation, the material slides and slumps into a bouldery, hummocky mass.

The other bedrock formation especially susceptible to failure is the Price River formation, of Cretaceous age. The Price River formation is largely a conglomeratic sandstone with some shale in the upper part. Failure of this bedrock commonly is associated with springs. Groundwater percolating in the sandstone intersects impermeable shales in the Price River formation. Laterally moving groundwater emerges as springs on hill slopes. Therefore, these locations are subject to numerous cycles of wetting

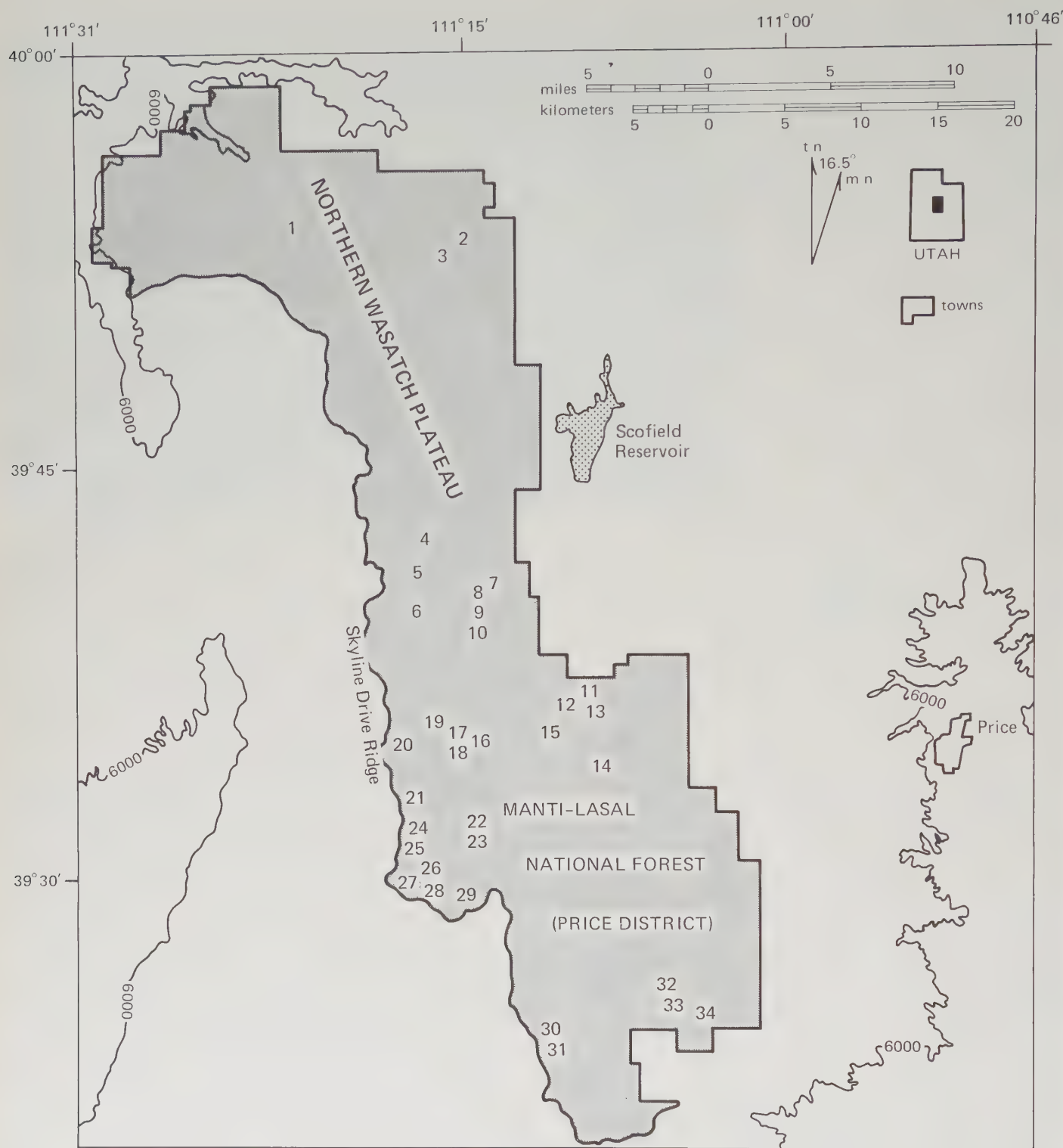


Figure 6. Index map locating the northern Wasatch Plateau study area in central Utah. Major valley and mountain areas are delineated along the 6000-ft contour line. The location of each landslide is indicated by a number corresponding to its description in Table 5.

Table 4 Generalized Stratigraphic Section in the Northern Wasatch Plateau*

Unit	Description	Landslides?
Tertiary System		
Green River Formation	Shale and siltstone	Absent
Colton Formation	Shale, sandstone, and limestone	Absent
Flagstaff Formation	Limestone with minor sandstone, shale, and volcanic ash	Absent
Tertiary-Cretaceous Systems		
North Horn Formation	Shale, sandstone conglomerate, and limestone	Present
Cretaceous System		
Price River Formation	Sandstone, shale, and conglomerate	Present
Castlegate Formation	Sandstone	Present
Blackhawk Formation	Sandstone, shale, and coal	Present
Star Point Formation	Sandstone	Absent
Mancos Formation		Absent
Masuk member	Shale	

*Data from Doelling (1972).

and drying. Hydration of clay minerals with associated swelling of the shale appears to be the cause of failure. Seepage pressures, loss of intergranular pressure, and similar action related to groundwater also may play a role (Schroder 1971). Slumped material exhibits lobate flow features at the toes of many slides in the Price River formation.

Landslides in the Wasatch Plateau are associated with a variety of slope angles. There is no single, failure-prone slope class. The susceptibility to landsliding appears greatest for slopes of between 20 and 60% (Fig. 9). The wide range of susceptible slopes reflects the two distinctive failure-prone bedrock units of the Wasatch Plateau landslides. The North Horn formation commonly forms steep slopes, whereas the Price River formation forms rounded, gentler slopes. The different slope-forming tendencies of the two most susceptible bedrock units result in a wide range of possible slope angles associated with landsliding.

Aspect appears to have little value in analyzing landslide areas in the Wasatch Plateau. A uniform distribution of landslides on all aspects cannot be rejected when a Rayleigh test is performed on the data (Table 3). The generally horizontal strata within the study area provide little structural advantage for landsliding. Therefore, all aspects appear to have an equal opportunity for failure.

In summary, landsliding in the northern Wasatch Plateau has the highest potential on slopes ranging from 20 to 60% and underlain by either North Horn or Price River formations.

Comparison of Landslide Factors

Schroder (1971) published an analysis of landslide factors in Utah based on all landslides described at that time. The analysis included evaluation of some passive conditions listed by Sharpe (1938). Schroder (1971) noted the dominant lithologic, stratigraphic, and structural conditions. It was noted that the greatest number of landslides occurred in mountainous terrain with steep slopes. Restriction of landslides to steep slopes qualitatively defines the topographic condition. No quantitative definition, in terms of slope angle, percent, or grade, is used.

In terms of lithologic conditions, landslides in Utah commonly involve bentonitic mudstone or sandstone, or an argillaceous lithology (Schroder 1971). This study finds failure susceptibility greatest on mudstone in the Bear River Range and on shales in

Table 5 Characteristics of Landslides in the Northern Wasatch Plateau

Landslide	Size (ha)	Slope (%)	Aspect (°)	Bedrock (formation)
1	3	49	268	Price River
2	7	39	340	North Horn
3	5	23	342	North Horn
4	8	42	270	Price River
5	4	59	282	Price River
6	6	35	270	Price River
7	5	22	340	Blackhawk
8	7	20	288	Blackhawk
9	3	22	258	Blackhawk
10	16	19	276	Blackhawk
11	4	21	82	Blackhawk
12	2	21	136	Blackhawk
13	2	65	146	Blackhawk
14	4	29	196	Price River
15	8	45	222	Blackhawk
16	9	19	216	Price River
17	2	24	218	Price River
18	2	36	232	Price River
19	11	26	228	Price River
20	6	20	142	North Horn
21	2	43	162	North Horn
22	3	36	268	Castlegate
23	2	32	274	Castlegate
24	4	35	178	Price River
25	1	36	192	North Horn
26	2	85	12	North Horn
27	6	59	10	North Horn
28	2	32	68	North Horn
29	33	15	106	North Horn
30	8	22	56	North Horn
31	12	36	124	North Horn
32	5	48	156	North Horn
33	8	48	262	North Horn
34	3	73	206	North Horn

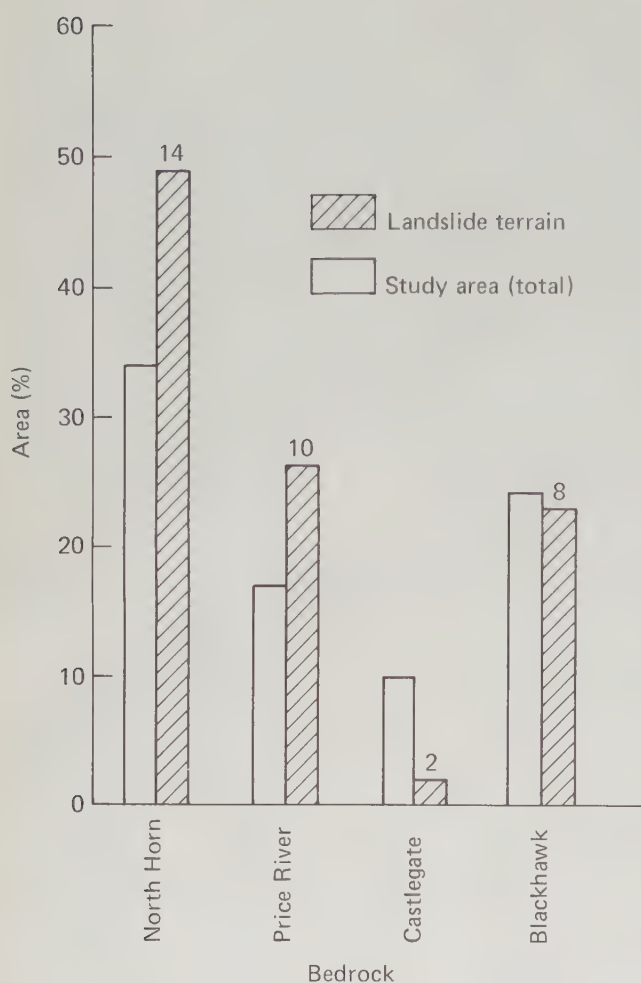


Figure 7. Graph comparing percentage of landslide terrain to percentage of total study area for bedrock formations involved in failures in the northern Wasatch Plateau, central Utah. Numerals over each landslide terrain bar indicate the number of landslides on that unit.

the northern Wasatch Plateau. Therefore, these two areas are consistent with statewide findings.

Stratigraphic conditions are noted as the most common passive condition in landsliding in Utah (Schroder 1971). Specifically, the most frequent circumstance associated with failure is a sandstone or conglomerate unit overlying mudstone, siltstone, claystone, or shale. In the Bear River Range, the common failure-prone stratigraphic circumstance is conglomerate overlying mudstone. In the northern Wasatch Plateau, it is sandstone overlying shale. The similarity of failure-prone stratigraphic conditions for both the two study areas and the entire state is particularly striking.

Structural conditions are noted as either fault zones or bedrock dipping parallel to the hillslope (Schroder 1971). One

landslide in the Bear River Range appears to be related to a fault zone. Bedrock dipping in a direction similar to the hillslope is also a factor in that fault zone-related landslide and, commonly, in other landslides in this range. However, structural conditions appear to have no relationship to landslides in the northern Wasatch Plateau.

Schroder (1971) used aspect or slope orientation as part of the statewide evaluation of landslide conditions. Unlike the Bear River Range and northern Wasatch Plateau evaluations, it is not used to detect statistically significant, preferred orientation that may be indicative of contributing structural conditions. Schroder (1971) does note the paucity of landslides on south and southwest aspects, which is attributed to more effective drying by solar radiation compared to other aspects. Landslide locations in both the Bear River Range and Wasatch Plateau receive precipitation ranging from about 500 to 900 mm annually (Utah State Engineer 1964). The dominant orientation in the Bear River Range is related to structure rather than to the climate. This observation and the absence of a preferred orientation for Wasatch Plateau landslides suggests that climatic factors, such as effective slope drying, are less influential than concluded from the statewide evaluation. Based on the two study areas, preferred aspect or slope orientation is more likely to indicate structural conditions conducive to failure than climatic conditions.

Schroder (1971) notes the influence of topographic (steep slopes) conditions as a dominant feature of the mountainous terrain widely distributed throughout the elevation zone having the highest percentage of landslides. A quantitative assessment of slope inclination is not included in the statewide evaluation. Therefore, no comparison, in quantitative terms, can be made between susceptible slope inclinations in the two study areas and the statewide evaluation.

Specific slope values define failure-prone areas in greater detail. This is because of the relationship of failure-prone slopes to the slope-forming characteristics of bedrock susceptible to landsliding within an area. A range of values, such as 10 to 40% in the Bear River Range or 20 to 60% in the Wasatch Plateau, more precisely indicates areas with a high landslide susceptibility.

Conclusions

Of the passive conditions noted by Sharpe (1938), stratigraphic and topographic conditions are the primary factors that control landsliding in the Bear River Range and Wasatch Plateau. Structural conditions influence landsliding in the Bear River Range but not in the Wasatch Plateau. Incompetent lithologies are involved in the stratigraphic circumstances in both study areas.

Compared to the statewide landslide evaluation (Schroder 1971), Bear River Range and Wasatch Plateau landslides involve stratigraphic and lithologic conditions identical to the statewide results. Aspect or slope orientation evaluation in both study areas detects the presence or absence of significant structural conditions rather than the influence of climate concluded from statewide data. Topographic (steep slope) conditions are equally as important as stratigraphic or lithologic conditions in defining



Figure 8. Landslide scarp and adjacent rotated block of upper slide mass near the head of the left fork of Rilda Canyon in the northern Wasatch Plateau. Failure involves interbedded shale and massive sandstone of the North Horn formation. Two people standing in the foreground (circled) indicate scale.

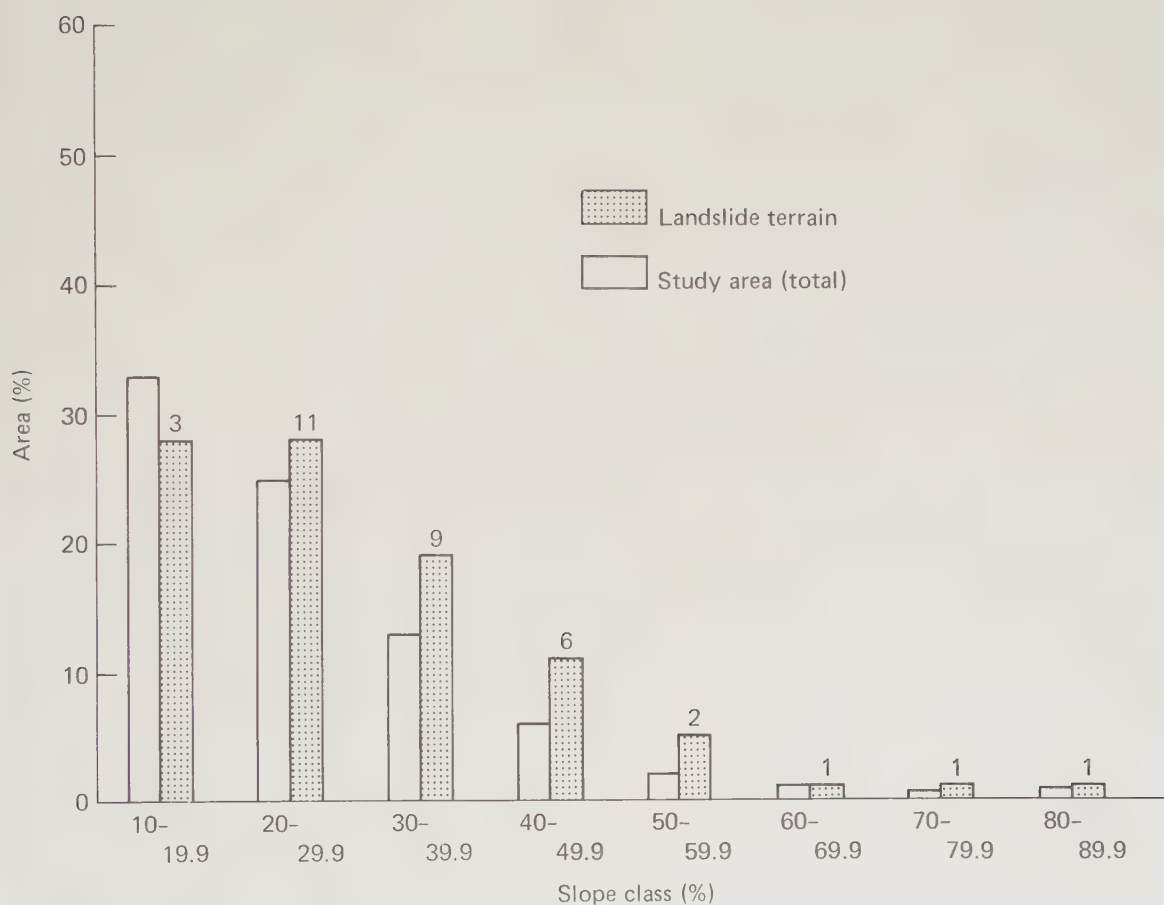


Figure 9. Graph comparing percentage of landslide terrain to percentage of total study area for each 10% slope class hosting landslide locations in the northern Wasatch Plateau, central Utah. Numerals over each landslide terrain bar indicate the number of landslides on that unit.

failure-prone areas in the Bear River Range and Wasatch Plateau. The exclusion of quantitative slope data from the statewide evaluation prevents comparison with the two study areas.

Some generalizations relating to regional landslide-susceptibility assessments can be made based on the results from both study areas and their comparison to the statewide evaluation. Sharpe's (1938) lithologic, stratigraphic, structural, and topographic passive conditions can be incorporated in landslide assessments as bedrock unit, slope inclination class, and statistically significant aspect (slope orientation). These measurable variables can be treated quantitatively to identify areas that exhibit failure-prone conditions.

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Glaucinitic Greensand: A Possible Filter of Heavy Metal Cations from Polluted Waters

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ABSTRACT / Experiments using distilled water, spiked with heavy metal cations and passed through a filtration system composed of greensand containing 80% glauconite at a rate of 2–4 ml/min, showed: (1) starting fluids containing Cd, Co, Cu, Pb, Mn, Ni, Ag, or Zn had an average of 90% of the contaminating cation removed from acidic solutions and an average of 84% removed from the basic solutions; and, (2) filtration through greensand tended to neutralize both acidic and basic solutions. The removal of the contaminant cation from starting fluids containing K, Na, Ca, Mg, Fe, Si, or Al (the principal constituents of glauconite plus Ca from shell material) is not as consistently effective as for the first named metals.

Introduction

As polluted water is constantly being added to local surface and ground waters by industry, municipalities, and landfill operations, the need for an inexpensive, effective, primary filter material for heavy metal cations becomes urgent. Preliminary results of the present investigation indicate that the Tertiary greensand deposits of the Maryland, Delaware, and New Jersey coastal plain (Fig. 1) have potential as a filter material of such polluted waters. In the Delaware coastal plain the glauconitic greensands are found in unconsolidated sediments ranging in age from Late Cretaceous to Miocene (Jordan 1962).

Glauconite, a clay mineral, is a hydrous aluminosilicate rich in ferric iron with significant amounts of potassium (Table 1; for additional information see McRae 1972). Glauconite in the Delaware coastal plain sediments occurs as dark-, light-, or yellowish-green pellets usually about 0.5–1 mm in size, as filling of fossil shells, coatings on other grains, and as a clayey matrix in the sediments.

In Delaware alone, easily accessible surface and near-surface greensand deposits account for approximately 180 km² of material in a wedge-shaped block up to 150 m thick along its southern border. The overburden of younger unconsolidated sediments averages 10 m in thickness. The Delaware outcrops occur in the Middletown–Odessa area and along the Chesapeake and Delaware Canal (Fig. 2; Pickett 1970, Pickett and Spoljaric 1971).

Early Tertiary greensand from the Odessa outcrop (Fig. 2) was used for this study. This unconsolidated sediment contains as much as 80% glauconite in spheroidal or mammillated pellets and as clayey matrix. The other principal constituents are sand-size quartz grains (10–15%) and fragments of invertebrate shells, primarily foraminifera (5–10%). Other minerals, such as feldspars and heavy minerals, are present in trace amounts only (1–3%).

Method

A modified 300-ml Fleaker (Corning Glass Works) was utilized as a filter unit. A flow direction from the bottom to the top of the filter unit prevented transport of clay-size particles by fluid flow. Glass wool packed about the inlet kept small particles of greensand from clogging the opening. The manufacturer's cap provided an adequate seal for the top of the vessel. Twigs and root material were removed from the sediment used in each filter. Large clots were disaggregated to obtain 150 cm³ of close packed greensand in the Fleaker.

Four different concentrations of starting solution were prepared for each contaminant ion. In each case 300 ml of starting solution were passed through its own filter at a rate of 2–4 ml/min (Fig. 3). The initial and final concentration of the contaminant ion

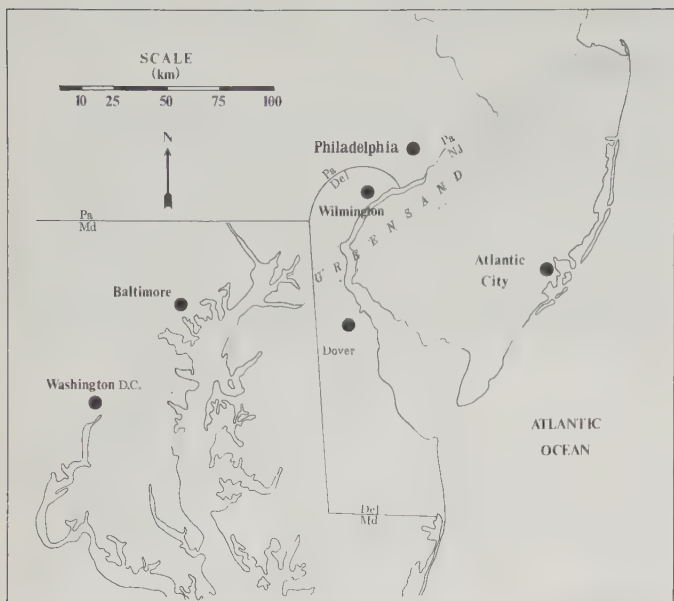


Figure 1. Areal distribution of accessible greensand deposits in Maryland, Delaware, and New Jersey.

