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FEASIBILITY OF HIGH LEVEL RADIOACTIVE WASTE DISPOSAL IN DEEP SEA SEDIMENTS: SITE ASSESSMENT AND SEDIMENT BARRIER CHARACTERISTICS

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ABSTRACT

For the past ten years, an international program has been conducted to investigate the concept feasibility for disposing of spent nuclear fuel waste in deep ocean sediments. These studies by the Seabed Working Group were coordinated by the Nuclear Energy Agency of the Organization for Economic Cooperation and Development. Penetrators have been considered as the primary method of waste emplacement. This required emphasis on studies of the nature of the plastic sediments which would form the primary barrier to the release of radionuclides into the biosphere. Site qualification guidelines, included criteria for tectonic and sedimentary stability over periods of at least 10^5 years. Using these guidelines two potential areas were identified: one in the Madeira Abyssal Plain; and one in the Southern Nares Abyssal Plain, both in the North Atlantic. The sediment barrier properties are quite different in terms of dominant mineralogy (carbonates in MAP, and silicous clays in SNAP). The MAP is dominated by thick wide-spread turbidites, but SNAP is dominated by thin discontinuous turbidites.

INTRODUCTION

The problem of devising an appropriate strategy for the management of high level nuclear waste has been intensively examined by several countries with developed nuclear energy technology. Active research to solve this problem has been underway for at least the last three decades. Various options have been explored for the safe management of heat-generating radioactive waste, with most countries favoring concepts of emplacement in stable geological formations below the land surface. Such formations include impermeable salt, clay and limestone deposits, and igneous rocks such as granite and basalt. Problems associated with the management of high level radioactive waste are difficult to solve partly because of the large quantities of waste accumulated from fueling of nuclear reactors over several decades. In addition, these spent fuel rods and the residue from reprocessing spent fuel continue to generate heat above ambient temperatures for 10's to 100's of years after removal from the reactors or reprocessing plants. The International Atomic Energy Agency (IAEA) has defined high level waste as material in which the concentration of radionuclides are high enough to be considered unsuitable for disposal (dumping) at sea (1). These limits were set at activities in which alpha emitters were at 1 curie or more per metric ton, beta or gamma emitters were at 100 curies or more per metric ton, and tritium was at 10^6 curies or more per ton.

In 1976 technical representatives from 8 countries met to assess interest in studying the feasibility of disposal of high level radioactive wastes by emplacement in deep sea sediments or rock beneath the sea floor. The following year the international Seabed Working Group was established, consisting of delegates from France, Japan, the United Kingdom and the United States. The research program of the Seabed Working Group (SWG) was coordinated through the auspices of the Nuclear Energy Agency (NEA) of the Organization of Economic Cooperation and Development (OECD). By 1986 the initial four member countries of the SWG had been joined by six other members, to carry out various aspects of the research program. These additional members include Canada, the Commission of the European Countries (CEC), the Federal Republic of Germany, Italy, the Netherlands, and Switzerland. In addition Sweden and Belgium have had observers attend annual meetings of the SWG.

The Seabed Working Group has been organized with seven technical task groups with responsibility to collect and exchange information that would allow national and international authorities to decide if the concept of waste disposal within deep ocean sediments and rock was feasible. This feasibility would be based on acquisition of suitable data to answer three important questions. (2): 1. "Are there sites in the ocean with suitable geologic stability and barrier properties for subseabed burial?" 2. "What would be the radiological consequences of subseabed disposal to humans and ocean organisms?" 3. "How might one emplace waste-filled canisters into the seabed and what will be the effect on the barrier properties of the sediment?"