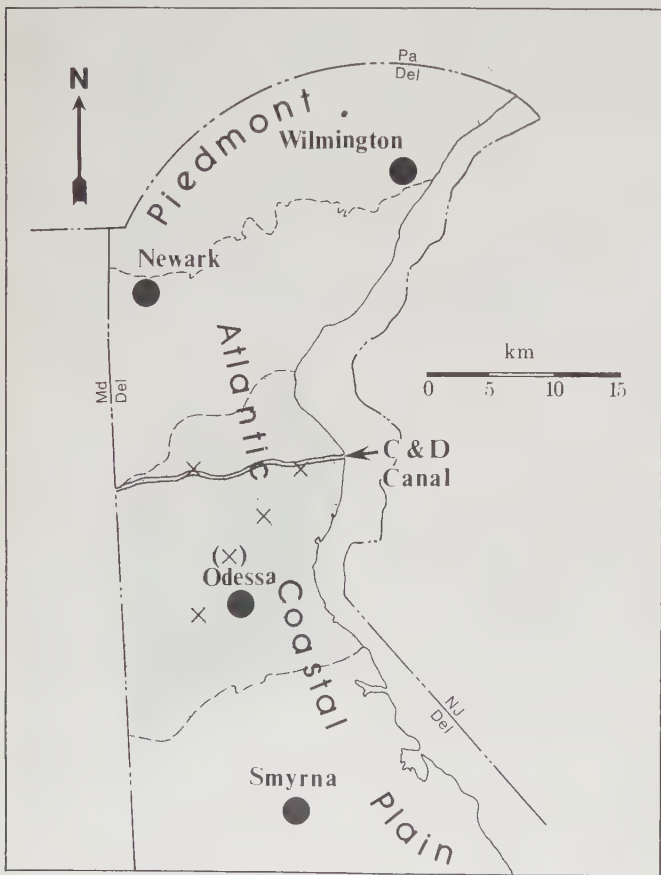


Figure 2. Areal distribution of accessible greensands in Delaware. x, Greensand outcrops; (x), Odessa outcrop sampled for this study.

Table 1 Chemical Composition of Glauconites from the Delaware Coastal Plain*

Oxide	In weight percent		
SiO ₂	49.6	47.3	47.3
TiO ₂	0.84	0.28	0.27
Al ₂ O ₃	9.6	7.1	7.2
Fe ₂ O ₃	14.0	17.6	17.5
FeO	2.26	1.89	2.30
MnO	0.04	0.03	0.03
MgO	3.1	3.7	3.6
CaO	Trace	2.1	2.2
Na ₂ O	0.11	0.11	0.05
K ₂ O	6.2	8.0	8.0
Cr ₂ O ₃	0.045	0.034	0.056
H ₂ O _{total}	10.13	8.99	8.2
CO ₂	—	1.0	1.1
Total:	95.9	98.1	97.8
(Fe _{total} as Fe ₂ O ₃)	(16.5)	(19.9)	(20.1)

*Analyses by atomic absorption spectrophotometry and wet chemical techniques.

were measured by various atomic absorption spectrophotometric techniques. The pH was adjusted to about 3 with nitric acid for the acidic solutions and to about 10 with ammonium hydroxide for the basic solutions. The actual pH of starting solutions and filtrates was measured during the run.

The compounds used to spike the solutions are listed in Table 2. Most are chlorides or hydrous chlorides with the exception of

Table 2 Compounds Used to Spike Solutions

Element	Compound
Aluminum	AlCl ₃ ·6H ₂ O
Arsenic	As ₂ O ₃
Cadmium	CdCl ₂
Calcium	CaCl ₂
Chromium	CrCl ₃ ·6H ₂ O
Cobalt	CoCl ₂ ·6H ₂ O
Copper	CuCl ₂ ·2H ₂ O
Iron	FeCl ₃ ·6H ₂ O
Lead	PbCl ₂
Magnesium	MgCl ₂ ·6H ₂ O
Manganese	MnCl ₃ ·4H ₂ O
Mercury	HgCl ₂
Nickel	NiCl ₂ ·6H ₂ O
Potassium	KCl
Selenium	SeO ₂
Silicon	NaSiO ₃ ·10H ₂ O
Silver	AgNO ₃
Sodium	NaCl
Zinc	ZnCl ₂

arsenic and selenium oxides, silver nitrate, and silica water-glass. A previous study (Spoljaric and Crawford 1975) demonstrated that the anion associated with any given heavy metal compound had little or no effect on the capacity of greensands to retain heavy metals from solutions.

Results

The complete results are shown in Tables 3a and 3b and summarized in Table 4. The pH change for acidic solutions averages from 3.2 to 4.0; however, the pH change for basic solutions is not as pronounced, being from 10.2 to 9.9.

The heavy metal cations of acidic solutions most effectively removed are Pb, Fe, Co, Cu, Cd, Mn, Cr, Ni, Zn, Ag, K, Hg, and Se (Table 3a). However, the retention of As, Si, Al, and Na by the greensand was not as effective. Calcium shows large increases in concentration in the filtrates over that of the acidic starting solutions; there is a modest increase in Mg content in the acidic filtrates. The relative concentrations of calcium and magnesium are of the correct ratio to be derived from foraminifera shells decomposed by the acidic starting solutions. Such shells vary in Mg content from about 1 to 16% (Chave 1954).

The heavy metal cations most effectively retained by the greensand from the basic solutions are: Ag, Cu, As, Hg, Cd, Ni, Pb, Cr, Co, Mg, and Mn (Table 3b). The removal of K, Na, Al,

Table 3a Spiked Acidic Solutions

Cation	Run no.	Cation concentration (ppm)		Percent retained (released) by filter	pH	
		Start	Filtrate		Start	Filtrate
Aluminum	1	21.8	14.2	35	2.46	3.59
	2	17.2	13.8	20	2.60	3.61
	3	13.8	11.4	17	2.71	3.85
	4	10.5	9.5	10	2.95	4.02
				Av. = 21		
Arsenic	1	3.13	2.20	30	3.15	3.69
	2	2.68	1.53	43	3.22	4.26
	3	1.88	1.27	32	3.50	4.32
	4	1.33	0.68	49	3.85	4.40
				Av. = 38		
Cadmium	1	3.07	0.16	94	2.92	3.80
	2	2.18	0.19	91	3.05	3.78
	3	1.31	0.03	98	3.21	3.95
	4	0.47	0.02	96	3.55	4.13
				Av. = 95		
Calcium	1	21.0	160.3	(663)	2.50	3.84
	2	16.7	126.6	(658)	2.60	3.95
	3	10.7	89.2	(734)	2.73	3.99
	4	4.2	52.0	(1138)	2.95	4.08
				Av. = (798)		
Chromium	1	3.96	0.25	98	2.77	3.38
	2	3.10	0.16	95	2.89	3.79
	3	1.86	0.13	93	3.06	3.83
	4	0.91	0.16	82	3.41	3.99
				Av. = 92		
Cobalt	1	3.16	0.09	97	3.10	3.70
	2	2.17	0.02	99	3.13	3.75
	3	1.34	0.04	97	3.25	3.75
	4	0.48	0.03	94	3.60	3.86
				Av. = 97		
Copper	1	3.45	0.03	99	2.82	3.82
	2	2.53	0.03	99	2.99	3.89
	3	1.50	0.09	94	3.14	3.99
	4	0.55	0.05	90		4.11
				Av. = 96		

Table 3a Spiked Acidic Solutions (Continued)

Cation	Run no.	Cation concentration (ppm)		Percent retained (released) by filter	pH	
		Start	Filtrate		Start	Filtrate
Iron	1	3.53	0.02	99	2.71	3.79
	2	2.61	0.12	95	2.87	3.80
	3	1.57	n.d.*	100	3.02	3.89
	4	0.53	n.d.*	<u>100</u>	3.45	4.01
				Av. = 99		
Mercury	1	1.62	1.17	28	2.86	3.93
	2	1.31	0.24	82	2.98	3.98
	3	1.48	0.65	56	3.13	3.96
	4	0.60	0.07	<u>88</u>	3.40	4.02
				Av. = 64		
Lead	1	6.65	(0.03)	99	2.80	3.90
	2	4.73	n.d.*	100	2.91	3.99
	3	2.82	(0.02)	99	3.13	4.15
	4	0.87	(0.02)	<u>98</u>	3.55	4.29
				Av. = 99		
Magnesium	1	9.77	15.79	(62)	2.75	3.79
	2	6.69	10.81	(62)	2.88	3.95
	3	4.93	8.01	(62)	3.00	4.01
	4	2.10	3.63	<u>(73)</u>	3.27	4.19
				Av. = (65)		
Manganese	1	3.57	0.18	95	2.80	3.69
	2	2.53	0.06	97	2.92	3.88
	3	1.61	0.05	97	3.09	3.97
	4	0.51	0.04	92	3.51	4.03
				Av. = 95		
Nickel	1	3.00	0.11	96	3.05	4.17
	2	2.35	0.09	96	3.18	4.31
	3	1.45	0.08	94	3.38	4.35
	4	0.58	0.16	<u>72</u>	3.72	4.27
				Av. = 90		
Potassium	1	61.8	10.0	84	4.41	4.01
	2	41.3	6.0	85	5.48	4.16
	3	28.7	5.2	82	5.63	4.20
	4	19.8	4.2	<u>79</u>	5.60	4.28
				Av. = 83		
Selenium	1	1.73	0.37	79	3.19	4.09
	2	1.25	0.95	24	3.30	4.10
	3	0.08	0.27	66	3.59	4.20
	4	0.64	0.32	50	3.83	4.27
				Av. = 55		
Silicon	1	37.0	23.4	37	2.67	3.66
	2	29.4	18.9	36	2.76	3.97
	3	20.3	15.9	22	2.97	2.67
	4	14.4	9.9	<u>31</u>	2.95	4.11
				Av. = 32		
Silver	1	2.64	0.03	99	5.22	4.13
	2	1.77	0.01	99	5.20	4.17
	3	1.27	0.73	43	5.22	4.56
	4	0.23	n.d.*	<u>100</u>	5.26	4.16
				Av. = 83		
Sodium	1	17.0	14.0	18	3.16	4.19
	2	12.3	11.6	6	3.24	4.23
	3	8.6	9.3	(8)	3.39	4.29
	4	4.1	5.8	<u>(4)</u>	3.61	4.39
				Av. = 3		
Zinc	1	3.03	0.25	92	2.85	3.73
	2	2.15	0.38	82	2.99	3.64
	3	1.36	0.07	95	3.15	3.98
	4	0.47	0.04	<u>91</u>	3.57	4.10
				Av. = 90		

*n.d. not detected.

Table 3b Spiked Basic Solutions

Cation	Run no.	Cation concentration (ppm)		Percent retained (released) by filter	pH	
		Start	Filtrate		Start	Filtrate
Aluminum	1	18.2	13.7	25	9.60	9.50
	2	12.0	14.5	(21)	9.70	9.63
	3	8.3	9.2	(11)	9.82	9.72
	4	5.0	8.5	(70)	10.05	9.91
				Av. = (19)		
Arsenic	1	6.53	0.50	92	10.36	9.95
	2	5.00	0.09	98	10.40	10.05
	3	3.46	0.27	92	10.49	10.20
	4	2.24	0.05	98	10.58	10.34
				Av. = 95		
Cadmium	1	3.06	0.02	99	10.29	9.86
	2	2.03	0.34	83	10.39	10.11
	3	1.17	0.04	97	10.49	9.88
	4	0.37	0.05	86	10.52	10.18
				Av. = 91		
Calcium	1	19.5	55.0	(182)	9.63	9.34
	2	14.6	31.0	(112)	9.71	9.51
	3	11.8	4.3	64 1	9.85	9.73
	4	4.9	8.4	<u>71</u>	10.01	9.79
				Av. = (75)		
Chromium*	1	1.93	0.34	82	10.23	9.87
	2	1.82	0.46	75	10.31	10.13
	3	1.35	0.12	91	10.38	9.74
	4	0.47	0.18	<u>62</u>	10.48	9.87
				Av. = 78		
Cobalt	1	2.96	0.65	78	10.25	9.73
	2	2.18	1.53	30	10.32	10.06
	3	1.26	0.34	73	10.39	9.78
	4	0.40	0.09	78	10.39	9.76
				Av. = 65		
Copper	1	2.65	0.20	92	10.60	10.35
	2	1.66	0.06	96	10.63	10.41
	3	0.98	0.08	92	10.69	10.42
	4	0.44	0.01	<u>98</u>	10.78	10.34
				Av. = 95		
Iron	1	4.1	12.6	(207)	10.20	10.04
	2	2.8	25.6	(814)	10.24	9.99
	3	1.7	36.4	(2041)	10.31	10.01
	4	0.8	33.3	<u>(4063)</u>	10.41	10.15
				Av. = (1782)		
Lead*	1	2.46	0.02	99	10.08	9.57
	2	3.08	1.30	58	10.18	10.03
	3	2.08	0.10	95	10.27	9.99
	4	0.66	0.22	<u>67</u>	10.47	10.26
				Av. = 80		
Magnesium	1	10.05	2.69	73	9.85	9.47
	2	7.08	1.03	85	9.82	9.76
	3	4.64	0.77	83	10.00	9.90
	4	2.54	2.02	<u>20</u>	10.22	9.30
				Av. = 65		
Manganese	1	3.54	1.22	67	10.29	9.96
	2	2.46	0.98	60	10.32	10.06
	3	1.54	0.64	58	10.47	10.08
	4	0.61	0.36	<u>41</u>	10.56	10.29
				Av. = 57		
Mercury*	1	0.94	0.13	86	10.53	10.39
	2	0.87	0.07	92	10.57	10.40
	3	0.77	0.03	96	10.68	10.50
	4	0.43	0.01	<u>98</u>	10.69	10.45
				Av. = 93		

Table 3b Spiked Basic Solutions (*Continued*)

Cation	Run no.	Cation concentration (ppm)		Percent retained (released) by filter	pH	
		Start	Filtrate		Start	Filtrate
Nickel	1	4.02	0.07	98	10.10	9.11
	2	3.35	0.06	98	10.15	9.42
	3	1.70	0.24	86	10.31	10.10
	4	0.34	0.08	76	10.37	9.90
				Av. = 90		
Potassium	1	75.4	34.6	54	10.50	10.15
	2	59.2	20.0	66	10.52	10.20
	3	35.9	22.5	37	10.50	10.11
	4	18.5	15.3	17	10.53	10.27
				Av. = 44		
Silver	1	4.02	0.02	99	10.31	9.75
	2	2.76	0.10	96	10.36	9.89
	3	1.68	0.08	95	10.40	9.90
	4	0.53	0.04	92	10.40	10.01
				Av. = 96		
Sodium	1	17.8	16.3	8	9.22	9.13
	2	13.7	12.3	10	9.20	9.07
	3	8.0	6.7	16	9.18	8.86
	4	4.7	4.9	(4)	9.19	8.99
				Av. = 8		
Zinc	1	3.13	0.24	92	10.18	10.01
	2	2.13	0.12	96	10.21	9.79
	3	1.35	0.05	96	10.29	9.63
	4	0.48	0.12	75	10.41	10.05
				Av. = 90		

*Partly precipitated.

Table 4 Average Percentages of Metal Cations Retained (Released) by Greensand Filter

Cation	Acidic solutions	Cation	Basic solutions
Lead	99	Silver	96
Iron	99	Copper	95
Cobalt	97	Arsenic	93
Copper	96	Mercury	93
Cadmium	95	Cadmium	91
Manganese	95	Nickel	90
Chromium	92	Zinc	90
Nickel	90	Lead	80
Zinc	90	Chromium	78
Silver	83	Cobalt	65
Potassium	83	Magnesium	65
Mercury	64	Manganese	57
Selenium	55	Potassium	44
Arsenic	38	Sodium	8
Silicon	32	Aluminum	(19)
Aluminum	21	Calcium	(75)
Sodium	3	Iron	(1782)
Magnesium	(65)	—	—
Calcium	(798)	—	—

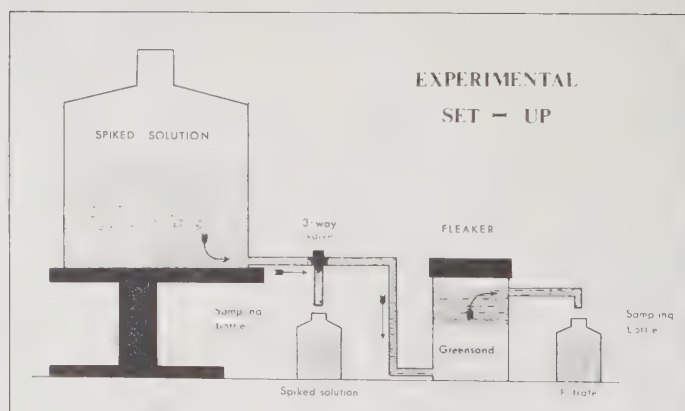


Figure 3. Sketch of a filter unit for one spiked solution. Four such units comprised the complete filtration system for one contaminating metal cation. Flow direction of spiked solution shown by arrows.

Ca, and Fe from the basic solutions was less effective. It should be noted that all five of the latter elements are essential constituents of glauconite. The basic solutions probably break down the glauconite structure and cause the release of Al, Ca, and Fe into the filtrate.

The addition of NH_4OH to the starting solutions spiked with $\text{FeCl} \cdot 6\text{H}_2\text{O}$ caused yellow colloidal particles of $\text{Fe}(\text{OH})_3$ to develop. Not only did these colloidal particles freely pass through the greensand filter but the basic starting solutions, by breaking down the glauconite structure, released additional iron into the filtrate. This iron also immediately formed $\text{Fe}(\text{OH})_3$ colloids. The high iron content in the basic filtrate therefore comes from both the starting solutions and the glauconite structure and is transported as colloidal $\text{Fe}(\text{OH})_3$.

Variations in all values from Tables 3a and 3b most probably result from a combination of the following factors:

1. Selective adsorption and exchange properties of glauconite
2. Breakdown of glauconite structure by basic solutions
3. Deviations from the selected rate of 2–4 ml/min
4. Natural variations in untreated greensands
5. Analytical error resulting from minute quantities of contaminating cation

Conclusions

Glauconitic greensands seem to be a useful filtration material for the removal of Pb, Co, Cu, Cd, Cr, Ni, Zn, Ag, and Hg from contaminated water regardless of the pH of the solution (Table 4). If the solution is acidic one may expect to remove Fe, Mn, and K in useful amounts and some Se, Si, Al, and Na. Calcium will be released into the acidic filtrate as long as shell material remains to be decomposed in the greensand.

If the solution is basic, one may expect to remove useful amounts of Ag and Mg and insignificant amounts of Na. However, Al, Ca, and Fe will be released into the filtrate in moderate to large quantities.

Solutions containing a mixture of contaminant ions will probably not behave precisely as these solutions spiked with single cations. In order to test this an investigation of the filtration capacity of glauconitic greensands on landfill leachates has been initiated.

The effectiveness of greensand as a filter for a specific cation may change with pH values that are markedly different from those of the experimental runs. The effects of total dissolved solids, Eh, contact time of the contaminated solution with glauconite, temperature, and other parameters remain to be evaluated.

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Effects of Thermal Discharges on Mortality of *Mercenaria mercenaria* in Barnegat Bay, New Jersey

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ABSTRACT / Thermal discharges from the Oyster Creek Nuclear Generating Station do not affect mortality in natural populations of *Mercenaria mercenaria* (Linné) in Barnegat Bay, New Jersey. The analyses of daily growth increments and disturbance bands in shell cross-sections of death assemblages of the pelecypods collected at the mouth of Oyster Creek (strongly affected by thermal discharges) and at three control sites (unaffected by thermal discharges) in the bay indicate that similar mortality patterns exist in all assemblages. This is revealed by mortality rate curves, survivorship curves, and life tables, which are nearly identical for each assemblage.

Each death assemblage results from natural and not census mortality, as is evident from its corresponding death-frequency histogram which shows that individuals have died at different times of the year. The peak frequency of stress and death occurs in older individuals of the populations and develops in the summer and winter. The high incidence of summer death may be associated with the effects of physiologic stress during spawning and with increased activity of predators and parasites during the warmer months of the year, whereas high winter mortality seems to be caused by harsh environmental conditions.

Mortality data recorded on life assemblages of *M. mercenaria* transplanted to the substrate for 1 year at the mouth of Oyster Creek and at a single control site in the bay show that mortality is significantly greater in the assemblage transplanted to the control site. Shell microgrowth analysis of the dead specimens collected from the transplanted assemblages reveals the following: (1)

Maximum frequency of death in clams is between 50 mm and 65 mm in h' (see text), and at 5 to 6 years of age; (2) peak frequency of death occurs in the summer; (3) no significant difference in the seasonal frequency of death exists between the two samples; and (4) natural instead of catastrophic mortality is evident.

It is concluded that mortality of *M. mercenaria* in Barnegat Bay is caused by the normal population dynamics of the species. The pattern of ontogenetic mortality in the bivalve is high-low-high. Mortality is high during the planktonic larval stages, low subsequent to spat settlement, and high again in the gerontic stage. Mortality rates rise significantly after sexual maturity is attained.

Introduction

One of the principal environmental concerns surrounding the operation of the Oyster Creek Nuclear Generating Station in Ocean County, New Jersey is its influence on the ecologic conditions in Barnegat Bay. Much of this concern centers around the vulnerability of many estuarine organisms to the effects of entrainment and passage through station condensers, impingement on intake screens, chemical and biocide releases, and thermal discharges. Research conducted by the Jersey Central Power and Light Company (United States Atomic Energy Commission, 1974) indicates that these factors are, in part, responsible for increased mortality of nekton and plankton at the station.

There has been much interest surrounding the possible relationship of thermal discharges to mortality of benthic organisms in the outfall canal and Barnegat Bay. For example, Loveland and others (1972) reporting on benthic faunal conditions in the bay for the first postoperational period of the station, 1969 to 1970, showed that a sharp reduction in the dominant benthic organisms *Pectinaria gouldii* (Verrill) and *Mulinia lateralis* (Say) had occurred in the region of Oyster Creek. During this interval *Pectinaria gouldii*, the golden bristled worm, increased in numbers at all sampled sites except Oyster Creek, where it decreased 78%. *Mulinia lateralis* experienced a "crash" in the summer of 1970 from which it has not recovered, and the clam's density dropped significantly at Oyster Creek and throughout the bay. Loveland and others (1972) later suggested that the decrease in density of *Mulinia* in the vicinity of Oyster Creek might have evolved from thermal mortality of meroplankton larvae by entrainment. The effects of entrainment would have precluded adult populations from maintaining normal levels. Nevertheless, these changes could have been caused by natural processes because they were so regional in scope (R. E. Loveland, Rutgers University, personal communication 1976).

In their last progress report Loveland and others (1974) noted that 1973 was an exceptionally poor year for benthic inverte-

brates throughout Barnegat Bay. All sampled sites showed a distinct decrease in diversity, biomass per square meter, and the number of individuals per square meter. The most significant change has been a decrease in the density and dominance of the populations—a situation that seems to have persisted through the summer of 1976 (J. J. Voughlitois, Jersey Central Power & Light Company, personal communication 1976). However, Loveland and others (1974) could not detect any statistically significant effect of the thermal discharges on the benthic faunal communities in the bay.

The abrupt changes in the population structure of *Pectinaria gouldii* and *Mulinia lateralis* subsequent to the initiation of operations of the nuclear power station raise a number of important questions pertaining to the possible connection between thermal discharges and mortality of benthic invertebrates in Barnegat Bay. Investigation of this problem requires a detailed analysis of the population dynamics of the benthos. Unfortunately, no complete population study of this kind has been undertaken in the past 6 years, since the station went on line.

A benthic species in Barnegat Bay ideally suited for initiating this type of research is the pelecypod *Mercenaria mercenaria* (Linné). It has a wide distribution that includes areas under the influence of the thermal plume, it is sufficiently abundant, it is sensitive to temperature changes in the bay (Kennish and Olsson 1975), and its ecology and physiology are well-known. The life-span of many of the clams also extends beyond the postoperational history of the station. In addition, the clam possesses a shell particularly useful for the study of population dynamics because it exhibits internal growth increments and growth breaks that are of value in age, growth rate, and mortality determinations.

The objective of this research project was to examine mortality patterns in life and death assemblages of juvenile and adult *M. mercenaria* in Barnegat Bay to determine the effects of thermal discharges on them. It was also hoped that the research would indicate the usefulness of this clam as a natural monitor of the thermal discharges (Kennish 1976, 1977). A number of techniques were used to attain these objectives. These included: (1) shell microgrowth analysis of specimens from natural and transplanted populations to establish growth rates and seasonal mortality patterns; and (2) construction of size- and age-frequency polygons, death-frequency histograms, and life tables to illustrate the type of clam mortality in different areas of the bay.

Study Area

Barnegat Bay, located along the east coast of New Jersey (Fig. 1), is a lagoon-type estuary. A barrier island system borders the bay on the east and the mainland bounds it on the west. A breach in the barrier island occurs at Barnegat Inlet and causes maximum tidal ranges and salinities in that region. Carpenter (1963) estimates exchange rates through Barnegat Inlet of approximately 7% per tide and a net discharge rate of 56.7 m³/sec. This amounts to a complete turnover of bay water every 96 tidal cycles.

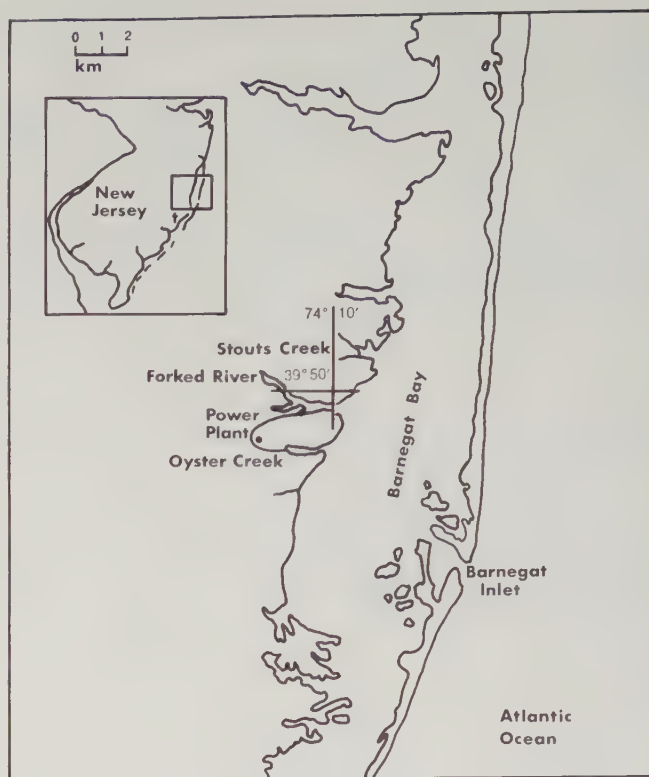


Figure 1. Barnegat Bay, New Jersey. The inset at the upper left shows the location of Barnegat Bay in relationship to the state of New Jersey. t (in inset) = Tuckerton, New Jersey. (After Phillips 1972.)

The bay stretches north-south for some 48 km but it is only 2–6.5 km in width. Its depth averages 1.5 m. The surface area is about 167,000,000 m² and the volume is 238,000,000 m³.

Salinity in the northern extremities of the bay approaches a brackish condition because of the influx of fresh water from drainage basins on the mainland and a decrease in the effect of tides. The position of Barnegat Inlet results in substantially higher salinities in the central and southern sectors. Tidal mixing is responsible for the uniform vertical salinity profiles observed by Carpenter (1963) in these areas. Data from Mountford (1971), Busch (1971), and Loveland and others (1972) indicate that salinities generally fall between 19 and 30 ‰ for the central bay.

Water temperatures recorded by Mountford (1971), Loveland and others (1972), and Kennish and Olsson (1975) beyond the effect of thermal discharges range from a winter low of approximately –1.5°C to a summer high of 28.0°C. Temperature inversions occur occasionally at the mouths of creeks when a wedge of warm, saline bay water intrudes upstream below a layer of cooler, fresher stream outflow. Local meteorologic conditions play a major role in regulating water temperatures because of the shallowness of the bay. A general condition of weak thermal stratification is often broken by wind action. Diurnal changes in temperature of 1–2°C are common.

Table 1 Summary of Climatologic Conditions at Tuckerton, New Jersey (39°36' N, 74°21' W) from July 1966 to July 1976

Month	Normal air temperature (°C)		Extreme air temperature (°C)			Total precipitation (cm)
	Mean maximum	Mean minimum	Mean	High	Low	
Jan	5.4	-4.9	0.3	16.1	-15.0	8.2
Feb	6.3	-4.3	1.0	16.2	-15.6	9.1
Mar	10.2	-0.2	5.0	22.3	-8.8	9.7
Apr	16.3	3.9	10.2	27.9	-4.4	9.7
May	20.7	9.4	15.1	30.2	1.6	8.8
Jun	26.1	15.6	20.8	33.7	7.3	9.0
Jul	28.6	18.4	23.5	34.6	11.4	9.9
Aug	28.9	18.1	23.5	34.7	10.6	10.5
Sep	25.2	13.9	19.6	32.0	4.3	9.2
Oct	19.6	7.9	13.8	27.8	-2.4	8.1
Nov	13.4	2.7	8.1	23.7	-7.0	10.5
Dec	8.1	-1.6	3.3	17.6	-10.8	11.8

Climatologic records for the region recorded at Tuckerton, New Jersey from June 1966 to June 1976 (Table 1) demonstrate the influence of the Atlantic Ocean throughout the year. Summer air temperatures are lower and winter air temperatures higher than those farther inland. Minimum temperatures for the 10-year period occur in January and February and maximum temperatures in July and August. Precipitation ranges from a minimum of 8.1 cm in October to a maximum of 11.8 cm in December. Winds predominate from the south and southeast in the summer, particularly after midday, and from the west and northwest during the winter. They are important in generating waves and affecting currents that transport a significant quantity of sediment.

The sediment in Barnegat Bay is broadly classified by Phillips (1972) and Kennish and Olsson (1975) as sand. The bay can be spatially subdivided on the basis of the character of its substrate (Fig. 2). The well-sorted fine sand in the eastern perimeter of the bay from Cedar Creek to Gulf Point is derived either from the continental shelf or from the erosion of beach materials north or south of Barnegat Inlet. Medium sand exists in a tract in the western perimeter of the bay from Gulf Point to the mouth of Oyster Creek and in two restricted sections between Oyster Creek, Forked River, and Stouts Creek. The bulk of sediment in the western perimeter of the bay from Oyster Creek to Stouts Creek is a muddy sand. The mouths of the streams draining the mainland consist mainly of sandy mud, as does the part of the bay north of Cedar Creek. The finer, poorly sorted sediment fraction in the western perimeter of the bay and north of Cedar Creek originates from the mainland and it is deposited in areas away from the influence of tidal currents through Barnegat Inlet. The overall sediment distribution in Barnegat Bay forms a spatial mosaic. This mosaic is ecologically important because it affects the distribution and density of benthic populations in the bay.

Figure 2. Sediment distribution in Barnegat Bay. (After Kennish and Olsson 1975.)

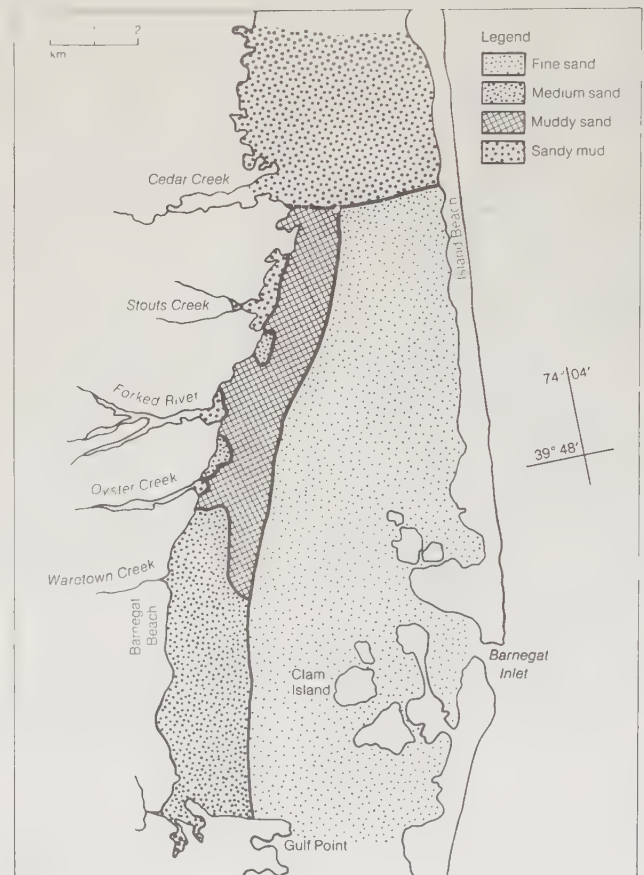


Table 2 Water Flow Through the Oyster Creek Nuclear Generating Station from 6/18/75 to 6/30/76

Dates	Number of days monitored	Mean flow (liters/day $\times 10^6$)	Standard deviation
6/18/75–6/30/75	13	4768.81	272.86
7/1/75–7/31/75	31	5212.31	71.58
8/1/75–8/31/75	31	4421.25	1224.30
9/1/75–9/30/75	30	2865.62	818.63
10/1/75–10/31/75	31	3642.76	1008.56
11/1/75–11/30/75	30	4014.25	859.78
12/1/75–12/31/75	31	3879.38	1309.21
1/1/76–1/31/76	31	2626.42	265.89
2/1/76–2/29/76	29	2592.20	375.23
3/1/76–3/31/76	31	3932.62	1358.55
4/1/76–4/30/76	30	5230.87	0.0
5/1/76–5/31/76	31	4002.45	443.87
6/1/76–6/18/76	18	4407.84	621.23
6/18/75–9/22/75 summer	97	4428.18	1087.14
9/23/75–1/2/76 fall	102	3687.48	1146.07
1/3/76–3/24/76 winter	82	2883.52	870.91
3/25/76–6/18/76 spring	86	4615.81	676.58

Thermal Discharges and the Oyster Creek Nuclear Generating Station

The Oyster Creek Nuclear Generating Station, in operation since December 1969, consists of a boiling water reactor with a forced circulation open-cycle system. The turbine generator uses steam produced in the reactor to yield 620 MW (net) of electric power. A maximum power level of 1930 MW thermal is obtainable.

At peak operation conditions approximately 1,741,100 liters of water per minute circulate through the turbine and reactor buildings for cooling purposes. The station does not operate at peak levels throughout the year, as is shown by flow measurements recorded at the station from June 18, 1975 to June 18, 1976 (Table 2). The temperature increase of cooling water across condensers, ΔT , amounts to a maximum of 12.8°C. Three axial flow dilution pumps, each with a 984,100 liter/min capacity, are used to control the temperature level of the circulating water discharge.

The source of water for circulation and dilution is Forked River and Barnegat Bay. This water flows up a semicircular, dredged canal connecting the South Branch of Forked River to Oyster Creek (Fig. 3). The canal averages 3 m in depth. Heated water discharged at the station flows down the outlet portion of the dredged canal into Barnegat Bay. The length of the discharge canal is about 3 km, and this distance allows a significant quantity of heat to be released to the atmosphere from the effluent. The effluent takes more than 2 hours to reach the bay.

A thermal plume forms in the bay as the thermal effluent flows out of the discharge canal. The morphology of the plume varies

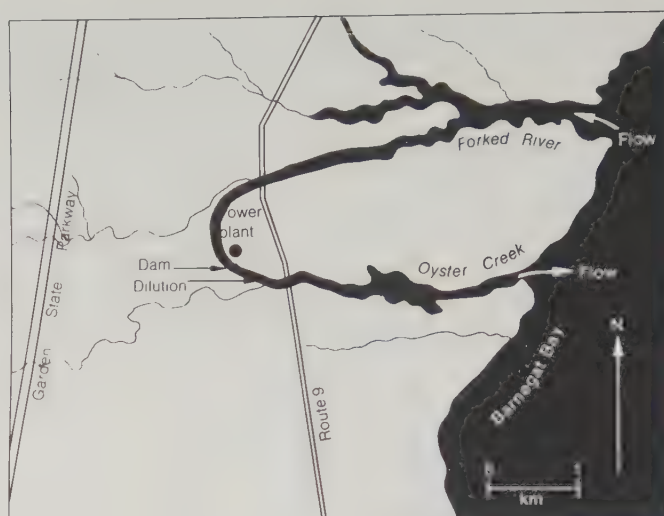


Figure 3. Flow characteristics at Forked River, Oyster Creek, and adjacent bay localities. (After Kennish and Olsson 1975.)

temporally and is confined to roughly a 1.6 km radius about the mouth of Oyster Creek. On calm days the plume often fans out about the mouth of Oyster Creek, its shape being affected by weak tidal currents (Kennish and Olsson 1975). However, when strong winds predominate from the north or south, it often appears as a narrow band abutting the shoreline. If strong south-east winds occur concurrently with flooding tide, a situation that is common in the summer months, some of the thermal discharges recirculate into the intake canal. The distribution of thermal effluent in the bay appears to be sensitive to local wind conditions.

Loveland and others (1974) and Kennish and Olsson (1975) discuss the magnitude of water temperature changes in Barnegat Bay during station operations. At times of peak operations, temperatures rise 3–5°C above ambient levels at the mouth of Oyster Creek (site 2, Fig. 4). This increase in temperature dissipates rapidly with distance from Oyster Creek and is undetectable along the substrate beyond 1.6 km.

Table 3 shows mean monthly water temperatures recorded at site 2 from August 1, 1974 to September 15, 1976. The data represent mean monthly values based on one temperature reading a day taken at both the surface and the bottom of the bay. Measurements could not be taken on a number of days, particularly in the winter, yielding an incomplete set of data. Nevertheless, the constant similarity between surface and bottom temperatures is evident. This seems to be caused by the shallowness of the bay at that point (approximately 1 m) and the close proximity to the discharge canal.

Mean monthly and seasonal water temperatures monitored in the subsurface within Oyster Creek (site 1, Fig. 4) and Forked River (site 3, Fig. 4) from June 18, 1975 to June 18, 1976 by the Jersey Central Power & Light Company are illustrated in Table 4. The data are based on water temperatures continuously recorded

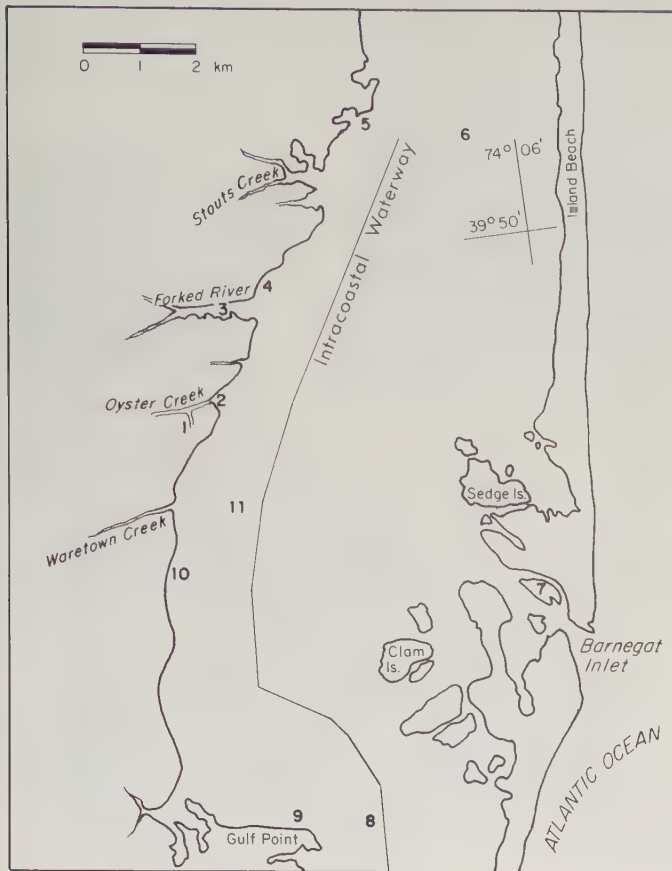


Figure 4. Sampling localities in Barnegat Bay.

Table 3 Water Temperatures Recorded at Site 2 from August 1974 to September 1976

Month	Number of days monitored	Mean water temperature (°C)			
		Surface	Std. dev.	Bottom	Std. dev.
8/74	28	30.89	1.73	29.79	1.64
9/74	28	25.79	3.54	25.14	3.26
10/74	30	17.13	1.97	16.77	1.79
11/74	25	13.92	4.89	13.40	4.43
12/74	26	8.15	1.69	7.85	1.49
1/75	29	6.74	2.55	6.60	2.60
2/75	20	6.74	2.99	6.39	2.67
3/75	21	9.12	2.48	8.78	2.36
4/75	18	10.01	2.66	9.73	2.63
5/75	19	20.52	2.94	20.22	2.89
6/75	28	25.89	2.10	25.27	2.00
7/75	29	27.47	1.42	27.17	1.64
8/75	27	28.24	2.07	28.03	2.14
9/75	25	23.61	2.02	23.26	1.92
10/75	26	18.98	.91	18.78	1.12
11/75	24	13.87	3.32	13.65	3.16
12/75	28	7.08	2.57	7.01	2.48
1/76	17	—	—	1.12	.95
2/76	19	—	—	5.26	3.05
3/76	20	11.26	3.62	11.24	3.59
4/76	30	16.73	4.08	16.58	3.94
5/76	31	21.05	1.45	21.00	1.45
6/76	—	—	—	—	—
7/76	28	26.29	1.37	26.22	1.34
8/76	29	26.21	1.14	26.05	1.05
9/76	15	25.30	1.28	25.18	1.28

by thermistors (Peabody Ryan Model G-45) located 0.15 m below the surface.

A comparison of water temperatures observed at sites 1 and 3 (Table 4) with station operations (Table 5) conducted from June 18, 1975 to June 18, 1976 indicates that significant temperature differences exist at the two sites when the station is operating. Thermal discharges strongly affect site 1 but not site 3, which is essentially at ambient bay conditions. Water temperatures are significantly higher at site 1 ($P < 0.05$) for the summer and fall of 1975 and for the spring of 1976. There is no significant difference (at the 0.05 level) in temperatures at the two sites for the winter of 1976. The similarity in temperatures during the winter of 1976 reflects the effect of a long station shutdown from December 28, 1975 to March 10, 1976.

Materials and Methods of Research

Nine sampling sites were established in Barnegat Bay to examine the effects of thermal effluent on mortality of juvenile and adult clams (sites 2 and 4–11, Fig. 4). Eight of these sites (sites 4–11) were located in areas unaffected by thermal effluent,

and they served as controls in the experiment. Site 2 was selected as the major test site because thermal effluent encompasses a natural population of *M. mercenaria* in that area.

In the summer of 1974 samples of death assemblages were collected at sites 2, 5, 6, and 9. Life and death assemblages of the bivalve were also sampled at these four sites and at sites 4, 7, 8, 10, and 11 in the summer of 1976. Specimens were washed on 0.5 cm and 1 cm mesh screens and were measured for size by means of vernier calipers accurate to 0.01 mm. Size-frequency polygons were constructed from these measurements.

Size measurements on the shells were made from the umbo to the ventral margin at a slight angle to the dorsal–ventral plane (see Fig. 5a). Therefore, the dimension measured only approximates the true height of the organism. This dimension has been labeled h' to differentiate it from the true shell height (h).

Shells from the death assemblages gathered in 1974 were employed to generate growth rate data, season of death data, life tables, mortality rate curves, and survivorship curves for the clam. This was done using the method of Rhoads and Pannella (1970). Following this method valves were sectioned from the umbo to the ventral margin along the h' plane and acetate peel replicas of the valve cross-sections were prepared. A phase

Table 4 Subsurface (0.15 m) Water Temperatures Recorded by the Jersey Central Power & Light Company at Sites 1 and 3 (see Fig. 4) from June 18, 1975 to June 18, 1976

Dates	No. of days	Mean water temperature (°C)			
		Site 1	Std. dev.	Site 3	Std. dev.
6/18/75–6/30/75	13	28.63	1.19	25.17	1.03
7/1/75–7/31/75	31	29.13	1.74	25.82	1.64
8/1/75–8/31/75	31	28.31	2.63	25.10	1.69
9/1/75–9/30/75	30	23.83	3.07	20.09	1.08
10/1/75–10/31/75	31	20.09	2.03	17.67	1.85
11/1/75–11/30/75	30	14.53	4.45	12.13	3.45
12/1/75–12/31/75	31	5.75	3.32	4.46	2.80
1/1/76–1/31/76	31	– 0.48	1.30	0.59	1.19
2/1/76–2/29/76	29	3.77	3.29	4.12	3.27
3/1/76–3/31/76	31	10.57	3.96	8.62	1.99
4/1/76–4/30/76	30	17.83	3.95	13.64	3.74
5/1/76–5/31/76	31	23.19	2.28	19.40	2.38
6/1/76–6/18/76	18	26.76	2.23	23.70	2.47
6/18/75–9/22/75 summer	97	27.85	2.68	24.26	2.60
9/23/75–1/2/76 fall	102	13.77	7.07	11.86	6.34
1/3/76–3/24/76 winter	82	3.72	4.54	3.89	3.65
3/25/76–6/18/76 spring	86	21.51	4.69	17.65	5.07

contrast petrographic microscope containing a graduated ocular was subsequently utilized to analyze microgrowth patterns in the peels. This technique yielded the observed growth and mortality data.