Each of the task groups addressed various aspects of these questions. The Site Assessment Task Group (SATG) was responsible for carrying out geophysical and geological surveys of possible disposal sites from a number of locations in the North Atlantic and North Pacific Oceans. The Sediment Barrier Task Group (SBTG) evaluated the physical and chemical properties of sediments that would be expected to act as the natural barrier to the migration of radionuclides released from the waste canisters. The Near Field Task Group (NFTG) assessed the impact of heat generating waste canisters on the physical and chemical properties of sediment within the thermally altered zone around a waste canister. The Engineering Studies Task Group (ESTG) coordinated studies on the transport of waste canisters, design of penetrators to carry waste-filled canisters into the sediment and conducted field experiments to test emplacement of prototype penetrators. This group was also responsible for studies of the effect of emplacement on the physical properties of sediments. The Physical Oceanography Task Group (POTG) and the Biological Oceanography Task Group (BOTG) identified processes and pathways through which radionuclides might be transported from the sea floor to the marine food chain and eventually to humans. Finally, the Radiological Assessment Task Group (RATG) assembled pertinent data from all of the other task groups in order to develop ion transport models and risk assessment models with respect to existing dose models in order to determine the overall feasibility of the seabed disposal concept.

Progress in the research activities coordinated by the SWG was reported in a series of annual reports (3, 4, 5, 6, 7, 8, 9). in addition a status report on the NEA coordinated research program was published by NEA/OECD, (10).

SITE ASSESSMENT

Initial Concepts and Search for Suitable Localities

Two primary methods for emplacing waste packages below the seafloor determined the general nature of possible waste disposal sites: (1) emplacement of a number of canisters in drilled holes penetrating through more than 150 m of sediments, with some reliance on the plastic nature of the sediments to "seal" the hole after emplacement; (2) emplacement of one or a few canisters per deployment by penetrators which would free fall into "soft" sediments to maximum subseabed depths of several tens of meters. With the first method, sites would have to be found with sediment thickness of at least 150 m (up to 400 m), while the second emplacement method could consider sites with somewhat thinner sediments over basement rock, but would probably require a more extensive area of acceptable consistent sediment type.

Other characteristics considered for a potential waste disposal site were that they should be located in the deeper portions of the oceans (below 4,000 m depth) in the areas remote from continental shelves and slopes. For subseabed disposal, it was considered that these locations would add an extra element of the ocean barrier to the migration of any released radionuclides, and the remoteness from continental margins would avoid unstable sedimentary environments which might cause catastrophic erosion at a disposal site. To add an extra element of geological (tectonic) stability it was thought that areas in the center of tectonic crustal plates should be sought. Thus the combination of geological stability and "closed" remote ocean circulation system lead to the common term "mid-plate, mid-gyre" sites which were presumed to be most desirable locations for waste disposal.

Several generic localities were investigated in a preliminary way in the late 1970's and early 1980's. These included locations in the North Atlantic and North Pacific (Figure 1, 2). Some of these locations were in abyssal plateaus (King's Trough Flank, Northern Bermuda Rise), some locations were in abyssal hill regions (Great Meteor West, and PAC II in the Pacific) and several locations on major abyssal plains were investigated (Great Meteor East in the Madeira Abyssal Plain, the Cape Verde Abyssal Plain, the Nares Abyssal Plain and the Southern Sohm Abyssal Plain).

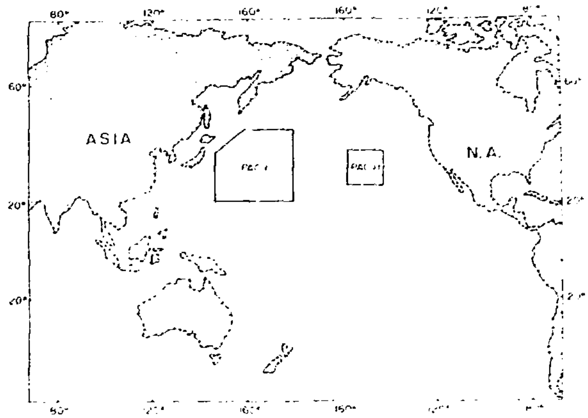

Figure 1: Location of SWG study areas in Northern Pacific Ocean.

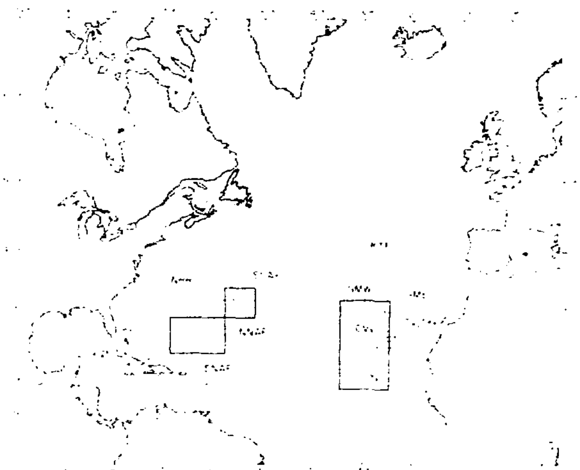

Figure 2: Location of SWG study areas in North Atlantic Ocean. Three large regions (outlined by heavy lines) represents the Southern Sohm Abyssal Plain in Northwestern Atlantic, the Nares Abyssal Plain, and the Cape Verde Region in the eastern Atlantic. Abbreviations signify study areas: NBR = Northern Bermuda Rise, SSAP = Southern Sohm Abyssal Plain, NNAP = Northern Nares Abyssal Plain, SNAP = Southern Nares Abyssal Plain, CU = Cape Verde Abyssal Plain, GMW = Great Meteor West, GME = Great Meteor East, KTF = King's Trough Flank.

Most of the preliminary investigations involved compilation and interpretation of existing archive data depicting bathymetry of the area of interest. In some cases data were also available on the nature of sediments as obtained from geophysical (acoustic profile) records and widely scattered sediment core samples. In most cases these data were insufficient to determine the potential suitability of an area, so additional geophysical survey lines and sediment samples had to be obtained. Geophysical surveys were usually carried out using both low frequency acoustic profilers, such as air or water guns and high frequency systems, ranging from 2.5 kHz to 14 kHz. These geophysical surveys provided information on the thickness of sediment overlying basement rock, with maximum penetration of acoustic energy to several hundreds of meters. The higher frequency records displayed detailed bathymetric features, as well as inferred stratigraphic character, at shallow depths of acoustic penetration of a few tens of metres.

Geological sampling in these initial investigations was limited by conventional oceanographic corers to the upper 10 to 15 m, in most cases. However, these samples provided information on the mineralogical and geochemical nature of sediments deposited during the past 200,000 to 1,000,000 years in several study areas.

Several other survey and characterization techniques were employed during the reconnaissance phase of site investigations. These included long-range sidescan sonar surveys using the GLORIA system (Institute of Oceanographic Sciences, U.K.), a multibeam bathymetric survey system (France) and a sparker profiler (University of Rhode Island, U.S.). Conventional bottom photographs were commonly used to determine the nature of small scale sedimentary features and effects of benthic animal populations. Heat flow or gradiometry measurements were sometimes conducted to determine if possible thermal convection existed in the uppermost sediment layers. Moored instruments were sometimes deployed to measure near-bottom current velocities, turbidity and sediment accumulation rates.

By 1983 sufficient data had been gathered to make a preliminary assessment of the potential suitability of a number of study areas in the North Atlantic and North Pacific Oceans (11, 10). On the basis of sometimes limited data several areas were considered to be unlikely to be chosen for further detailed study because of possible undesirable characteristics. There was doubt whether any extensive areas of flat sediments existed in the King's Trough Flank area. In the Cape Verde Abyssal Plain (CV1) area sediment samples revealed the presence of local thick sand layers which was considered undesirable for penetrator deployment of waste canisters. In the Southern Sohm Abyssal Plain a number of closely spaced large abyssal hills and the presence of turbiditic sand layers made this area unattractive for further investigation. Evidence that strong erosive currents had scoured broad areas of the Northern Bermuda Rise over the past 100,000 years precluded this area from further consideration. The Great Meteor West area in the Madeira Abyssal Plain was found to have rough topography and unstable sediments making it unsuitable for consideration. After preliminary surveys in the Northern Nares Abyssal Plain only small sediment-filled basins were found among rough topography, suggesting that no extensive flat-lying sediments would be found in this area. In the Pacific Ocean the PAC II region was found to contain less than 40 m of sediment overlying basement, and this thickness of sediment was considered insufficient.