Mortality was also recorded in transplanted populations of *M. mercenaria*. A total of 3129 clams ranging from 20 mm to 75 mm in *h'* were transplanted in a series of separate experiments to sites

Table 5 Operational History of the Oyster Creek Nuclear Generating Station from June 18, 1975 to June 18, 1976*

Dates of operation	Dates of outage
6/18/75–8/27/75	8/28/75–9/2/75
9/3/75–9/23/75	9/24/75–10/3/75
10/4/75	10/5/75
10/6/75–11/24/75	11/25/75–12/1/75
12/2/75–12/19/75	12/20/75
12/21/75–12/27/75	12/28/75–3/10/76
3/11/76–6/18/76	

*Data from James J. Vouglitois, Jersey Central Power and Light Company, 1976.

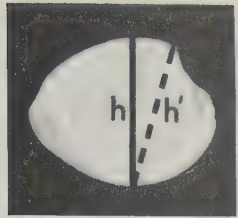
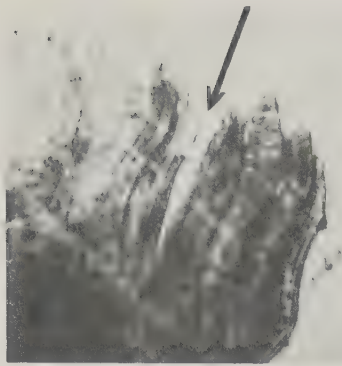
2 and 5 (control) in the summers of 1974 and 1975, and valves of dead specimens recovered from the transplanted populations were studied microscopically. Absolute age and season of death data were recorded from the dead specimens.

Description and Application of Shell Microgrowth Patterns in *Mercenaria mercenaria*

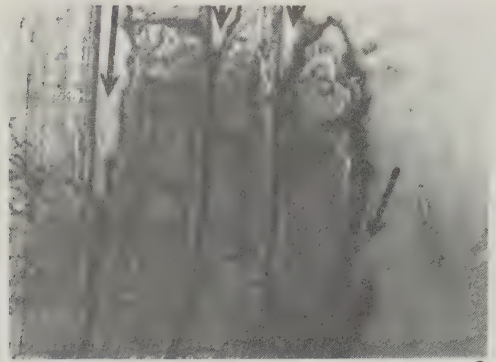
Pannella and MacClintock (1968), Rhoads and Pannella (1970), Cunliffe (1974), Cunliffe and Kennish (1974), and Kennish and Olsson (1975) discuss shell microgrowth patterns of *M. mercenaria* in detail. Two categories are recognized: (1) cyclical patterns and (2) growth breaks. Cyclical growth patterns include subdaily, daily, bidaily, fortnightly, lunar monthly, and annual types. These reflect periodic fluctuations in environmental stimuli and the existence of biologic clock mechanism in the organism.

Viewed in cross-section, cyclical patterns consist of sequential layers of calcium carbonate bounded by fine, dark bands of conchiolin (see Fig. 5e–h). The bands of conchiolin are secreted during the day, whereas the layers of calcium carbonate (in the mineral form aragonite) are deposited at night (MacClintock and

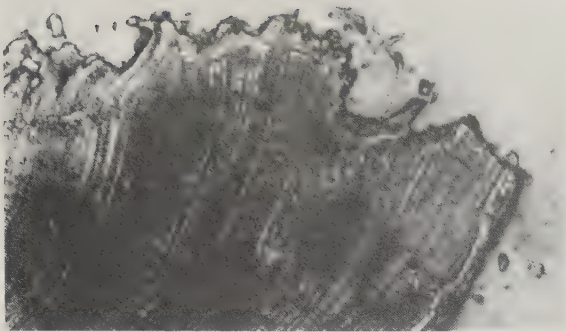
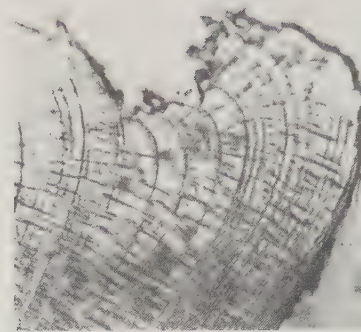
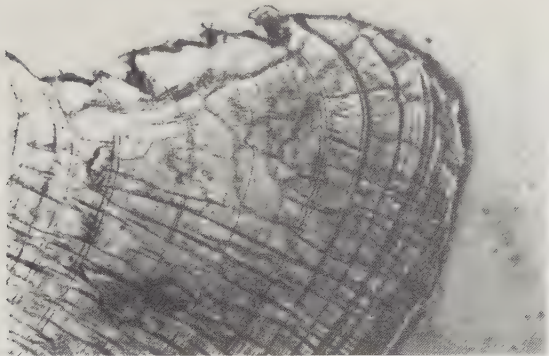
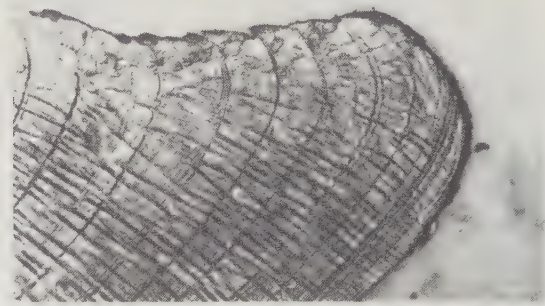
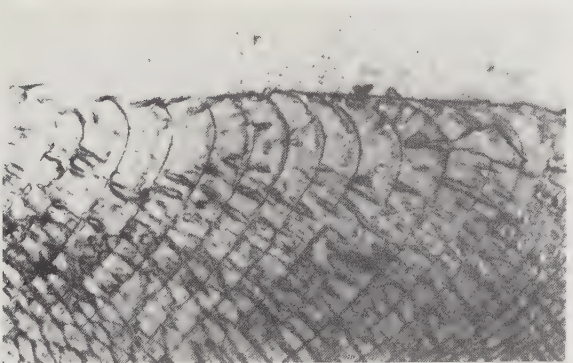
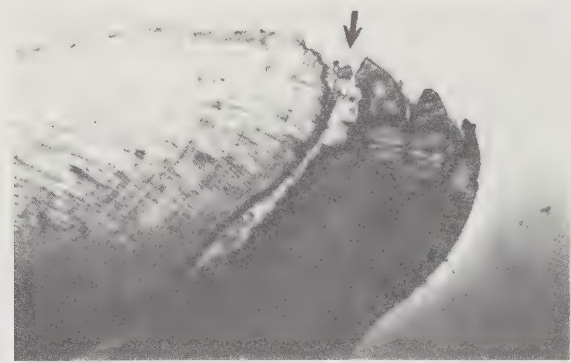
Figure 5. (a) Shell of the northern quahog, *Mercenaria mercenaria* (Linneé). The solid line (*h*) defines the true height of the organism. The dashed line (*h'*) represents the dimension of height utilized in this investigation (see text). (b, c, d) Early spring death recorded in shells of *M. mercenaria* from Barnegat Bay, New Jersey. Growth breaks (arrows) lie adjacent to the ventral margins. A crossed-lamellar shell structure and thin increments of growth characterize the margins. (e) Late spring death as reflected in the ventral valve margin of a specimen from site 5. Note the relatively large daily growth increments as compared to those of Fig. 5b, 5c, and 5d. Also note bands of conchiolin (thin, dark bands) bounding layers of calcium carbonate (thick, light layers). (f, g) Typical microgrowth patterns of clams that expire in the summer. The shell edge is preceded by large increments of growth diagnostic of the summer season. (h) Daily summer growth. Note the conchiolin layers (thin, dark bands) separating large, undivided calcium carbonate layers (thick, light bands). Summer growth patterns are distinctive and their position in the shell can be used to accurately determine season of death. (i) Summer storm break (arrow) in an individual from site 2. Note the sudden occurrence of the break and the silt grains at the base of the break. These silt grains were trapped between the shell and the organisms's mantle during the storm and subsequently incorporated into the shell. This growth break indicates that the organism has died in the summer season. Note: The direction of shell growth (from the umbo to the ventral margin) in each photo is from left to right. The scale for photos d, e, f, g, and h is equal to that of photo c. The scale for photo i is equivalent to that of photo b.

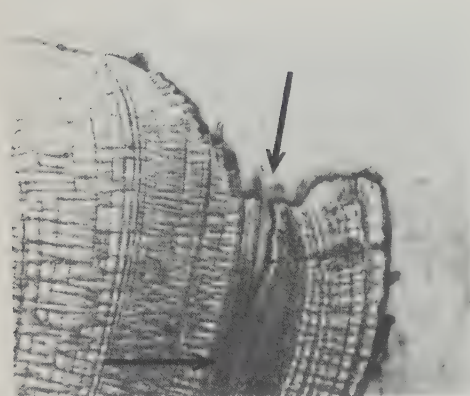
**a**

200 microns

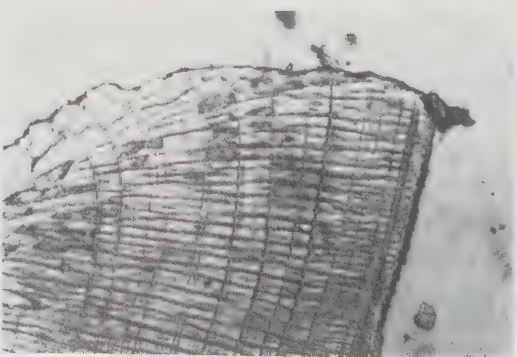
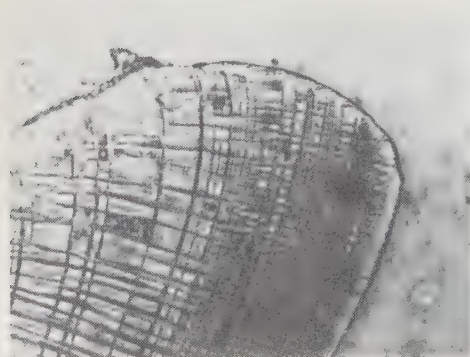
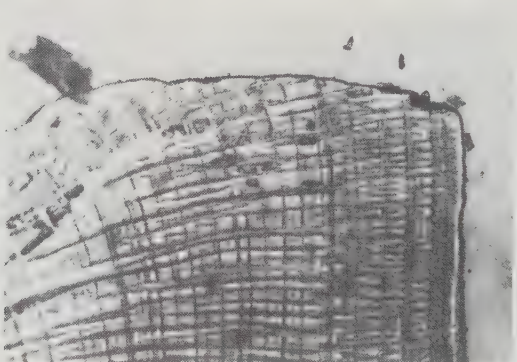
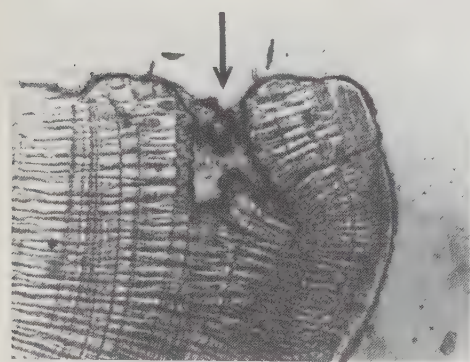
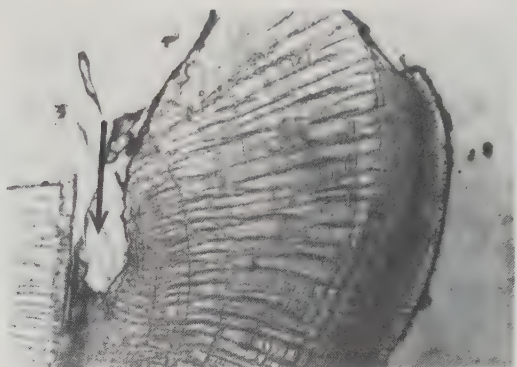
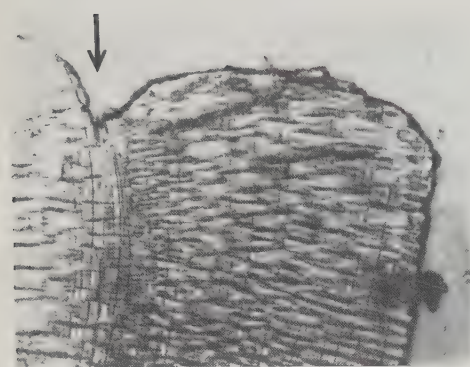
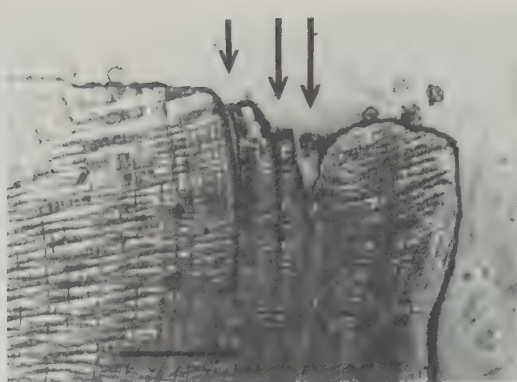
b

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c**d****e****f****g****h****i**



100 microns



Pannella 1969). Secretion of calcium carbonate by the mantle is continuous in the sense that it occurs on a daily basis; however, the amount of shell accretion is quite variable.

Occasionally, daily secretion of calcium carbonate is interrupted by periods of environmental and physiologic stress resulting in growth cessation. Growth cessation causes a break in the cyclical growth patterns of the shell. Such events are shown in the shell microstructure as V-shaped indentations in the prismatic layer and, in most examples, as a reduction in growth increment thicknesses on one or both sides of the break. A crossed-lamellar shell structure often marks the site of the break (see Figs. 6, a, b, and 7, a–c). Breaks in growth develop specifically from freeze shocks in the winter, heat shocks in the summer, artificially induced shocks, spawning periods, storms, and neap tides (Pannella and MacClintock 1968; Rhoads and Pannella 1970; Kennish and Olsson 1975).

Because the shell microgrowth patterns in *M. mercenaria* vary directly with cyclical and random fluctuations in such environmental parameters as temperature, salinity, tides, storms, and other variables, the shell of the bivalve is an effective tool for monitoring these factors. In addition to monitoring environmental parameters, the shell also records the physiologic condition of the clam throughout ontogeny. In essence, the shell continuously records daily, monthly, seasonal, and annual changes in environmental and physiologic conditions.

Because they record physiologic and environmental conditions, shell microgrowth patterns of *M. mercenaria* can be applied to the study of growth rates and mortality. For example, counts of daily growth increments from the umbo to the ventral margin in valves of dead specimens yield data on absolute age at death (Rhoads and Pannella 1970). If these daily increments are lumped together into annual units and measured, yearly growth

rates can be established. Probably the most accurate method of determining the season of death is to combine growth increment counting with the interpretation of growth patterns at the ventral margin of the shell (Tevesz 1972). By relating the position of the last increment of growth before death to seasonal growth breaks incurred earlier in life, season of death can be estimated. A ventral margin preceded by a long period of winter growth suggests spring death (see Fig. 5, b–e). Thick increments at the outer margin preceded by a winter (freeze) shock break displaced 160–200 increments dorsally signify summer death (see Fig. 5, f, g). A summer storm break (see Fig. 5, i), a summer (heat) shock break (see Fig. 6, a, b), or a spawn break (see Fig. 6, c, d) bordering the leading edge of the shell likewise denote summer death. A margin following a complete sequence of summer growth increments implies fall death (see Fig. 6, e–h). A winter (freeze) shock break associated with thin growth increments adjacent to the ventral margin indicates winter death (see Fig. 7, a–c), as do thin increments at the shell edge following a summer (heat) shock break located approximately 160–200 increments dorsally (see Fig. 7, d). Although this technique is efficient, it is desirable to verify data obtained in this manner with independent evidence drawn from daily growth increment counts across the shell.

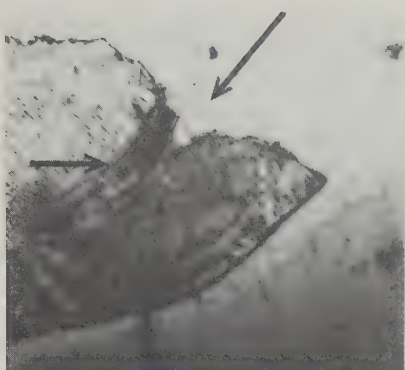
Microgrowth analysis is valuable not only for generating information on the season of death and the age at the time of death on specimens from death assemblages but also for differentiating a census mortality from a natural one in different populations. Because some growth breaks occur synchronously in a large part of a population (Pannella and MacClintock 1968), it is possible to use them as microgrowth data planes for purposes of correlation. Particularly useful in this respect are universal events, such as major storm breaks and thermal shock breaks, that can be precisely dated by alternate means. Census mortality of a population is substantiated when growth breaks match up across many individuals in a death assemblage and the terminal microgrowth patterns are alike. In this case, mortality is confined almost exclusively to a single season of the year. Natural mortality, in contrast, is manifested as a high diversity in the growth patterns present at the ventral valve margins. This diversity reflects the high variability in seasonal mortality of members of the population.

These methods of analysis have been utilized successfully in the study of population dynamics in the past (Rhoads and Pannella 1970; Tevesz 1972; Cunliffe 1974). Because of this, all of them have been incorporated to this research project. Their use has generated data on growth and mortality in populations of *M. mercenaria* throughout Barnegat Bay. They have also provided evidence of significant temporal changes in the population dynamics of the clam.

Growth Rates of *Mercenaria mercenaria* in Barnegat Bay

Growth rates of *M. mercenaria* in Barnegat Bay were determined by measuring annual increments of growth in valve cross-sections from the umbo to the ventral margin. The basic micro-

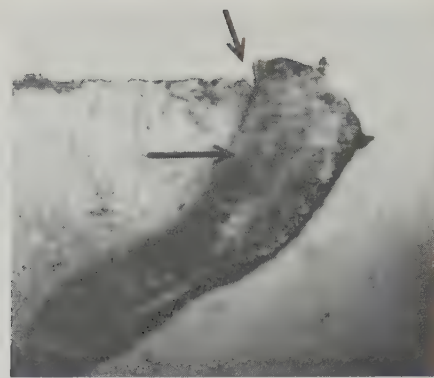
Figure 6. (a, b) Shell microgrowth patterns of specimens that died in the summer. Summer death is manifested by summer (heat) shock breaks (downward pointing arrows) which border the margins. A transgressing crossed-lamellar shell structure (horizontal arrows) marks the growth breaks. (c, d) Summer death monitored in shells of *M. mercenaria*. Spawn breaks (arrows) rim the leading edge of the shells. The existence of spawn breaks at the valve margins signifies summer mortality because spawning of *M. mercenaria* in Barnegat Bay is confined to the summer season. (e, f, g, h) Ventral valve margins of clams that died in the fall. Growth increments are of a thickness intermediate between summer and winter thicknesses. Fall microgrowth patterns are differentiated from spring patterns by the occurrence of summer growth patterns immediately dorsal to them. Note the slowdown in growth as the ventral margin is approached. This slowdown in growth denotes a moribund condition prior to death. A break in growth (arrow) is present in Fig. 6e. Note: The direction of shell growth (from the umbo to the ventral margin) in each photo is from left to right. The scale for photos b, c, d, e, f, g, and h is the same as that for photo a.



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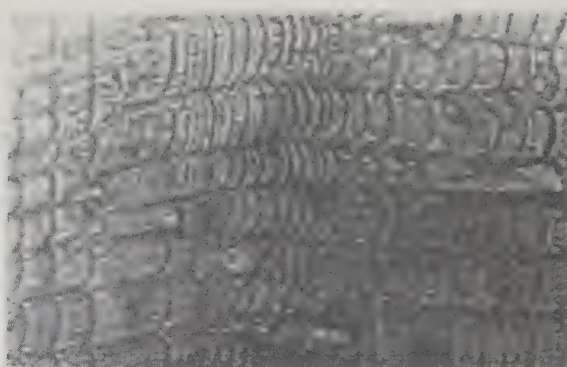
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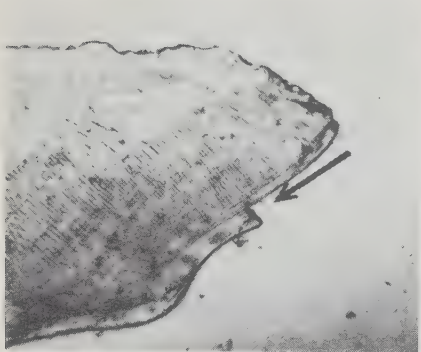
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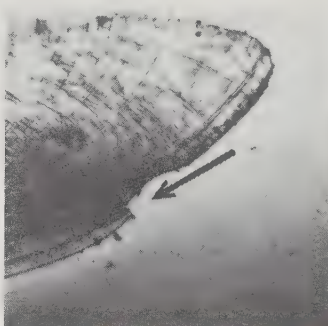
100 microns d



100 microns e



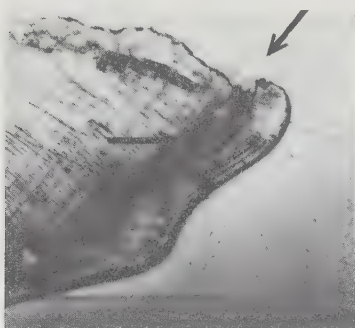
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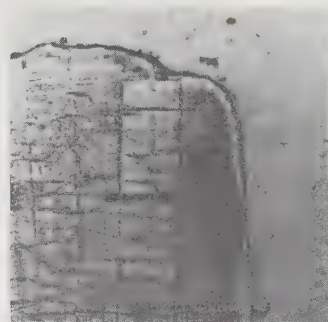
g



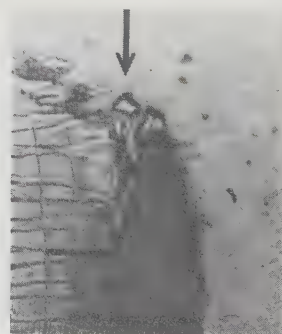
h



i



j



k

growth analysis employed to obtain these measurements were daily growth increment and seasonal growth break counts. A total of 277 specimens from the death assemblages collected in 1974 at sites 2, 5, 6, and 9 was examined. This included 101 valves from site 2, 74 from site 5, 46 from site 6, and 38 from site 9. The valves ranged from 14.0 mm to 76.5 mm in h' . The age- h' statistics of these samples are presented in Table 6.

Table 7 summarizes the age- h' relationships observed in each assemblage, and Table 8 records the pooled age- h' values as calculated by means of a Statistical Analysis Systems computer program run on an IBM 370/158 computer. Most of the clams are under 7 years old; data for older clams are therefore based on fewer measurements. Inspection of the data reveals extremely uniform growth rates at all four localities, with growth being fastest and nearly linear for the first 3 years of life and generally slowest in the gerontic stage.