Two large abyssal plains in the Atlantic and one abyssal hill region in the Pacific appeared to include areas that might contain thick flat-lying sediments over broad expanses. The Great Meteor East area in the Madeira Abyssal Plain was found to contain thick accumulations of turbidites with dominant carbonate mineralogy. The Southern Nares Abyssal Plain was also found to contain thick accumulations of mostly clay turbidities with low carbonate content. Several areas within the PAC I region in the Pacific Ocean appeared to have thick well-stratified sediment sections under a gently rolling seafloor, so it was concluded that further evaluation of these areas could be continued (11).

Development of Site Assessment Guidelines

As preliminary investigations of possible disposal sites were carried out concepts were evolved for the development of site qualification guidelines (12, 13, 14, 15, 11). These guidelines were based on assumed desirable geological, chemical, biological and physical characteristics of an acceptable site. The goal of these guidelines was to provide a somewhat idealistic framework within which the characteristics of any site might be compared and evaluated with respect to its potential acceptance as a waste disposal area.

The site assessment guidelines accepted by the SWG were based on two primary geoscience criteria: (1) geological stability and predictability of the site over periods of several hundred thousand years; (2) existence of an effective sediment barrier which would prevent significant release of radionuclides from the buried waste to the oceans.

The important factors considered in these criteria are briefly summarized below. For a more complete description of these factors other references should be examined (11, 16).

<u>Site area</u>: Based on an assumption of the number of canisters (~15,000) and spacing of penetrators (~150 m) that might be deployed in a site an area of approximately 100 to 150 km^2 was required.
<u>Bathymetry</u>: Seafloor slopes should be sufficiently low to ensure that the site could not be affected by mass movement of sediment that could cause erosion of the sea floor.
<u>Sediment thickness and structure:</u> Minimum sediment thickness for drilled emplacement was several hundred meters, and for penetrator emplacement the required thickness was to be twice the depth of burial requiring at least 50 ± 20 m. The sedimentary layers should have simple geometries, and therefore structures such as faults and diapirs were undesirable.
<u>Stratigraphy</u>: There should be a uniform thickness and continuity of horizontal strata with continuous accumulation of sediments or absence of erosion for at least 100,000 to 250,000 years.
<u>Volcanism, seismicity and tectonics:</u> All such potentially disruptive activity should not be likely to occur in the site.
<u>Pore water advection</u>: Evidence should indicate that the rate of pore water advection results in chemical transport that is less than that caused by chemical

diffusion.

Sorption capacity: Sediments containing an abundance of minerals with high chemical sorption capacities for relevant radionuclides would be desirable; normally this would favor the predominance of clay (phyllosilicate) minerals.

Redox conditions: Sites containing sediments with a variety of oxidation and reduction conditions ranging from conditions in which manganese oxides (Mn^{4+}) are stable, to reduced conditions in which ferrous iron (Fe^{2+}) is stable in pore water, are desirable. These conditions would enhance the possibility of sorption of migrating radionuclides in both the oxidized and reduced sediments.

Erratic boulders: The presence of significant numbers of large erratic clasts in sediments could prevent successful emplacement of waste, therefore such areas are to be avoided.

Sand layers: Layers of sand could hinder emplacement, and moreover, such layers tend to be more permeable and have less chemical sorption capacity. Therefore, significant thick layers of sand are undesirable.

Bioturbation: Significant disruption or burrowing by benthic animals, where they leave open burrows in the sediment, is an undesirable characteristic because of potential increased bulk permeability.

Physical Properties: Sediments should have suitable viscoelastic characteristics to assure adequate sealing of the emplacement hole.

Other use avoidance: The international seafloor and subseabed might potentially be used for mineral and energy exploitation, commercial fisheries or for the construction of communication systems. Sites should therefore be selected in areas where other conflicting uses are unlikely.

GEOSCIENCE CHARACTERISTICS OF TWO POTENTIAL SITES IN THE NORTH ATLANTIC OCEAN

As indicated in the preliminary investigations, three localities were found, two in the Atlantic and one in the Pacific Ocean, that appeared to meet most of the qualification guidelines as a possible suitable waste disposal area. Because of limited resources available to carry out further detailed investigations in a number of possible sites, the SWG decided to concentrate geoscience characterization studies on two areas in the North Atlantic Ocean, The Great Meteor East area in the Madeira Abyssal Plain and the Southern Nares Abyssal Plain. The geoscience characteristics of these two areas will be briefly described and compared.

The Great Meteor East Area

Most of the SWG work in GME was carried out between 30 to 33°N and 23 to 26°W (Figure 3). Geophysical and geological investigations carried out in this area between 1980 and 1985 included 32,000 km² of long-range sidescan sonar (GLORIA) data, 550 km of deep-tow seismic survey lines, 9,600 km of single-channel seismic profiling with air- and water-guns, 16,500 km of high resolution acoustic profiling with 3.5 kHz systems, 10,550 km of magnetic survey lines, 84 conventional piston cores, 5 long (STACOR) cores, 17 bottom photograph transects, 5 heatflow transects and 12 in situ pore pressure stations, as well as several box cores and dredge stations.

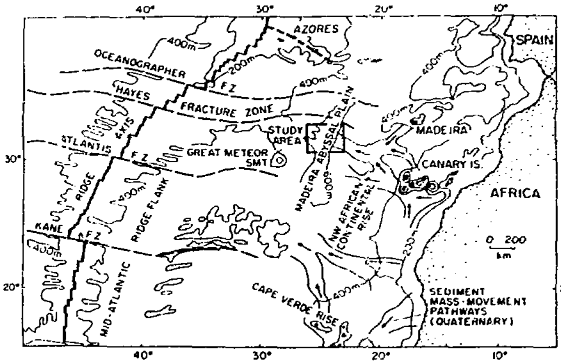

Figure 3: Eastern North Atlantic showing location of Great Meteor East study area in Madeira Abyssal Plain.

The Madeira Abyssal Plain has accumulated thick sequences of carbonate-rich turbidites derived mainly from the continental margin of northwest Africa, although some local turbidity flows may have come from abyssal hills on the eastern flank of the Mid-Atlantic Ridge. Abyssal hills occupy about 30 percent of the study area and these hills rise to a few hundred meters above the gently sloping abyssal plain between 5430 and 5450 m depth (17). On the basis of acoustic profile data the plain can be characterized as consisting of thick (up to 75 m) sequences of well stratified sediments (18). Below the acoustically highly stratified sediments generally fewer and less continuous reflectors indicate somewhat different sediment layers extend from 250 to 1000 m below the seafloor.

Detailed knowledge of the uppermost sediment stratigraphy has been gained from piston core samples which extend to maximum depths of 35 m. Many of these cores demonstrate that the sediments consist of multiple calcareous turbidite sequences, with individual turbidites ranging in thickness from 20 cm to 500 cm. Interlayered between the turbidites are thin (10 cm) intervals of pelagic clay. Nearly all of the turbidites and pelagic clays can be traced and correlated across the whole study area (19).

Most of the turbidites are fine-grained with silty laminated bases grading upward into marly clay (50 to 80 percent clay sized, 40 to 80 percent calcium carbonate). Organic carbon content varied between values of 2.0 percent in unoxidized turbidites to low values of 0.1 percent in the oxidized tops of some turbidites (19). Two layers of foraminiferal sand were found in a clastic turbidite buried at 19 to 21 m depth in a western portion of GME (20).

The bulk accumulation rate of sediments in the GME area for the past 450,000 years (which includes 13 major turbidites) ranges up to 10.5 cm/ka (21). The initial deposition rate of turbidites is probably very rapid, but the pelagic clays and oozes have been estimated to accumulate at rates of only 0.25 cm/ka to 0.6 cm/ka (22, 21).