A comparison of the age- h' relationship of clams at site 2 with those at sites 5, 6, and 9 indicates that thermal discharges from the Oyster Creek Nuclear Generating Station have had little effect on the growth rates of clams in death assemblages of Barnegat Bay. There is excellent agreement of growth rates in clams at site 2 with those at all other locations. Juvenile and adult growth rates are nearly identical at sites 2 and 5, slightly greater

Table 6 Age- h' Statistics for Samples of Clams from Sites 2, 5, 6, and 9

Site	No. of clams	Mean h' (mm)	Standard deviation	Mean age (yr)	Standard deviation
2	101	43.12	12.81	3.92	1.70
5	74	46.82	12.57	4.25	1.72
6	64	49.74	9.65	5.03	1.31
9	38	46.82	17.05	4.03	1.79

at site 9, and somewhat reduced at site 6. A tendency exists for clams to reach a common size in old age in all assemblages because of a reduction in growth rates and a decline in absolute and relative variability of growth.

The clams are so regular in their growth characteristics that the analysis of growth in even one specimen within an assemblage can reveal a substantial amount of information concerning growth rates in the population as a whole. For example, Table 9 displays age- h' relationships of one clam from site 5 compared to that of the entire assemblage from which it was taken. Note the close fit of the growth rate of this individual to that of the entire assemblage. Only a few specimens per sample need be analyzed microscopically to obtain the overall growth plan of the species at that site.

Figure 7. (a, b, c, d) Winter death recorded in shell microgrowth patterns of *M. mercenaria* from Barnegat Bay. The ventral valve margins are preceded by winter (freeze) shock breaks (downward pointing arrows) and thin increments of growth typical of the winter season. A crossed-lamellar shell structure (horizontal arrows) lines the growth breaks. (e) Daily winter growth. Note the extremely thin growth increments as compared to those of the summer (Fig. 5f, 5g, 5h). The location of winter growth in relationship to the ventral margin of the shell is critical in the determination of the season of death of the organism (see text). (f, g, h) Shell microgrowth patterns of clams transplanted in cages for 1 year in Barnegat Bay. Arrows point to shell growth subsequent to transplantation. Note the aberrant growth patterns, with little shell being added after transplantation. Shell added during the experiment has failed to reach the upper margin of the prismatic layer; this indicates an abnormal growth condition. (i, j, k) Summer mortality patterns reflected in the shell microstructure of clams transplanted to the substrate in Barnegat Bay in 1975. Horizontal and vertical arrows point to the time of notching (transplantation). Note the reduction in growth and the alteration of prismatic to crossed-lamellar shell structure following transplantation. The number of growth increments added after transplantation signifies summer death for all three specimens. Summer mortality is common in transplanted populations. Note: The direction of shell growth (from the umbo to the ventral margin) in each photo is from left to right. The scale for photos b, c, f, g, h, and i equals that of photo a. The scale for photos j and k is equivalent to that of photo d.

Size Distributions of Life and Death Assemblages of Clams in Barnegat Bay

Table 10 summarizes the size characteristics of life and death assemblages of *M. mercenaria* collected in Barnegat Bay during the summers of 1974 and 1976. The data indicate a remarkable similarity in clam sizes throughout the bay. Only at site 7, which is located in Barnegat Inlet, do the clam sizes diverge appreciably from the other samples.

Mean h' values of the death assemblages of clams gathered at sites 2, 5, 6, and 9 in the summer of 1974 are not all equal ($P < 0.0005$). A Student-Newman-Keuls multiple range test performed on these 1974 samples shows that mean h' are not significantly different ($P < 0.05$) between the death assemblages at sites 5 and 6 but are significantly different ($P < 0.05$) between all other death assemblages. The mean size of values at the mouth of Oyster Creek (site 2) is significantly lower ($P < 0.001$) than at all other locations.

A single factor analysis of variance on death assemblages sampled at sites 2, 4, 5, 6, 7, 8, 9, 10, and 11 in the summer of 1976 also reveals an inequality among the mean h' of specimens ($P < 0.0005$). A Student-Newman-Keuls test on these assemblages discloses no significant differences ($P < 0.05$) in mean h' between sites 2 and 4, 9 and 10, and 6, 8, and 11. With the exception of sites 4 and 7, the mean clam h' at site 2 is significantly lower ($P < 0.05$) than at all other locations.

There is no significant difference ($P < 0.05$) between the mean

Table 7 Mean Age-h' Relationships Observed in Death Assemblages of Clams at Sites 2, 5, 6, and 9

Age	Site 2, N* = 101			Site 5, N* = 74			Site 6, N* = 64			Site 9, N* = 38		
	N**	Mean h' (mm)	Std. dev.	N**	Mean h' (mm)	Std. dev.	N**	Mean h' (mm)	Std. dev.	N**	Mean h' (mm)	Std. dev.
1	101	12.39	3.76	74	11.36	4.16	64	7.04	2.71	38	12.72	5.15
2	89	23.00	4.49	68	23.51	4.96	64	17.70	4.24	35	25.61	6.19
3	65	32.91	4.49	63	35.01	4.89	63	29.54	5.22	25	37.30	6.42
4	50	42.36	5.26	44	43.78	4.15	54	39.55	5.23	19	46.97	5.25
5	28	49.37	6.27	19	49.89	3.01	28	47.75	5.81	12	55.58	7.05
6	16	57.61	7.76	9	56.18	3.94	10	55.11	4.05	6	62.13	8.88
7	6	59.52	5.41	6	63.60	1.70	7	63.30	4.56	3	65.80	3.04
8	0	—	—	4	70.60	1.75	3	69.13	5.95	0	—	—

*N = number of clams.

**N = number of size measurements per age.

h' values of life assemblages of clams collected in 1976 at sites 4, 5, and 6, and at sites 2, 10, and 11, but there is a significant difference ($P < 0.05$) between all other life assemblages. The life assemblage at site 3 has a higher mean value of h' than at all locations except site 9. This is opposite to the array of sizes observed in the corresponding death assemblages.

Significant differences ($P < 0.05$) in mean sizes exist between life and death assemblages at sites 2, 4, 6, 7, 8, and 11. No significant differences in mean h' are found between life and death assemblages at site 9 ($0.10 < P < 0.20$) and site 10 ($0.20 < P < 0.50$).

Thermal discharges from the Oyster Creek Nuclear Generating Station seem to have no effect on the distribution of clam sizes in Barnegat Bay. This is graphically reflected by the close agreement in size (h')-frequency distributions (Figs. 8a-8m) of the life and death assemblages at site 2 (affected by thermal

discharges) with those at the control sites (unaffected by thermal discharges). Moment measures about the mean sizes of the samples are also alike, and they clearly describe the size distributions (Table 11).

Size-frequency polygons constructed for the samples consist of unimodal curves with a negative skewness in all death assemblages and most of the life assemblages. The occurrence of a single mode dominating each death assemblage is not surprising. The death assemblages develop from the accumulation of many generations of clam shells, which tends to smooth out the short-term fluctuations in population structure. In essence, population stability is assumed over long periods of time. This assumption is borne out by the research of Olson (1957), who found that in approximately 200 size-frequency distributions of fossil organisms about 85% were unimodal.

Polymodality in size-frequency distributions of death assem-

Table 8 Mean Age-h' Relationships for the Pooled Death Assemblages of Clams from Sites 2, 5, 6, and 9

Age	N**	N* = 277	
		Mean h' (mm)	Standard deviation
1	277	10.92	4.44
2	256	22.17	5.51
3	216	33.05	5.67
4	167	42.35	5.47
5	87	49.82	6.11
6	41	57.35	6.65
7	22	62.69	4.37
8	7	69.97	3.73

*N = number of clams.

**N = number of size measurements per age.

Table 9 Observed Age-h' Relationships of a Single Specimen from Site 5 Compared to That of the Entire Death Assemblage

Age (yr)	h' (mm) of single specimen	Mean h' (mm) of all specimens*
1	11.2	11.4
2	23.9	23.5
3	34.5	35.0
4	43.8	43.8
5	50.9	49.9
6	56.9	56.2
7	63.3	63.6
8	70.2	70.6

* = 74 specimens.

Table 10 Size Statistics for Life and Death Assemblages of *Mercenaria mercenaria* in Barnegat Bay

Site (Fig. 4)	Year	Life assemblage				Death assemblage			
		No. of clams	Mean h' (mm) $\pm$ 95% C.I.	Std. dev. for mean	Median h' (mm)	No. of clams	Mean h' (mm) $\pm$ 95% C.I.	Std. dev. for mean	Median h' (mm)
2	1974	No data				405	51.75 $\pm$ 1.06	10.81	54.50
5	1974	No data				446	55.38 $\pm$ 0.74	7.91	57.00
6	1974	No data				464	55.89 $\pm$ 0.73	7.97	56.50
9	1974	No data				261	60.47 $\pm$ 1.29	10.56	62.00
2	1976	435	54.56 $\pm$ 0.75	7.97	55.20	499	53.36 $\pm$ 0.76	8.69	54.45
4	1976	342	50.33 $\pm$ 0.91	8.52	49.60	280	54.16 $\pm$ 1.11	9.47	55.48
5	1976	446	51.07 $\pm$ 0.78	8.38	49.45	445	59.17 $\pm$ 0.78	8.37	60.60
6	1976	441	51.24 $\pm$ 0.88	9.41	52.70	408	56.45 $\pm$ 0.87	8.95	57.80
7	1976	416	11.84 $\pm$ 0.37	3.85	11.10	16	17.52 $\pm$ 3.44	6.45	16.85
8	1976	450	52.52 $\pm$ 0.70	7.54	52.63	413	57.78 $\pm$ 1.02	10.53	57.80
9	1976	436	56.26 $\pm$ 0.63	6.64	56.25	214	55.25 $\pm$ 1.30	9.63	56.30
10	1976	440	54.24 $\pm$ 0.70	7.51	53.77	436	54.62 $\pm$ 0.84	8.89	55.60
11	1976	208	54.20 $\pm$ 1.04	7.63	55.00	438	57.27 $\pm$ 0.85	9.07	58.60

blages of *M. mercenaria* can arise in one of two ways (Sheldon 1965): (1) by catastrophic death of the life assemblage, which freezes the size distribution of the living population; and (2) by high mortality in the life assemblage within a short interval of time or during a period of little growth and at the same time each year. In the first case, successive modes correspond to distinct year classes of clams because annual recruitment is confined to the summer months. In the second, they represent the accumulation of particular shell sizes each year because high mortality coincides with times when the size structure of the life assemblage is similar.

Neither of the cases applies to death assemblages of *M. mercenaria* in Barnegat Bay. This is evident not only from the unimodal size-frequency distributions but also from the seasonal mortality patterns of the clam, which show that individuals die at different times of the year.

The unimodality of the life assemblage polygons, in contrast, suggests a failure of annual recruitment. Because spawning and recruitment of *M. mercenaria* in New Jersey takes place within a short time span in the summer (Carriker 1961; H. H. Haskin, Rutgers University, personal communication 1976), a series of modal peaks corresponding to successive yearly broods is to be expected in these diagrams if recruitment has been successful the past few years (Hallam 1972). In such a case troughs between modal peaks would coincide with periods of growth of each generation from one recruitment stage to the next (Craig and Hallam 1963; Schmidt and Warne 1969).

This situation can be simulated. For example, Table 8 displays a growth rate for *M. mercenaria* in Barnegat Bay based on microgrowth analysis of 277 specimens from sites 2, 5, 6, and 9. Assuming these data represent the average rate of growth for *M. mercenaria* in the bay, and assuming the bay possesses a stable

clam population with constant annual recruitment and no mortality, a polymodal size-frequency distribution can be produced (Fig. 9). Of course, this model is unrealistic because it fails to take into account natural fluctuations in mortality and recruitment. Nevertheless, it serves as an ideal, theoretical population structure for comparison to the observed size-frequency distributions of the life assemblages in Barnegat Bay.

The model has well-defined, symmetrical peaks at 1.5 mm, 10.9 mm, 22.2 mm, 33.0 mm, and 42.4 mm that correlate with the 1976, 1975, 1974, and 1972 year classes, respectively. Beyond 50 mm the modes tend to merge and the age classes become obscured because of the reduction in growth rates and the spread of sizes of older clams, which causes an overlapping of the larger classes.

With the exception of site 7, there are no peaks in the observed size-frequency polygons of the life assemblages in Barnegat Bay that can be ascribed to single year classes from 1973 to 1976. Certainly, young *M. mercenaria* are being added to the populations not on a yearly basis, but sporadically. The effect of coalescence of the larger size classes is readily apparent as in the model. The rapid dissipation in the number of larger clams in the observed distributions compared to that of the model results from the precipitous increase of mortality in older clams.

Site 7 is composed of a juvenile population of clams—seemingly the only one in Barnegat Bay at present. The life assemblage polygon for site 7 contains a sharp peak at 11.8 mm but no others at smaller or larger sizes. This peak corresponds to the 1975 year class and relates favorably to that of the model. The absence of a peak between 0 and 5 mm is probably the consequence of poor recruitment in 1976, whereas the lack of peaks beyond 11.8 mm reflects poor recruitment at the site prior to 1975.

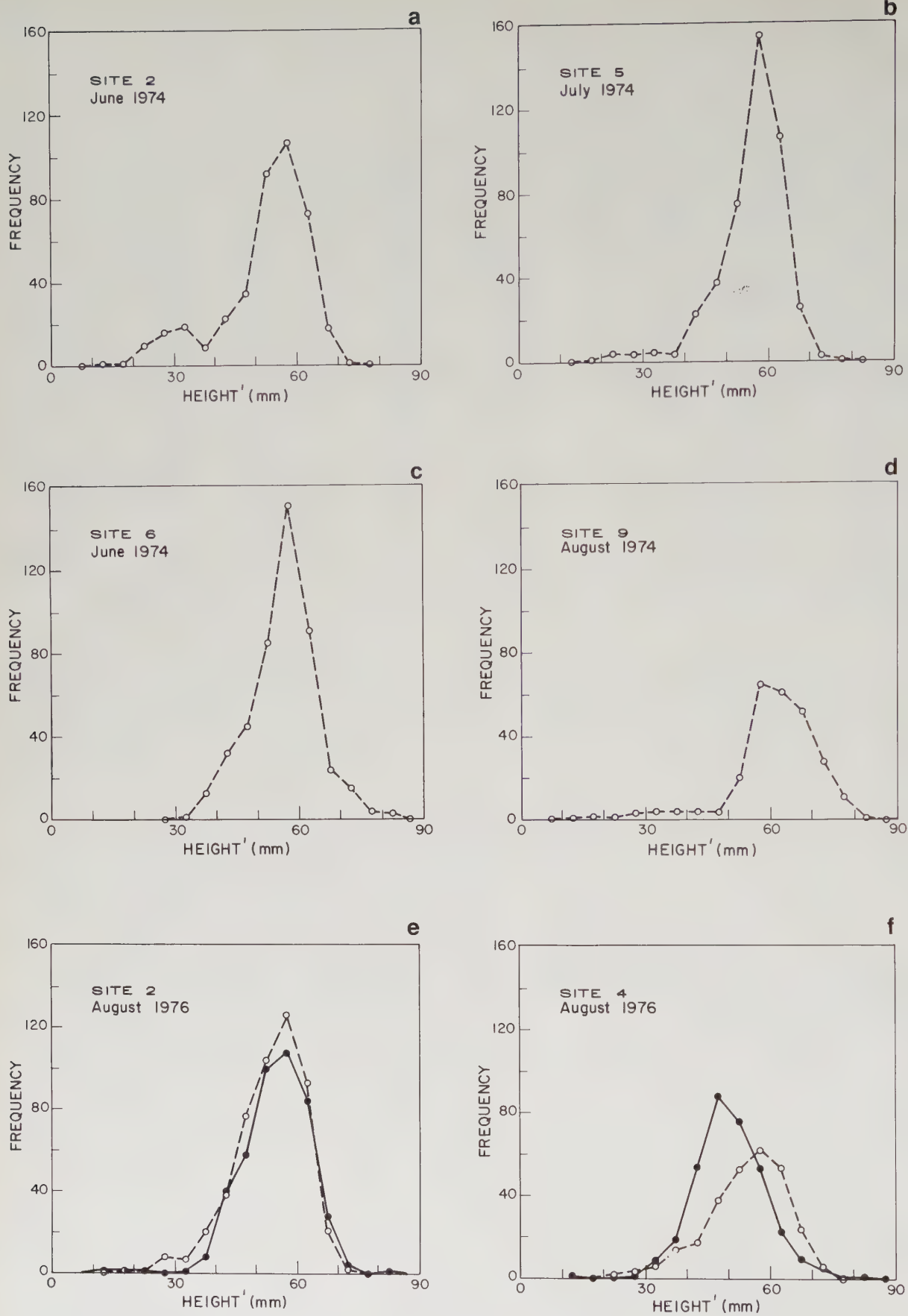
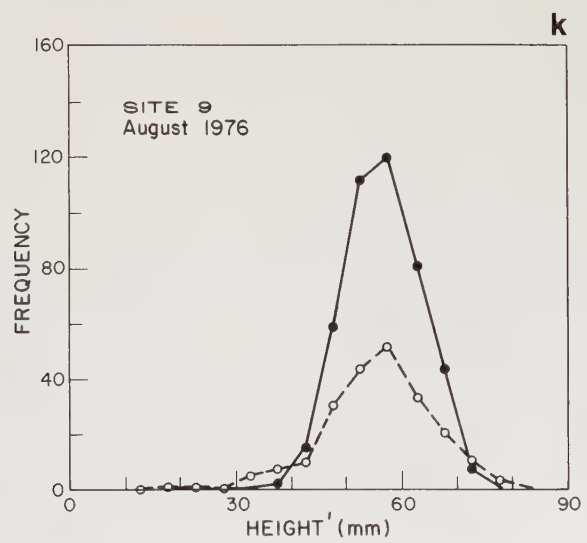
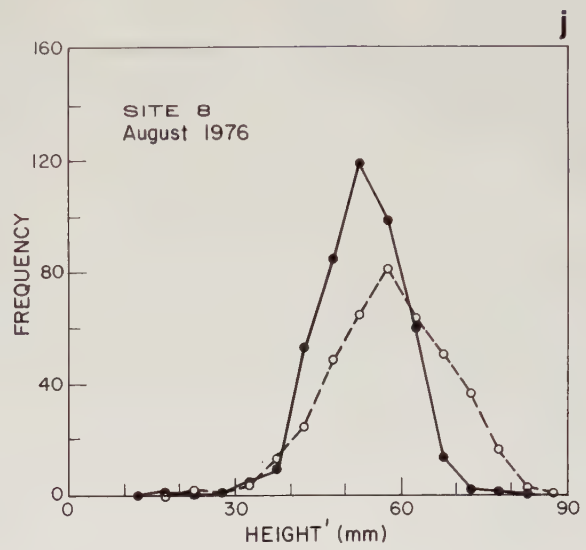
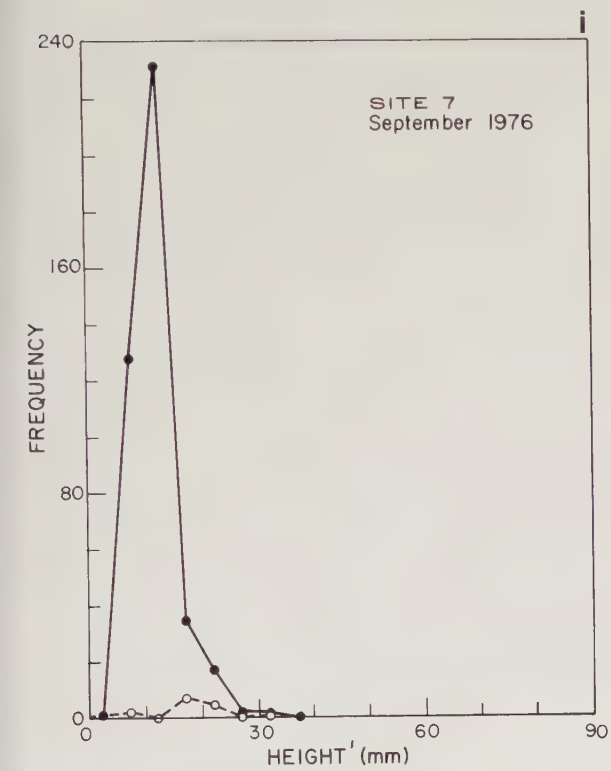
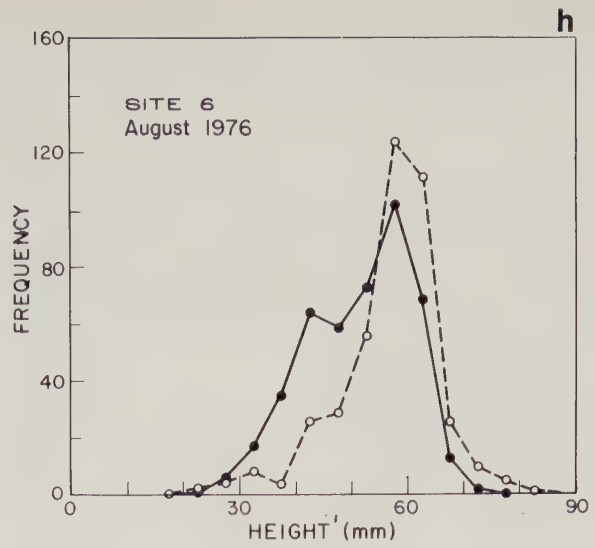
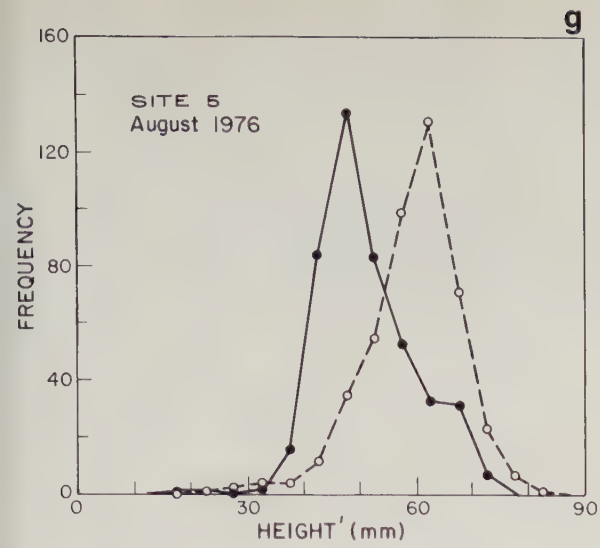
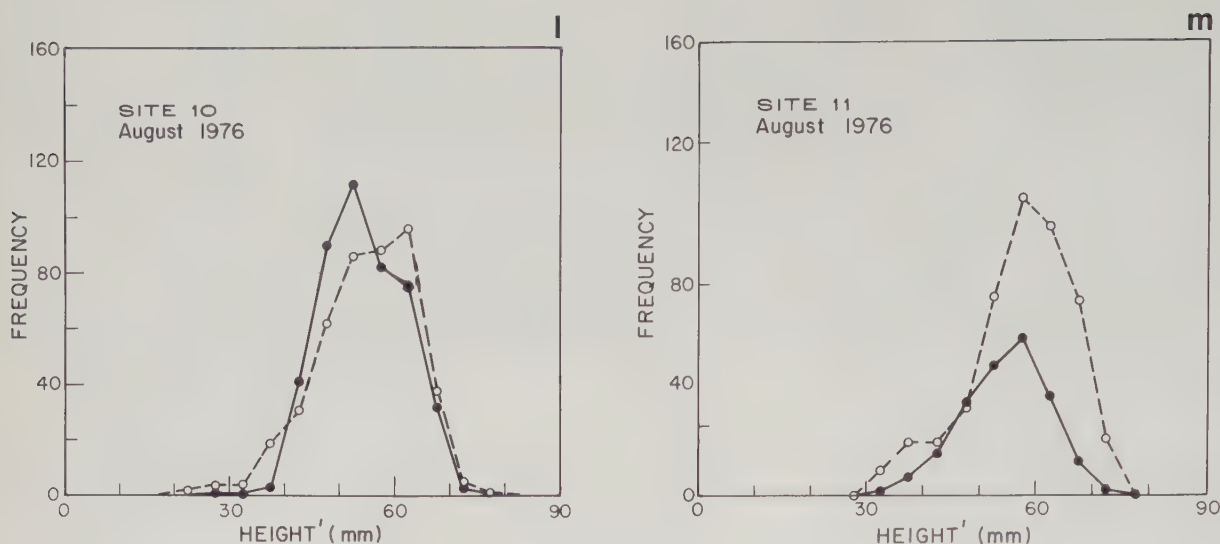


Figure 8. (a-m) Size (h')-frequency distributions for life and death assemblages of *Mercenaria mercenaria* collected at sites 2, 4, 5, 6, 7, 8, 9, 10, and 11 in Barnegat Bay in 1974 and 1976. (---) Death assemblage; (—) life assemblage.





It is not known why recent recruitment has almost totally failed in the bay. Starypan (1976) notes the same effect in populations of *Spisula solidissima* (Dillwyn) all along the South Jersey coast. Evidence from the size-frequency distributions of both life and death assemblages of *M. mercenaria* suggests that the problem lies with the ineffectiveness of either the planktonic larval or the pediveliger stages. If clams had grown successfully through the juvenile plantigrade stage (approximately equal to 10 mm), live specimens and empty valves of dead juveniles should be present in the assemblages. That they are not (except at site 7) affirms this conclusion.

The variability in recruitment of *M. mercenaria* in Barnegat

Bay is indirectly reflected in Table 12. The data record the fluctuation of bivalve catches from 1960 to 1969, and some cyclicity is evident. However, no statistics are available on the changes in fishing effort during this interval that may have contributed to this cyclicity.

The recent failure of recruitment may be caused by the normal population dynamics of the species. All bivalve species with a planktotrophic pelagic larval stage during ontogeny, such as *M. mercenaria*, are subject to a significant wastage of numbers associated with predation and inadequate food supply (Thorson 1950). Once the spat set, predation (Carriker 1956, 1959, 1961) and disease during the pediveliger and early plantigrade stages

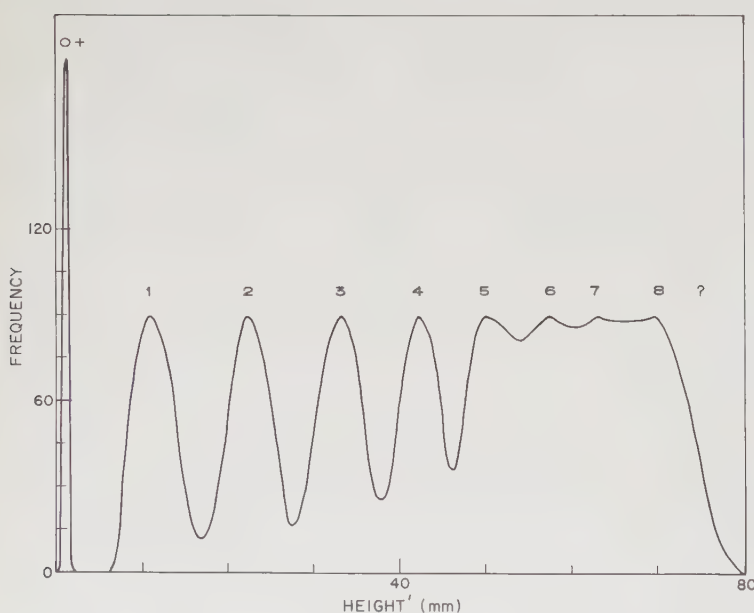


Figure 9. Theoretical population model for 8 years of growth of *Mercenaria mercenaria* in Barnegat Bay. The model assumes population stability with constant annual recruitment and zero mortality.

Table 11 Moment Measures about the Mean h' for Life and Death Assemblages of *Mercenaria mercenaria* in Barnegat Bay

Site	Sample	Mean h' (mm)	Moment measures				
			m_2	m_3	m_4	K^*	S_K^*
2	Death assemblage, 1974	51.75	116.82	-1442.51	52318.14	3.85	-1.14
5	Death assemblage, 1974	55.38	62.59	-739.34	25745.93	6.60	-1.50
6	Death assemblage, 1974	55.89	63.53	-39.71	13883.51	3.45	-0.08
9	Death assemblage, 1974	60.47	111.45	-1904.20	85648.74	6.95	-1.63
2	Death assemblage, 1976	53.36	75.61	-554.99	22083.39	3.88	-0.85
4	Death assemblage, 1976	54.16	89.77	-562.22	26125.33	3.26	-0.66
5	Death assemblage, 1976	59.17	70.11	-447.50	21064.05	4.30	-0.76
6	Death assemblage, 1976	56.45	80.04	-628.25	29662.52	4.65	-0.88
7	Death assemblage, 1976	17.52	41.60	-34.76	4321.23	2.83	-0.14
8	Death assemblage, 1976	57.78	110.79	-223.40	35463.95	2.90	-0.19
9	Death assemblage, 1976	55.25	92.80	-586.28	38287.19	4.49	-0.66
10	Death assemblage, 1976	54.62	79.15	-467.54	21520.60	3.45	-0.67
11	Death assemblage, 1976	57.27	82.36	-534.88	22036.53	3.26	-0.72
2	Life assemblage, 1976	54.56	63.66	-333.34	20355.23	5.05	-0.66
4	Life assemblage, 1976	50.33	72.66	97.89	23053.99	4.39	0.16
5	Life assemblage, 1976	51.07	70.38	229.43	16685.61	3.38	0.39
6	Life assemblage, 1976	51.23	88.58	-349.19	19407.02	2.49	-0.42
7	Life assemblage, 1976	11.84	14.83	99.03	1743.31	7.95	1.74
8	Life assemblage, 1976	52.52	56.99	-154.32	12621.92	3.90	-0.36
9	Life assemblage, 1976	56.26	44.15	-67.62	7113.87	3.67	-0.23
10	Life assemblage, 1976	54.24	56.40	2.79	8013.65	2.53	0.01
11	Life assemblage, 1976	54.20	58.27	-156.08	9528.10	2.83	-0.35

* K = kurtosis.* S_K = skewness.

can reduce the population substantially. Complete failure of annual recruitment is known to occur in some pelecypods (Baxter 1962; Coe 1956). In *M. mercenaria* it seems possible for recruitment to fail for as long as 5 or even 10 continuous years, with the proliferation of the population being dependent on a single good year of recruitment (H. H. Haskin, Rutgers University, personal communication 1976).

It is interesting that at sites 2, 4, 5, 6, 8, 9, 10, and 11, adult clams exist without any juveniles. At site 7, however, the opposite occurs—juveniles exist without any adults. This indicates an inverse association between adults and juveniles. Possibly adult populations preclude successful settlement of young clams because of competition for food. Therefore, successful recruitment of *M. mercenaria* may be regulated by a density-dependent factor. When the density of the adult population is high, juveniles are forced to settle in unoccupied areas of the bay, which may be unfavorable for the species. In connection with this hypothesis juveniles may reenter the adult population only when the adult population becomes depleted to a critical density level.

Another possible cause of the impoverished recruitment is entrainment of meroplankton of *M. mercenaria* in the Oyster Creek Nuclear Generating Station. Laboratory experiments (Kennedy and others 1974) clearly demonstrate increased mortality of early cleavage stages (2 hr old), trochophore larvae (10–11

hr old), and straight-hinge veliger larvae (32–50 hr old) of *M. mercenaria* with increased temperature and, at higher temperatures, with increased exposure time. After subjecting clam larvae to temperatures ranging from 33.8 to 39.8°C for various lengths of time to simulate temperature conditions incurred while passing through a standard power plant, the authors drew the following

Table 12 Catches of *Mercenaria mercenaria* in Barnegat Bay (1960–1969)*

Year	Catch (kg shell weight)
1960	1,186,609.8
1961	794,702.0
1962	714,868.9
1963	812,845.9
1964	1,005,896.8
1965	1,082,463.9
1966	1,808,219.2
1967	1,353,533.5
1968	1,267,531.5
1969	1,215,277.1

*Data from United States Atomic Energy Commission, 1974.

conclusions. In the summer 90% of the cleavage stages would be eliminated if entrained for 1 min or less, 90% of the trochophores in 5 min, and 90% of the straight-hinge veligers in over 360 min.

Because ambient summer water temperatures in Barnegat Bay range from 22 to 27°C (Loveland and others 1972, 1974), larvae would be subjected to a maximum temperature range of 34.5–39.5°C for 1 min to 2 hr in the Oyster Creek Station (United States Atomic Energy Commission 1974). The exact exposure time and temperature depend on the number of dilution pumps in operation. Water of comparable volume to that in the bay is turned over by the station within a period of 53 days (M. B. Roche, Jersey Central Power & Light Company, personal communication 1976). Because under normal conditions larvae of *M. mercenaria* set in 1–2 weeks (Carriker 1959, 1961; H. H. Haskin, Rutgers University, personal communication 1976), a substantial quantity of meroplankton conceivably passes through the station. The exact amount of larval mortality caused by this passage is unknown and the problem should be investigated in the future.

Some evidence indicates that entrainment of larvae by the power station is not responsible for the ineffective recruitment pattern in the bay. First of all, the station first came on line in December, 1969; yet recruitment was successful at a later post-operative period between 1970 and 1972 as inferred from the comparison of absolute growth rates of clams in the bay (Tables 7 and 8) with their size distributions (Figs. 8a–8m). Second, recruitment failure has been so widespread, even in areas adjacent to Gulf Point, some 7 km south of the power station, that it is difficult to envision larvae being pulled northward into the station from these marginal areas, especially when currents are not flowing toward the station. Furthermore, larvae originating in Little Egg Harbor and Manahawkin Bay to the south and floating northward should have set in the southern extremities of Barnegat Bay, if conditions had been conducive for survival there. Third, clams successfully set at site 7 in the summer of 1975 when the station was operating.

Survival of *M. mercenaria* seems to greatly improve once the larvae set and the spat pass through the early plantigrade stage. This is shown by the comparison of life and death assemblages collected at site 7. Of the 432 specimens in both assemblages, only 16 belong to the death assemblage and they have a mean h' (17.52 mm) that is significantly larger than those of the life assemblage (11.84 mm). These differences reflect low mortality rates and high growth rates in the smaller size clams. The absence of juvenile valves in the death assemblages from the remaining sites also supports this contention.

The absence of dead juvenile valves at all sites except site 7 is surprising, considering the long list of predators capable of attacking young stages of postset clams in the bay (Carriker 1959, 1961). Nevertheless, there is little evidence that predators are killing large numbers of clams. For instance, only four valves from all death assemblages sampled in 1976 are drilled, and very few have chipped or serrated margins.

One possible explanation for the absence of small valves in the death assemblages is size-preferential solution. Preferential solution of smaller valves of *M. mercenaria* no doubt occurs, because of their greater surface area per unit weight compared to

larger valves (Driscoll 1967, 1970). The presence of partly dissolved valves at all sampling sites in Barnegat Bay is direct evidence of this effect. Indirect evidence of this effect exists in the presence of small valves in the death assemblage at site 7, which has been forming only since the summer of 1975, and in the absence of comparable size valves in the death assemblages at all other localities. Because the last successful settlement of spat at sites 2, 4, 5, 6, 8, 9, 10, and 11 was at least 5 or 6 years ago, there may have been sufficient time for dead juvenile valves to completely dissolve at these sites. The valves in the death assemblage at site 7, however, had been accumulating for only about 1 year prior to being collected, and this would appear to be an inadequate length of time for the valves to dissolve completely.

The lack of small valves in death assemblages does not seem to be associated with their selective removal by currents. The similarities in the size-frequency distributions from site to site minimizes the probability of current sorting as a viable factor (Levinton and Bambach 1970). Also, if smaller valves have been swept away from the larger ones by wave or current sorting and deposited elsewhere in the bay, they should have been found. Several years of intense sampling throughout Barnegat Bay have never recovered valves less than 10 mm in h' except at site 7. This is true for both quiet, low-energy muddy areas as well as for high-energy, sandy regions. However, numerous minute shells of other species of organisms, such as *Gemma gemma* (Totten), *Mulinia lateralis* (Say), *Spisula solidissima* (Dillwyn), and *Pectinaria gouldii* (Verrill), are commonly seen. These shells should also be missing if currents have removed small *M. mercenaria* (Linné) valves.

In addition, four death assemblages analyzed for valve ratios all show similar distributions (Table 13). Application of a chi-square (χ^2) test on these samples reveals no significant difference ($P < 0.05$) in the ratio of right to left valves in each assemblage. If these valves were allocthonous, significant differences should occur in their ratios. This would be particularly true for site 2, where the current flow from Oyster Creek is substantial. These conclusions parallel those of Craig (1967) and Cadée (1968), who have rejected the importance of postmortem transport of shells in many modern coastal environments.

The bulk of valve sizes in the death assemblages falls between 40 mm and 70 mm in h' , which corresponds to clams of 4–9 years of age (Tables 7 and 8). Obviously, mortality is extremely high in

Table 13 Valve Ratios in Death Assemblages of Clams from Barnegat Bay

Site	Year collected	No. of specimens	No. of left valves	No. of right valves	No. articulated
2	1976	499	230	223	46
6	1974	464	228	236	—
6	1976	408	185	181	42
11	1976	438	196	182	60

this interval and appears to be reflective of gerontic death. Fitch (1965) reports a similar increase in death during old age in the pismo clam, *Tivela stultorum* (Mawe). The negative skewness of clam sizes in the death assemblages is caused by growth rates that decrease with age and mortality rates that increase with age subsequent to spat settlement. The similar distribution of sizes of dead clams in Barnegat Bay therefore results from similar growth and mortality rates throughout the bay.

Most of the sizes of live clams also range from 40 mm to 70 mm in h'. Therefore, the live clam populations in Barnegat Bay, are, for the most part, in old age. This is visually apparent from the equivalence of the size distributions of the life and death assemblage polygons (Fig. 8, a-m). The predominance of mostly old clams in the life assemblages suggests that these populations should be declining in size. If recruitment is not successful in the next few years, the pelecypod may become much less common or even locally extinct in the bay. In any event, the clam industry in Barnegat Bay could encounter a reduction in total annual catches sometime in the near future.

Mortality Patterns of *Mercenaria mercenaria* in Barnegat Bay

Thermal discharges from the Oyster Creek Nuclear Generating Station may be associated with mortality of *M. mercenaria* in Barnegat Bay in the following ways. First, mortality rates may be higher in the populations effected by thermal discharges because the elevated water temperatures cause increased mortality especially in the summer. Second, mortality may be lower in these populations as a consequence of more optimum temperature conditions in the fall, winter, and spring. Third, mortality at the mouth of Oyster Creek may be a census (massive) type, related to physiologic shocks developing from rapid fluctuations in water temperatures in connection with abrupt changes in operations of the nuclear power station. Fourth, mortality in the populations at the mouth of Oyster Creek may be normal and totally unrelated to the effluent.

These possibilities have been investigated by examining mortality in both transplanted and natural populations of *M. mercenaria* in Barnegat Bay. Mortality in transplanted populations was studied using specimens planted directly into the substrate and individuals housed in cages. Shell samples collected from death assemblages in the summer of 1974 served as specimens for the analysis of mortality in natural populations.

Mortality in populations transplanted to the substrate

An initial transplantation experiment was conducted on July 6, 1974, when 980 healthy *M. mercenaria* ranging from 20 to 40 mm in h' were transplanted from Little Egg Harbor, New Jersey, to the substrate at site 2 in Barnegat Bay.

Before the clams were planted, the valves were measured for h' and sanded at their growing edge with fine- and medium-grained sandpaper, which produced growth breaks in the specimens (see Fig. 7, i, k). These growth breaks were important because they served as microgrowth reference planes. All clams

also received a coating of Volger's red ink to insure proper identification at the time of recovery.

These clams were sampled for mortality on September 10, 1974; no dead specimens were found, however, although shell microgrowth analysis of ten live bivalves revealed a sharp reduction in growth following transplantation. The population was resampled for mortality in July 1975, when a total of 217 live and four dead clams were recollected, and in June, 1976, when 74 live and no dead clams were gathered. Both years of data indicated low mortality under the influence of the thermal discharges.

Of the 980 specimens of *M. mercenaria* originally transplanted, 291 live and four dead specimens were retrieved. Over a 23 month period, therefore, 30.1% of the bivalves were recovered. Only 1.3% mortality was observed in the recovered assemblage. The 685 clams that were not recovered may have died subsequent to transplantation and their shells may have been removed by bottom currents. However, no direct evidence exists to support this suggestion.

Transplantation experiments were continued in the summer of 1975 to establish seasonal mortality patterns of the clam and to correlate these patterns with operations of the nuclear power station (Table 5). A total of 1486 clams, ranging from 20 to 80 mm in h', were transplanted from Little Egg Harbor and site 6 in Barnegat Bay to the substrate at sites 2 and 5. Each location received 743 specimens of *M. mercenaria* of comparable size (Table 14) with the clams at site 5 acting as controls. The shell of every specimen was sanded at its growing edge, stained with Volger's red ink on the umbo, and numbered with enamel paint for purposes of recovery. The experimental populations were

Table 14 Size (h')-Frequency Distributions for Clams Transplanted to the Substrate at Sites 2 and 5 in June 1975

Size class (mm)	Frequency of clams transplanted to site 2	Frequency of clams transplanted to site 5
20-25	1	0
25-30	9	10
30-35	103	103
35-40	69	68
40-45	116	117
45-50	115	114
50-55	124	124
55-60	103	103
60-65	66	67
65-70	24	24
70-75	10	10
75-80	3	3
	N* = 743	N* = 743

*N = Total number of clams.

Table 15 Size (h')-Frequency Distributions for Live and Dead Clams Recovered from the Substrate at Sites 2 and 5 in June 1976*

Size class (mm)	Frequency of live clams recovered from site 2	Frequency of dead clams recovered from site 2	Frequency of live clams recovered from site 5	Frequency of dead clams recovered from site 5
20-25	0	0	0	0
25-30	0	0	0	0
30-35	11	12	20	3
35-40	43	2	31	1
40-45	86	1	73	7
45-50	104	1	90	1
50-55	97	5	62	10
55-60	113	8	64	12
60-65	49	5	44	11
65-70	11	2	12	2
70-75	1	0	2	1
75-80	0	0	0	0
				+3 (broken)
	N** = 515	N** = 36	N** = 398	N** = 51

*Clams were originally transplanted in June 1975.

**N = Total number of clams.

retrieved and measured for h' on June 23, 1976 (site 2) and June 24, 1976 (site 5), 1 year after transplantation. Empty valves were examined microscopically to specify their absolute age and season of death.

A total of 67.29% of the clams transplanted to the two regions were recovered in the life and death assemblages. Recovery at site 2 was greater (74.15%) than that at site 5 (60.43%). Only 6.53% mortality was observed in the total assemblage retrieved at site 2, but 11.36% mortality occurred in the assemblage at site 5. A chi-square test (χ^2) employed on these assemblages showed that mortality was significantly greater ($0.005 < P < 0.01$) at site 5 than at site 2.

Table 15 compares the size (h')-frequency distributions of the live and dead clams sampled at sites 2 and 5 1 year after they were planted. Broken valves are not included in the measurements. The size statistics of the assemblages are presented in Table 16. Student's t-tests performed on these specimens demonstrate that no significant difference ($0.20 < P < 0.50$) exists between the mean h' of live clams sampled at the two sites. However, the mean h' of the dead clams at site 2 are significantly less ($0.01 < P < 0.02$) than those at site 5. This appears to be mainly a result of higher mortality in the 30-35 mm size class at site 2 and the 50-65 mm size classes at site 5.

Figure 10 compares the sizes of dead specimens of *M. mercenaria* at the two locations. The size-frequency polygon for site 2 consists of a bimodal distribution, but the distribution is polymodal for site 5. The h' of dead clams peaks in the 30-35 mm size class at site 2 and in the 40-45 mm size class at site 5. Beyond the 45-50 mm size class, the sizes of dead clams are similar at both sites. The most notable equivalence exists in the size range from 50 to 65 mm, where mortality rises in each sample. The high

mortality in this interval exactly parallels that in death assemblages of natural populations of *M. mercenaria*, and it reflects the increasing rate of mortality with age in the clam.

Shell microgrowth analysis of the majority of dead clams recovered from sites 2 and 5 reveals the following age distributions. The death assemblage at site 2 displays an absolute age distribution that is bimodal, with highest frequencies of death between the ages of 2 and 3 and of 5 and 6 years. However, the distribution of absolute age at death data for clams at site 5 approximates a unimodal, slightly negatively skewed curve with a maximum frequency of death between the ages of 5 and 6 years (Fig. 11). These age distributions clearly correspond to the size-frequency distributions of the death assemblages.

The seasonal frequency of death in both assemblages is also

Table 16 Size Statistics for Live and Dead Clams Recovered from the Substrate at Sites 2 and 5 in June 1976*

Site	No. of clams	Mean h' (mm)	Standard deviation
2 (live clams)	515	50.31	7.99
2 (dead clams)	36	47.72	12.74
5 (live clams)	398	49.77	8.66
5 (dead clams)	48**	53.50	9.23

*Clams were transplanted in June 1975.