Evidence of faults through the sedimentary strata in the central part of GME was obtained from acoustic profile records (23). Faults observed on 3.5 kHz records of the uppermost hundred meters of sediments have vertical offsets of up to ten meters at depth, but diminish to virtually zero at the sea floor. These faults have been attributed to processes of differential compaction and possible dewatering of the sediments (24).

Chemical redox conditions in the upper 35 m of sediments have been determined by a number of analytical measurements performed on the pore waters and sediments. Both oxidizing and reducing conditions can be recognized by the remobilization of Mn^{2+} in the pore water. Characteristically, nitrate decreases to near zero concentrations in the upper few tens of centimeters of the sediment column and below this depth both reduced iron and manganese are found. However, conditions do not appear to become strongly reducing, even at maximum depths sampled, because sulphate is not strongly depleted and free sulphide is not detected (16).

In the past such oxidation fronts appear to have developed at the top of turbidite sequences resulting in the oxidation of organic matter in the sediments and probably causing the temporary oxidation and precipitation of reduced metals such as Fe^{2+} and Mn^{2+} that were diffusing upward from deeper within the sediment column. With the deposition of a new turbidite on top of the oxidized front, conditions reverted to suboxic, or mildly reducing, and the redox sensitive metals were remobilized. The preservation of metal accumulation zones, particularly uranium, below the fossil oxidation fronts, indicates that the original unoxidized turbidites have not subsequently been subjected to oxidation, as might occur by downward advection of oxidants. Thus it appears that no gross advective events have occurred in GME for the last several hundred thousand years (16). In addition, analyses of chemical gradients of ammonia, chloride and silica in pore water profiles all indicate that changes in concentration of these constituents are consistent with simple diffusion models, and that any advection has been less than about 10^{-3} m a^{-1} (25, 26).

Southern Nares Abyssal Plain

The Southern Nares Abyssal Plain is located between latitudes 22°N and 24°N and longitudes 62°W and 67°W (Figure 4). SWG investigations were carried out by a number of expeditions over most of this area between 1982 and 1985. High density geophysical survey lines and sediment sampling were concentrated in a reference site located between latitudes 22°35'N and 23°N and longitudes 63°20'W and 63°35'W (Figure 4). In the overall area geophysical and geological investigations carried out between 1982 and 1985 included 15 km deep-tow seismic survey lines, 25,000 km² of long-range sidescan sonar (GLORIA) data, 8,500 km of single-channel seismic profiling with 12 and 3.5 kHz systems, 7,100 km of magnetic survey lines, 59 conventional sediment cores and 8 long (STACOR) cores, 6 bottom photograph transects, and 15 bottom-moored instrumented experiments to measure current velocity, suspended sediments, and benthic boundary layer biological activity.

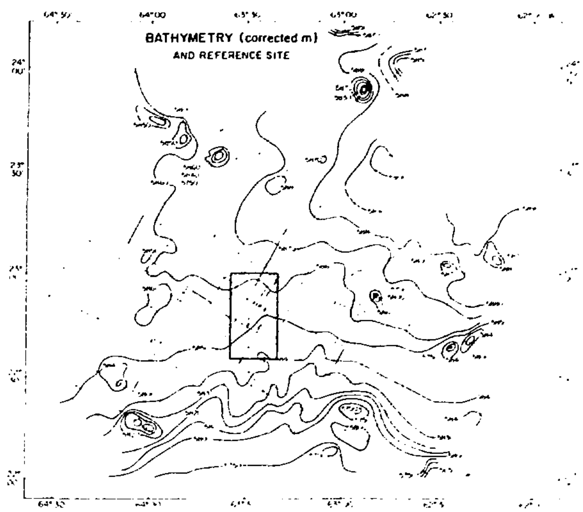

Figure 4: Southern Nares Abyssal Plain showing survey track lines for geoscience studies carried out by SWG. Box outline in centre of area represents location of reference site.

Sediments deposited in the SNAP are mainly derived from turbidity currents that appear to enter the plain through Vema Gap to the west of SNAP (27). The source of these sediments may thus be the continental slope of eastern North America and the Hatteras Abyssal Plain. Only very widely scattered abyssal hills break through the nearly flat surface of the abyssal plain. Some low-relief bathymetric features rise 50 m above the average depth of 5850 m.

From 3.5 kHz acoustic profile records a complex pattern of sediment distribution could be determined which indicated that multiple phases and episodes of turbidites had been deposited over much of the plain amongst the low-relief ridges. Some of the ridges appeared to be draped with pelagic sediments. There is some evidence that more highly stratified sediments may be found in the western part of SNAP as compared with the central and eastern portions (28, 29).

The highly stratified sediments vary in thickness from 200 to 400 m and appear to represent distal turbidite deposits accumulated since mid-Eocene times (30). Below these sedimentary sequences lies a thick sequence of acoustically less stratified sediments extending to a maximum depth of 1000 m below the seafloor where they overlie the Cretaceous oceanic crust.

The turbidite sequences were generally quite thin, beginning with a 2 to 30 cm thick silt-laminated base and grading upward into homogeneous silty clay and clay. The thickness of individual turbidites generally varied between 10 and 50 cm. Many of the turbidites were capped by thin (2-10 cm) layers of pelagic clay. Several attempts were made to correlate individual turbidites between adjacent cores spaced as close as 1 km distance, but no successful correlations could be confirmed. This result suggested that the turbidites were discontinuous over lateral distances as little as 1 km in most areas of SNAP.

Most of the turbidites samples in the central SNAP were fine-grained with even the silty bases having mean grain sized less than 7 µm and average clay contents around 40 percent. The upper portions of the turbidites consisted of about 50 percent clay-sized material. Some turbidites from the western and northern parts of SNAP were slightly more coarse textured. Pelagic sediments also consisted of mostly (65 percent) clay. The calcium carbonate content of both the turbidite sediments and the pelagic sediments was generally less than 5 percent in cores taken from the central SNAP. Turbidite sequences sampled form the north and western regions of SNAP contained somewhat higher concentrations of calcium carbonate, varying between 3 and 18 percent (31).

The organic carbon content in sediments also varied regionally in SNAP. In the central region most of the turbidites contained between 0.15 and 0.25 percent organic carbon. In the northern and western regions the unoxidized turbidites commonly contained organic carbon contents around 0.5 percent with a few samples as high as 1.0 percent (31).

The mean sedimentation rate for pelagic sediments on SNAP during the Holocene has been estimated as 2.2 ± 0.6 cm/Ka (16). Various estimates of the sedimentation rate of turbidites range from minimum values of about 1.0 cm/Ka (16) to high rates of several decimeters per Ka (22). Estimates of the bulk sedimentation rate for both turbidites and pelagic sediments combined, over the past 500,000 years range from 2.0 to 2.8 cm/Ka (16).

Acoustic discontinuities in the subsurface reflectors are common in the central area of SNAP. Although some of these features may be caused by echo focusing, many are attributed to faulting caused by differential compaction (30, 24).

Geochemical characteristics of sediments from SNAP vary regionally and with the dominance of turbidites or pelagics in the sediment column. In purely pelagic sediments, such as were found over a few of the buried ridges, the extent of surface oxidation may reach to at least 8 to 10 m depth. This type of sediment contains pore water in which nitrate concentrations are easily measured at significant levels (greater than 20 µ M), ammonia is undetectable, and Mn^{2+} has been oxidized and removed from solution. In core samples containing dominantly turbiditic sediments the surface oxidized zone may extend only a few cm to a few metres below the surface. Chemical analyses of the pore water from these cores reveal that nitrate decreases to zero within the first few cm or m of the surface, ammonia is detectable at a few cm or m depth and increases linearly with depth, and dissolved Mn^{2+} is detected within the first 1 to 3 m depth and increases rapidly to concentrations as high as 100 µ M (26, 16).