**Three broken valves are not included in the analysis.

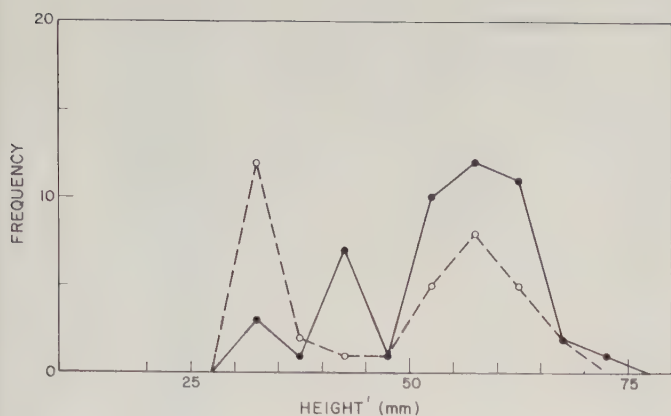


Figure 10. Size (h')-frequency distributions for death assemblages of transplanted clams recovered from the substrate at sites 2 and 5 in June 1976. (---) Site 2; (—) site 5.

analogous. Death frequency diagrams constructed from data on 73 of the dead specimens (Fig. 12) indicate that mortality is concentrated in the summer (see Fig. 7, i–k). Minimum frequency of death occurs in the winter and intermediate frequency occurs in the spring and fall. A chi-square test (χ^2) executed on these data exhibits no significant difference ($0.10 < P < 0.25$) in the season of death between the two samples.

Although the clams died primarily in the summer, they did not do so simultaneously as is evident from the high variability in the terminal microgrowth patterns of their shells. In essence, the death assemblages developed from natural rather than massive mortality in the transplanted populations. The existence of mortality during other seasons of the year is added proof of this effect (Kurtén 1964; Rhoads and Pannlla 1970; Tevesz 1972).

The high incidence of summer death correlates well with increased predator and parasitic activity during the warmer months of the year. H. H. Haskin (Rutgers University, personal communication 1976) notes this effect in populations of *Crassostrea virginica* (Gmelin) in Delaware Bay, New Jersey, where much of the mortality is associated with parasitic activity of the haplosporidian *Minchinia nelsoni* (Haskin, Stauber, and Mackin). Higher summer mortality in *M. mercenaria* may also be associated with the physiologic stress of spawning. During spawning the percentage wet and dry flesh weights and the nitrogen content of the animal drops and, in many clams, so does the carbohydrate content (Ansell and Lander 1967). These changes may leave the bivalve particularly vulnerable to the vagaries of environmental stresses. Sellmer (1967) suggests the same possibility for populations of *Gemma gemma* (Totten), as does Paine (1963) for populations of the brachiopod *Glottidia pyramidata* (Stimpson).

High summer mortality would not appear to be associated with elevated water temperatures alone; otherwise, mortality would have been higher in the population transplanted at site 2 which was subjected to water temperatures as high as 30–34°C in

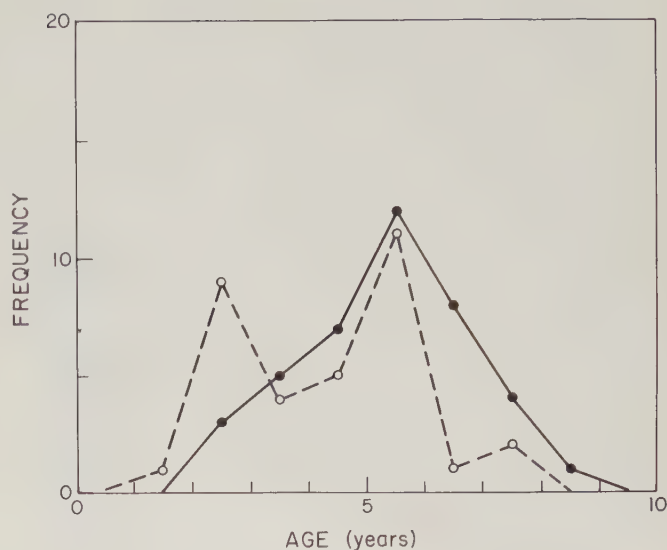
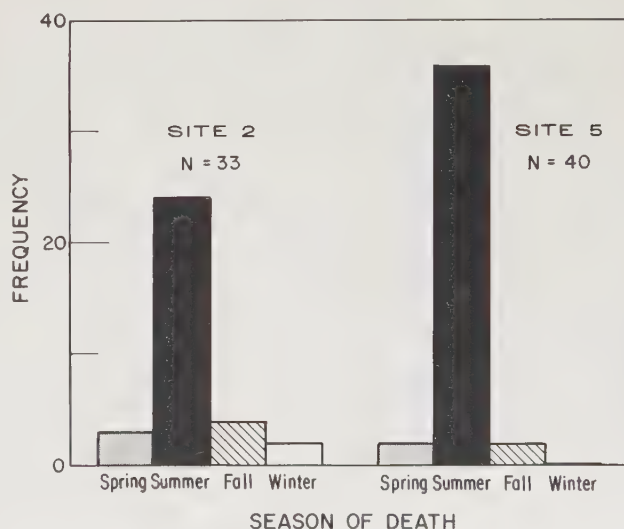


Figure 11. Absolute age-frequency distributions for death assemblages of transplanted clams retrieved from the substrate at sites 2 and 5 in June 1976. (---) Site 2; (—) site 5.

July and August. Ansell (1968) places the upper temperature threshold of stress on growth of *M. mercenaria* at 31°C, but this value may be too low because *M. mercenaria* have been found to grow in the thermal discharges at slightly higher temperatures. Ansell (1968) also proposes that mortality increases in populations continuously exposed to temperatures above 31°C. Hender-

Figure 12. Death-frequency distributions per season for death assemblages of transplanted clams collected from the substrate at sites 2 and 5 in June 1976.



son (1929) sets the lethal temperature level of *M. mercenaria* at 45.2°C, which is far above the stress limit on growth set by Ansell (1968).

The similarities and differences of mortality in the two transplanted assemblages strongly indicate that thermal discharges do not adversely affect mortality in the pelecypod. In fact, given the above data, which indicate mortality to be significantly less at site 2, one may argue that the thermal discharges here are responsible for a reduction in mortality. The similarity in the size and age at which the peak frequency of death occurs in the two assemblages and the nearly identical distribution of seasonal mortality suggests, however, that no relationship exists between the thermal effluent and mortality of the transplanted clams. Furthermore, changes in operations of the Oyster Creek Nuclear Generating Station during 1975 and 1976 do not correlate with periods of increased mortality in the population transplanted at site 2. These observations support the view that mortality in both assemblages results from the natural population dynamics of the species.

Mortality in populations transplanted in cages

Several problems affecting the study of mortality in assemblages of clams transplanted to the substrate at sites 2 and 5 were the inability to completely remove the effects of predation and the incapacity to sort out those variables associated with the substrate that could have contributed to the observed mortality patterns. In addition, it was impossible to recover 100% of the specimens released. To alleviate these shortcomings, a third transplantation experiment was attempted. On June 18, 1975, 676 marked clams ranging from 20 mm to 73 mm in h' were placed in plastic, cylindrical cages and anchored to the substrate at site 2 and 5. Each cage measured 43.2 cm in length and 22.9 cm in diameter at its midpoint. Nine cages containing a total of 338 clams were planted at each location, but the ninth cage at site 5, holding 13 specimens, was lost several weeks after transplantation. This left only eight cages and 325 clams at that spot. The cages were checked for mortality at the end of each

Table 17 Size (h')-Frequency Distributions for Clams Transplanted in Cages at Sites 2 and 5 in June 1975

Size class (mm)	Frequency of clams transplanted to site 2*	Frequency of clams transplanted to site 5**
20-25	3	4
25-30	26	27
30-35	81	83
35-40	47	50
40-45	60	48
45-50	37	42
50-55	32	30
55-60	31	26
60-65	19	15
65-70	1	0
70-75	1	0
	N† = 338	N† = 325

*Includes measurements of clams in nine cages.

**Includes measurements of clams in eight cages.

†N = total number of clams.

season and empty valves were removed, sectioned, and analyzed microscopically. The experiment yielded five seasons of mortality data for site 5 but only four seasons for site 2. Unfortunately, all nine cages at site 2 were lost in the summer of 1976 either because bottom currents removed the cages or because of pilferage by man. The cages planted at site 5 were subsequently removed on September 18, 1976.

The size (h')-frequency distributions of the transplanted clams are listed in Table 17. These measurements do not include

Table 18 Summary of Seasonal Mortality of *Mercenaria mercenaria* Transplanted in Cages at Sites 2 and 5

Season	Frequency of death site 2*	Frequency of survival site 2	Frequency of death site 5*	Frequency of survival site 5
Summer 1975 6/18/75-9/22/75	118 (34.91%)	220	44 (13.53%)	281
Fall 1975 9/22/75-1/2/76	39 (11.53%)	181	12 (3.69%)	269
Winter 1976 1/2/76-3/24/76	37 (10.94%)	144	32 (9.84%)	237
Spring 1976 3/24/76-6/18/76	35 (10.35%)	109	22 (6.76%)	215
Summer 1976 6/18/76-9/18/76	—	—	93 (28.61%)	122

*Mortality rate per season in parentheses.

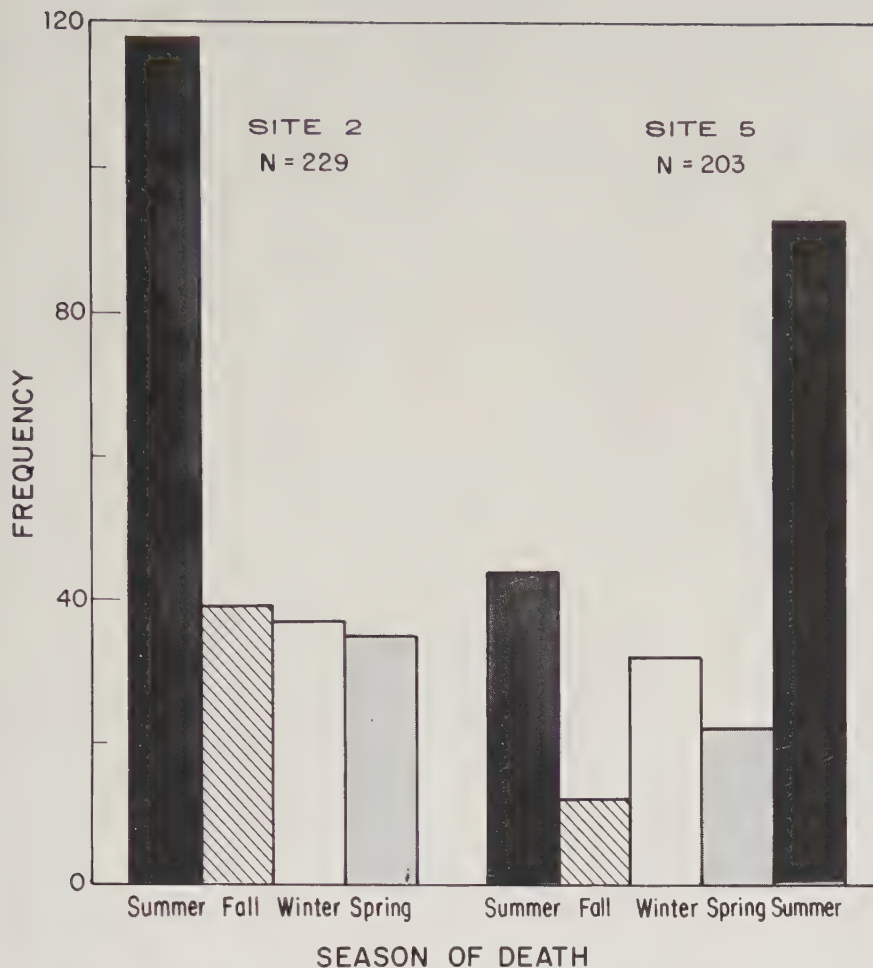


Figure 13. Death-frequency distributions per season for death assemblages of *Mercenaria mercenaria* retrieved from cages at sites 2 and 5 in 1975–1976.

those of *M. mercenaria* lost with cage nine at site 5 in the summer of 1975. Table 18 summarizes the seasonal mortality and survivorship observed at each location, and Fig. 13 compares the frequency of seasonal mortality. The size-specific mortality rate, defined as the percentage of the initial transplanted size class dying within each season, is included in Tables 19 and 20.

Statistically, mortality is significantly greater each season at site 2 ($P < 0.001$ for the summer and fall of 1975 and the spring of 1976; $0.01 < P < 0.025$ for the winter of 1976). The magnitude of these differences can be realized if the number of clams surviving after 1 year of transplantation is noted. This amounts to 215 clams at site 5 but only 109 at site 2—a survival ratio of nearly 2 to 1. By far the largest differences in mortality appeared in the summer and fall of 1975, when the frequency of death at site 2 was 2.7 and 3.3 times greater, respectively, than at site 5. As in the populations transplanted to the substrate, maximum frequency of death rises in the summer. This is shown by well-defined peaks in the death-frequency diagrams.

No relationship exists between the size of the organism and its frequency of death. This is evident from data in Tables 19 and 20,

which display uniform frequencies of death throughout the size classes. Mortality is not concentrated in the larger or older clams as in natural and transplanted substrate populations; however, fewer, larger clams were initially transplanted, which could account for this result. The persistent trend of constant mortality irrespective of size class might well be a consequence of the unnatural, epifaunal habit forced upon the transplanted specimens. This change in lifestyle was apparently detrimental to the normal physiology of the clam. For instance, shell growth was extremely impaired following transplantation to cages (see Fig. 7, f–h) with the amount of accretion of calcium carbonate ranging from 0 to 387 μm per specimen (Table 21). Some clams did not grow at all during the experiment. Mortality was also far greater in the populations placed in cages than in those planted in the substrate. The number of dead clams in cages after 1 year of transplantation amounted to 67.8% of the original assemblage at site 2 and 33.8% of the original assemblage at site 5. The number of dead specimens in cages at site 5 rose to 62.5% of the original assemblage only 1 year and 3 months after transplantation.

These percentages represent exceptionally high mortality

Table 19 Seasonal Mortality per Size Class of Clams Transplanted in Cages at Site 2

Size class (mm)	Frequency of death, 6/18/75–9/22/75*	Frequency of death, 9/22/75–1/2/76*	Frequency of death, 1/2/76–3/24/76*	Frequency of death, 3/24/76–6/18/76*
20–25	2 (66.66%)	—	1 (33.33%)	—
25–30	9 (34.61%)	0 (0.00%)	4 (15.38%)	1 (3.84%)
30–35	16 (19.75%)	3 (3.70%)	2 (2.46%)	12 (14.81%)
35–40	18 (38.29%)	3 (6.38%)	3 (6.38%)	2 (4.25%)
40–45	22 (36.66%)	9 (15.00%)	6 (10.00%)	11 (18.33%)
45–50	15 (40.54%)	7 (18.91%)	5 (13.51%)	2 (5.40%)
50–55	13 (40.62%)	7 (21.87%)	6 (18.75%)	4 (12.50%)
55–60	14 (45.16%)	7 (22.58%)	8 (25.80%)	2 (6.45%)
60–65	8 (42.10%)	2 (10.52%)	2 (10.52%)	1 (5.26%)
65–70	1 (100.00%)	—	—	—
70–75	—	1 (100.00%)	—	—

*Specific mortality rate per size class given in parentheses.

rates. Obviously, *M. mercenaria* requires a natural, granular substratum for proper growth and survival. The overall impact of the cages has been to accentuate the mortality rates of the bivalve without influencing the seasonal distribution of death. The similarity of the death–frequency diagrams of the assemblages transplanted to the substrate and to the cages is reflective of this.

Mortality in natural populations

The effects of thermal discharges on mortality of natural populations of *M. mercenaria* were examined by utilizing death assemblages collected in 1974 at sites 2, 5, 6, and 9. The death assemblages at sites 5, 6, and 9 acted as controls for comparison to the assemblage affected by thermal discharges at site 2.

Death–frequency histograms, mortality rate curves, survivorship curves, and life tables were constructed for each assemblage.

Table 22 records the seasonal frequency of death of *M. mercenaria* at all four sites based on microgrowth analysis of 278 specimens. Trends in mortality are conspicuous (Fig. 14); the frequency of death reaches a maximum in the summer and winter and a minimum in the spring and fall. There is no significant difference in the distribution of seasonal mortality between sites 2 and 5 ($0.50 < P < 0.75$), sites 2 and 6 ($0.25 < P < 0.50$), and sites 2 and 9 ($0.10 < P < 0.25$). This implies that the thermal discharges have not affected seasonal mortality patterns of *M. mercenaria* in the past.

Mortality ranges from 12% (site 2) to 24% (site 9) in the spring,

Table 20 Seasonal Mortality per Size Class of Clams Transplanted in Cages at Site 5

Size class (mm)	Frequency of death, 6/18/75–9/22/75*	Frequency of death, 9/22/75–1/2/76*	Frequency of death, 1/2/76–3/24/76*	Frequency of death, 3/24/76–6/18/76*	Frequency of death, 6/18/76–9/18/76*
20–25	1 (25.00%)	0 (0.00%)	0 (0.00%)	1 (25.00%)	0 (0.00%)
25–30	8 (29.62%)	2 (7.40%)	2 (7.40%)	2 (7.40%)	1 (3.70%)
30–35	20 (24.09%)	3 (3.61%)	7 (8.43%)	4 (4.81%)	11 (13.25%)
35–40	6 (12.00%)	4 (8.00%)	4 (8.00%)	3 (6.00%)	10 (20.00%)
40–45	3 (6.25%)	0 (0.00%)	3 (6.25%)	3 (6.25%)	15 (31.25%)
45–50	3 (7.14%)	1 (2.38%)	1 (2.38%)	4 (9.52%)	21 (50.00%)
50–55	1 (3.33%)	1 (3.33%)	6 (20.00%)	2 (6.66%)	14 (46.66%)
55–60	2 (7.69%)	1 (3.84%)	7 (26.92%)	2 (7.69%)	9 (34.61%)
60–65	0 (0.00%)	0 (0.00%)	2 (13.33%)	1 (6.66%)	12 (80.00%)
65–70	—	—	—	—	—
70–75	—	—	—	—	—

*Specific mortality rate per size class given in parentheses.

Table 21 Size-Age Characteristics for Clams Transplanted in Cages at Sites 2 and 5*

Site	No. of clams	Mean age (yr)	Mean growth after transplantation (m μ)	Mean no. increments after transplantation
2	62	4.48	60.44	6.23
5	35	3.87	78.71	6.77

*Clams transplanted in June 1975.

from 30% (site 6) to 42% (site 9) in the summer, from 17% (site 5) to 25% (site 2) in the fall, and from 16% (site 9) to 33% (site 5) in the winter. The variation in the distribution of seasonal mortality indicates that each death assemblage is the result of natural rather than census mortality. As in the transplanted populations, high summer mortality in natural populations may be caused by physiologic stress associated with spawning and increased predator and parasitic activity. The organism spawns at water temperatures of approximately 24–25°C, which are beyond the optimum temperature for growth in the species. Environmental stress, therefore, concurrent with the physiologic stress of spawning, may also contribute to the observed summer frequency of death. Increased winter mortality seems to be associated mainly with harsh environmental conditions. Low food supply and low water temperatures force the pelecypod to live on stored carbohydrate reserves and these reserves, may be insufficient in some individuals.

The high frequency of death in the winter in death assemblages of natural populations does not correspond to the low winter frequencies found in the transplanted populations. However, death assemblages of the transplanted populations represent only 1 year of seasonal mortality data, whereas those of natural populations depict cumulative mortality over many years. This factor may be responsible for the observed differences in the

seasonal mortality data. Because death assemblages of natural populations record long-term trends in mortality of *M. mercenaria*, they are more reflective of the true population dynamics of the species.

Life tables have been formulated for natural populations of *M. mercenaria* in Barnegat Bay by determining the age at death of death assemblages of clams at sites 2, 5, 6, and 9. These tables (Tables 23–26) give the most concise summary of mortality in the clam. The method of computation of a life table is reviewed by Deevey (1947), Barclay (1958), Reymont (1971), and Gani (1973). Mortality rates (q_x) are calculated first from the original array of mortality data, and the remaining entries in the table are calculated from them. Because mortality in the meroplanktonic and pediveliger stages of *M. mercenaria* has not been examined in this study, life tables have been built beginning at age one of a hypothetical cohort (radix) of 1000 clams.

The entries in the four life tables can be compared for the purpose of studying mortality characteristics in populations from different areas of the bay. This is possible because the entries are structured with respect to a common variable—age. Comparison of mortality on any other basis would be far less accurate.

Figure 15, a–d, illustrates the mortality rates of clams at sites 2, 5, 6, and 9. The similarity of the curves is quite evident. The greatest agreement of the data occurs between the ages of 1 and 4 years, when mortality rates are extremely low and uniform at all locations. After the fourth year of life mortality increases markedly, although less consistently, from one site to the next. The probability of death decreases somewhat between the ages of 6 and 7 years for *M. mercenaria* at sites 2 and 9, only to increase precipitously in the age interval from 7 to 8 years. Site 6 shows the same trend, with a decline in the probability of death between the ages of 7 and 8 years but an acute rise from the age of 8 to 9 years. Only at site 5 does the rate of mortality increase continuously through all the age intervals. These effects are also apparent from the age-specific mortality rates estimated for each population (Table 27).

Survivorship curves (Fig. 16, a–d) constructed from each life table display a strongly convex morphology indicative of populations that experience low mortality until near the end of their

Table 22 Death-Frequency Distributions per Season for Natural Populations of *Mercenaria mercenaria* at Sites 2, 5, 6, and 9

Site	No. of clams	Season of death*			
		Spring	Summer	Fall	Winter
2	101	12 (11.88%)	33 (32.67%)	25 (24.75%)	31 (30.69%)
5	75	13 (17.33%)	24 (32.00%)	13 (17.33%)	25 (33.33%)
6	64	13 (20.31%)	19 (29.69%)	12 (18.75%)	20 (31.25%)
9	38	9 (23.68%)	16 (42.11%)	7 (18.42%)	6 (15.79%)
All sites	278	47 (16.91%)	92 (33.09%)	57 (20.50%)	82 (29.50%)

*Percentage of mortality per season in parentheses.

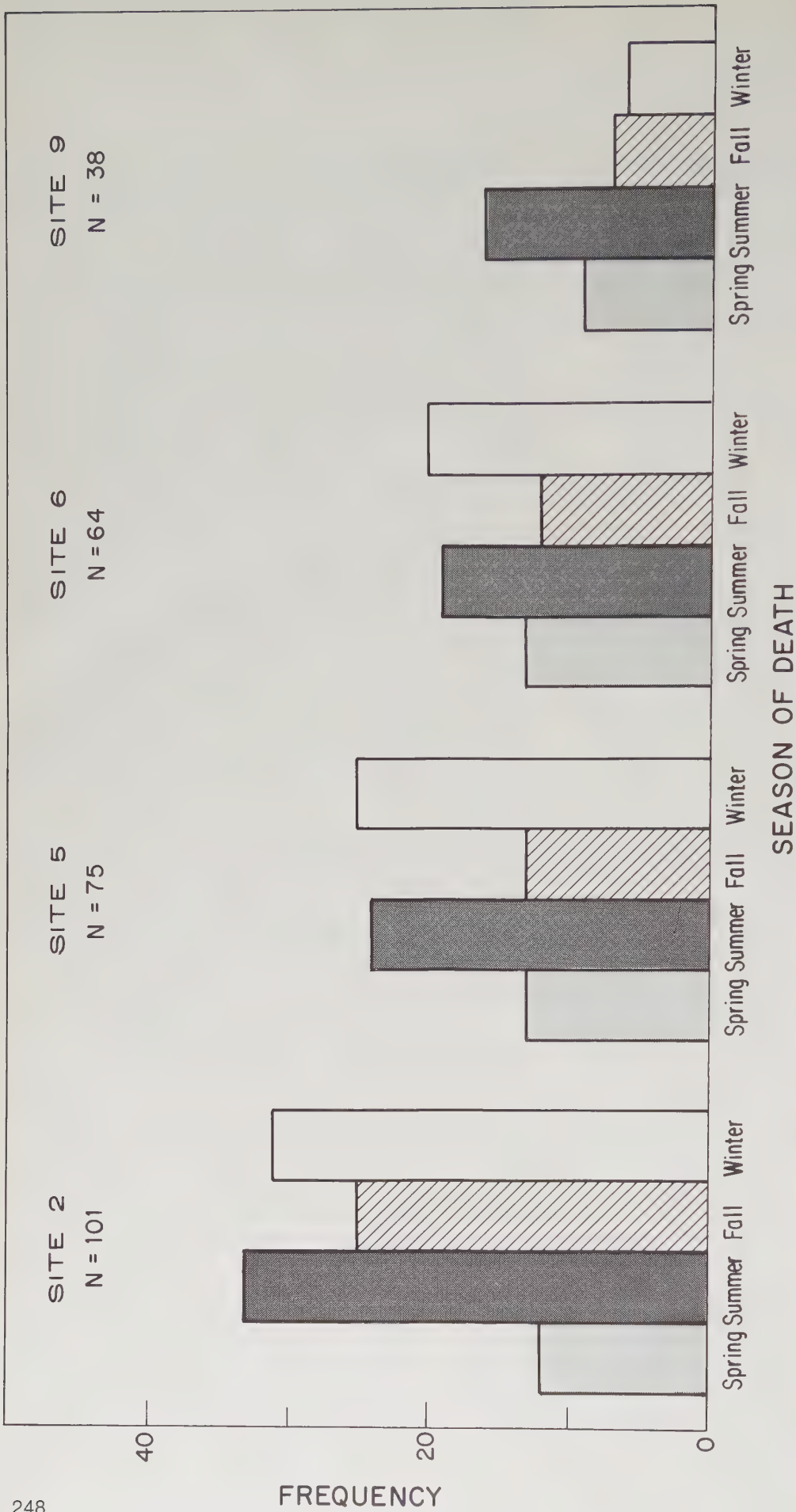


Figure 14. Death-frequency distributions per season for death assemblages of natural populations of *Mercenaria mercenaria* at sites 2, 5, 6, and 9.

Table 23 Life Table for *Mercenaria mercenaria* at Site 2

Age interval x to $x + 1$ years	Proportion dying in interval $(x, x + 1)$ 1000 q_x	Number living at age x l_x	Number dying in interval $(x, x + 1)$ d_x	Number of time-spans lived in interval $(x, x + 1)$ L_x	Total number of time-spans lived past age x T_x	Average life expectancy (in years) at age x e_x	Proportion surviving in interval $(x, x + 1)$ p_x
1-2	22.00	1000	22	989.0	4508.0	4.5080	0.9780
2-3	68.51	978	67	944.5	3519.0	3.5982	0.9315
3-4	83.42	911	76	873.0	2574.5	2.8260	0.9166
4-5	130.54	835	109	780.5	1701.5	2.0377	0.8695
5-6	544.08	726	395	528.5	921.0	1.2686	0.4559
6-7	314.20	331	104	279.0	392.5	1.1858	0.6858
7-8	1000.00	227	227	113.5	113.5	0.5000	0.0000

Table 24 Life Table for *Mercenaria mercenaria* at Site 5

Age interval x to $x + 1$ years	Proportion dying in interval $(x, x + 1)$ 1000 q_x	Number living at age x l_x	Number dying in interval $(x, x + 1)$ d_x	Number of time-spans lived in interval $(x, x + 1)$ L_x	Total number of time-spans lived past age x T_x	Average life expectancy (in years) at age x e_x	Proportion surviving in interval $(x, x + 1)$ p_x
1-2	7.00	1000	7	996.5	4844.0	4.8440	0.9930
2-3	27.19	993	27	979.5	3847.5	3.8746	0.9728
3-4	39.34	966	38	947.0	2868.0	2.9689	0.9607
4-5	113.15	928	105	875.5	1921.0	2.0700	0.8869
5-6	343.86	823	283	681.5	1045.5	1.2704	0.6561
6-7	829.63	540	448	316.0	364.0	0.6741	0.1704
7-8	978.26	92	90	47.0	48.0	0.5217	0.0217
8-9	1000.00	2	2	1.0	1.0	0.5000	0.0000

Table 25 Life Table for *Mercenaria mercenaria* at Site 6

Age interval x to $x + 1$ years	Proportion dying in interval $(x, x + 1)$ 1000 q_x	Number living at age x l_x	Number dying in interval $(x, x + 1)$ d_x	Number of time-spans lived in interval $(x, x + 1)$ L_x	Total number of time-spans lived past age x T_x	Average life expectancy (in years) at age x e_x	Proportion surviving in interval $(x, x + 1)$ p_x
1-2	0.00	1000	0	1000.0	5074.0	5.0740	1.0000
2-3	0.00	1000	0	1000.0	4074.0	4.0740	1.0000
3-4	30.00	1000	30	985.0	3074.0	3.0740	0.9700
4-5	122.68	970	119	910.5	2089.0	2.1536	0.8773
5-6	324.32	851	276	713.0	1178.5	1.3848	0.6757
6-7	775.65	575	446	352.0	465.5	0.8096	0.2244
7-8	620.16	129	80	89.0	113.5	0.8798	0.3798
8-9	1000.00	49	49	24.5	24.5	0.5000	0.0000

Table 26 Life Table for *Mercenaria mercenaria* at Site 9

Age interval x to x + 1 years	Proportion dying in interval (x, x + 1) 1000 q _x	Number living at age x l _x	Number dying in interval (x, x + 1) d _x	Number of time-spans lived in interval (x, x + 1) L _x	Total number of time-spans lived past age x T _x	Average life expectancy (in years) at age x e _x	Proportion surviving in interval (x, x + 1) P _x
1-2	19.00	1000	19	990.5	4951.0	4.9510	0.9810
2-3	34.66	981	34	964.0	3960.5	4.0372	0.9653
3-4	24.29	947	23	935.5	2996.5	3.1642	0.9757
4-5	124.46	924	115	866.5	2061.0	2.2305	0.8755
5-6	398.02	809	322	648.0	1194.5	1.4765	0.6020
6-7	377.82	487	184	395.0	546.5	1.1222	0.6222
7-8	1000.00	303	303	151.5	151.5	0.5000	0.0000

lifespan. However, mortality is known to be heavy during the meroplanktonic stages of *M. mercenaria* (Thorson 1950; Carriker 1961). In respect to this phenomenon the survivorship curve for the entire ontogeny of the pelecypod must be sigmoidal. A high risk of death exists during the free-swimming larval stages; a low risk ensues once the organisms become established on a favorable substrate, but the risk rises again in old age. This pattern corresponds to the type B₃ survivorship curve of Odum (1971, p. 174).

The life expectancy of a clam increases significantly after it successfully sets in an area. This insures the survival and proliferation of the species, because *M. mercenaria* has a relatively long generation time and does not reach sexual maturity until the age of 2 years. If mortality were great from the setting stage to age two, populations might not attain the proper density for successful spawning to take place. Once sexual maturity is acquired, mortality rates increase significantly into old age.

The abrupt rise in mortality between the ages of 5 and 9 years seems to be ultimately controlled by the effects of senescence.

Table 27 Age-Specific Mortality Rates Computed for Death Assemblages of Natural Populations of *Mercenaria mercenaria* at Sites 2, 5, 6, and 9

Age interval (yr)	Specific mortality rate			
	Site 2	Site 5	Site 6	Site 9
1-2	0.0222	0.0070	0.0000	0.0192
2-3	0.0709	0.0276	0.0000	0.0353
3-4	0.0871	0.0401	0.0305	0.0246
4-5	0.1397	0.1199	0.1307	0.1327
5-6	0.7474	0.4153	0.3871	0.4969
6-7	0.3728	1.4177	1.2670	0.4658
7-8	2.0000	1.9149	0.8989	2.0000
8-9	—	2.0000	2.0000	—

The onset of senescence in *M. mercenaria* is reflected in its outer shell layer as a permanent alteration of prismatic to crossed-lamellar structure along with the development of frequent growth breaks. This alteration in shell microstructure occurs exclusively in older specimens ranging from 50 to 65 mm in h'. This correlates well with Hopkins's (1930) finding of a diminishing metabolism with increasing age in the species. The clam therefore must be less capable of coping with periods of physiologic and environmental stress as it ages. In essence, high mortality appears to be associated with both physiologic degeneration and ecologic influences, although no clear distinction can be made concerning the relative contribution of either factor to the observed mortality rates.

There is no apparent impact of the thermal discharges on these mortality patterns. Clearly, the four life tables, mortality rate curves, and survivorship curves for the populations investigated are remarkably similar. If the thermal discharges were affecting mortality patterns in populations of *M. mercenaria* in Barnegat Bay, significant variations should be expected between the life table for site 2 (affected by thermal discharges) and those for sites 5, 6, and 9 (unaffected by thermal discharges). It is reasonable to conclude, therefore, that no relationship exists between mortality in postset *M. mercenaria* and thermal discharges from the Oyster Creek Nuclear Generating Station.

Summary and Conclusions

The relationship of thermal discharges from the Oyster Creek Nuclear Generating Station to mortality of *Mercenaria mercenaria* (Linné) in Barnegat Bay, New Jersey has been investigated using life and death assemblages of the pelecypod. Observations were made on natural and transplanted samples in an effort to establish growth rates, size and age distributions, and seasonal and absolute mortality rates in populations from areas that are both affected and unaffected by thermal discharges. Specimens were studied by means of shell microgrowth analysis.

The study of life and death assemblages of natural clam

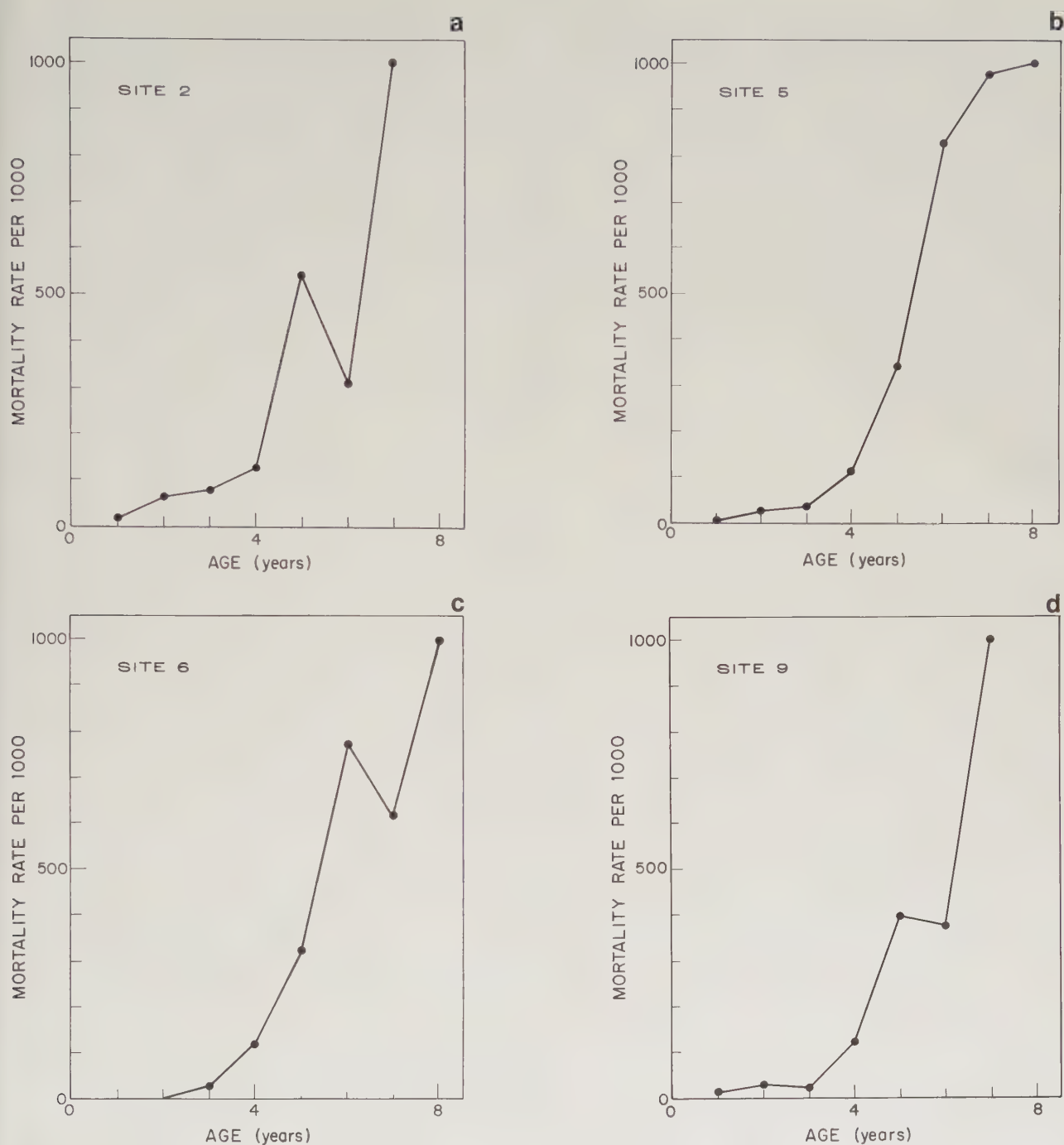


Figure 15. (a–d) Mortality rate curves for natural populations of *Mercenaria mercenaria* at sites 2, 5, 6, and 9. Data are presented as mortality rate per 1000 for each age interval of 1 year ($1000 q_x$), plotted against the start of the interval.

populations in the bay yields the following information:

1. *Mercenaria mercenaria* undergoes a slow decline of growth with increasing age.
2. Mortality rates of *M. mercenaria* vary significantly with age. The trend of mortality during ontogeny is high–low–high,

with mortality being great in the planktonic larval stages, low subsequent to spat settlement, and high again in the gerontic stage. The probability of death is very low for clams between the ages of 1 and 3 years, but it increases after sexual maturity is attained. Between the ages of 4 and 9 years the probability of

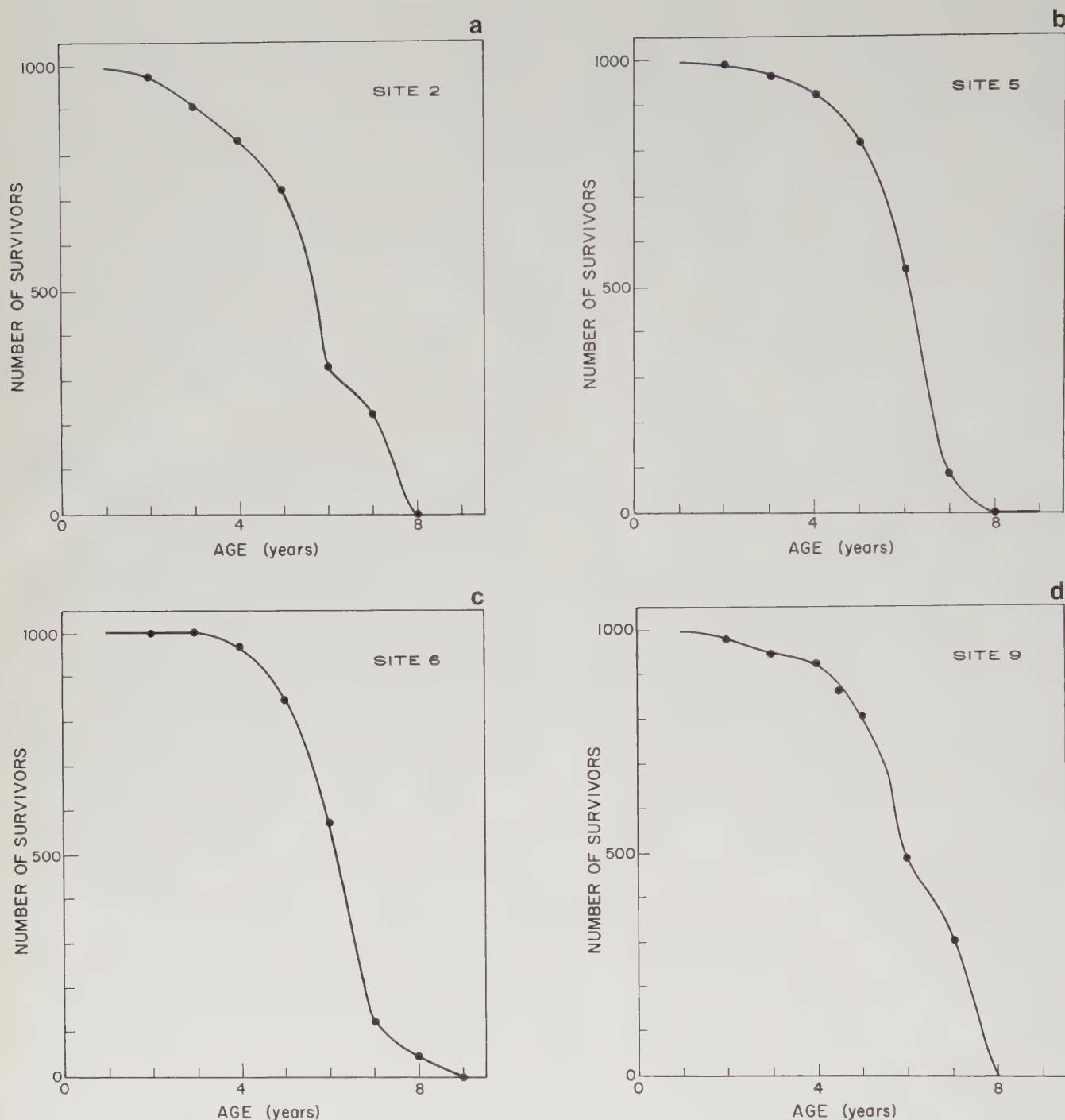


Figure 16. (a–d) Survivorship curves for natural populations of *Mercenaria mercenaria* at sites 2, 5, 6, and 9. Data are plotted as the number of clams surviving at the beginning of each age interval (l_x) from an initial cohort of 1000 specimens.

death rises sharply and appears to be associated with the effects of senescence.

3. Mortality rates and survivorship curves of *M. mercenaria* subjected to the thermal effluent are remarkably similar to those of *M. mercenaria* from control sites unaffected by it.

4. The season of death and absolute age at the time of death of

M. mercenaria are alike irrespective of location in the bay. Maximum frequency of death in postset clams occurs in the summer and winter, and it is concentrated in individuals between the ages of 5 and 9 years. Variation in the season of death data shows that death assemblages have developed from natural rather than census mortality.

5. The maximum longevity of *M. mercenaria* in Barnegat Bay is 8–9 years.

6. Size-frequency distributions of death assemblages of natural populations throughout Barnegat Bay exhibit unimodal, negatively skewed curves. The bulk of dead specimens ranges from 40 to 70 mm in h'. These size distributions result from an interplay of growth and mortality rates, although mortality rates exert the major controlling influence.

7. Unimodal, negatively skewed curves are also common in the size-frequency distributions of life assemblages of natural populations. With the exception of the population in Barnegat Inlet, the majority of live clams ranges from 40 to 70 mm in h'. Therefore, most live *M. mercenaria* in Barnegat Bay are in maturity or old age.

8. Recruitment is not a dependable annual event in Barnegat Bay. The unimodal nature of the size–frequency distributions of the life assemblages reflects this. The last successful spat settlement was in Barnegat Inlet during the summer of 1975. The remainder of the bay has not experienced successful recruitment since at least as far back as the summer of 1972.

Examination of assemblages of *M. mercenaria* transplanted to the substrate at the mouth of Oyster Creek (affected by thermal discharges) and at a control site adjacent to Stouts Creek (unaffected by thermal discharges) in Barnegat Bay reveals:

1. Mortality in the assemblage transplanted at the control site is significantly greater than in the assemblage transplanted at the mouth of Oyster Creek.

2. The greatest frequency of death at both localities develops in individuals between 50 mm and 65 mm in h'. This size interval corresponds to clams between 5 and 6 years of age. These mortality patterns correlate well with those of natural populations, and they appear to be reflective of gerontic death.

3. The seasonal frequency of death is analogous in the two assemblages. Mortality peaks in the summer and subsides in the spring, fall, and winter. Mortality is a consequence of natural rather than catastrophic effects.

Seasonal observations made on assemblages of clams transplanted in cages at the mouth of Oyster Creek and at the control site adjacent to Stouts Creek show:

1. Seasonal and annual mortality are significantly greater in the assemblage affected by thermal effluent than in the assemblage unaffected by it.

2. The frequency of death in cages does not vary significantly with either the size or age of the organism.

3. The seasonal distribution of death is similar at each site. Mortality reaches a maximum in the summer and declines in the spring, fall, and winter. This pattern, which parallels that of specimens transplanted to the substrate, results from natural rather than massive mortality.

4. Clams transplanted in cages display aberrant growth and mortality patterns. Little or no shell growth occurred in specimens subsequent to transplantation, whereas their rate of mortality attained abnormally high levels.

Mortality of *M. mercenaria* in Barnegat Bay is attributed to the natural population dynamics of the species and not to thermal discharges from the Oyster Creek Nuclear Generating Station. Peak frequency of death in natural populations of postset clams

occurs in older individuals and develops predominantly in the summer and winter months. It is proposed that high summer mortality is associated with the physiologic stress of spawning, which would partially account for the large number of postreproductive clams in the death assemblages, and with the increased activity of predators and parasites during the warmer months of the year. High winter mortality, however, seems to be caused mainly by such ecologic factors as low food supply and low water temperatures concurrent with inadequate carbohydrate reserves in the clams.

Subsequent to setting on a favorable substrate, the life expectancy of *M. mercenaria* increases significantly. This allows most individuals in a population to reach sexual maturity and to perpetuate the species. The stability of the clam during this period of life tends to offset the totally unpredictable nature of its meroplanktonic stages. A young population therefore can persist relatively intact for several years at a time without the need of recruitment.

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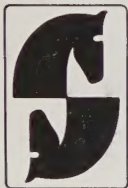
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