Two long piston cores taken form the northern and western regions of SNAP have geochemical characteristics that are generally different than a number of cores taken from the central and southern regions of SNAP. The turbidites deposited in the northern and western region are significantly more organic rich and contain consistently more calcium carbonate. In addition the turbidites in these cores show clear, well defined paleo-oxidation fronts. The organic carbon content within the oxidized portion of the turbidite is often less than half the organic carbon content in the lower unoxidized portion of the turbidite. A corresponding decrease in $CaCO_3$ is also found with concentrations changing from about 11 percent to 6 percent (31).

Geochemical evidence of early stages of mineral diagenesis was found in a number of cores. Linear increases in alkalinity and dissolved Ca confirms dissolution reactions with calcium carbonate. Apparent loss of K^+ from the pore water in several cores is attributed to selective ion exchange with clay minerals, particularly the mica type minerals. The characteristics of the dissolved silica profiles also suggest some diagenetic reactions, possibly resulting in the formation of authigenic clay minerals. Usually the near-surface concentration of dissolved silica was about 100 µ M and increased to about 150 µ M within the top 1 or 2 m of sediment and then decreased to minimum values, sometimes less than 100 µ M. This characteristic profile suggests silicate dissolution in the near surface sediments with silica uptake in the sediments buried at depth.

CONCLUSIONS

Initial application of the site assessment guidelines to the available information that has been obtained from geological studies of 15 areas in the North Atlantic and North Pacific Ocean indicated that three areas might meet requirements for selection as possible nuclear waste disposal sites. Intensive studies with available technology in two of these areas in the North Atlantic, the Great Meteor East Area in the Madeira Abyssal Plain, and the Southern Nares Abyssal Plain, demonstrated that only part of the GME area appeared to meet nearly all of the site assessment guidelines. Some important questions must be resolved before the feasibility of the concept of subseabed disposal can be established. Is it essential to obtain sediment core samples to the depth of waste emplacement and beyond in order to demonstrate knowledge of the sediment barrier properties? Are apparent compaction faults potential conduits for rapid advective migration of pore fluids and therefore unpredictable breaching of the sediment barrier? Are there other deep sea areas existant that could meet all of the site assessment guidelines?

Summary Comparison of Two Atlantic Study Areas

In the following table, capsule summaries of factors considered in the assessment of potential sites in the Great Meteor East area and the Southern Nares Abyssal Plain are compared.

Factor	GME	SNAP
Area	Sufficiently large areas with most desirable characteristics appear to exist.	Inconsistent character of sediments over sufficiently large area.
Bathymetry	Areas below 5000 m depth, smooth and flat	Areas below 5000 m depth, smooth and flat
Sediment Thickness and Structure	Total sediment depth sufficiently thick, but only sampled to 35 m. High degree of continuity over distance of 100 km. Compaction faulting in most areas.	Total sediment depth sufficiently thick, but only sampled to 26 m. Low degree of continuity over distance of 1 km. Compaction faulting in most areas.
Stratigraphy	Essentially continuous deposition and no large-scale erosion for at least 200 Ka.	Essentially continuous deposition and no large-scale erosion for at least 200 Ka.
Volcanism Seismicity Tectonics	No volcanism. No significant seismic activity.	No volcanism. High frequency seismic activity south of area, detectable in area; a few hypocentres in the area.
Pore Water Advection	Less than diffusion rate, 10^{3} m a^{1}.	Less than diffusion rate, 10^{3} m a^{1}.
Sorption Capacity	Dominant minerals are carbonates.	Dominant minerals are clays.
Redox Conditions	Oxidizing conditions extend to maximum depth of 3 m in turbidites. Suboxic reducing conditions with no sulfate reduction to maximum depth sampled. Silicate mineral diagenesis may occur in pelagic clays.	Oxidizing conditions extend to depth of at least 8 m in pelagic sediments. Suboxic reducing conditions with no sulfate reduction to maximum depth sampled. Silicate mineral diagenesis may occur in all sediments.
Erratic boulders	No natural erratics. Some potential sites contain lost oceanographic equipment.	No natural erratics. Some potential sites contain lost oceanographic equipment.
Sand layers	Along eastern margin and areas of west.	No sand layers.
Bioturbation	Not significant	Not significant
Physical properties	All fine-grained sediments are viscoelastic	All sediments are viscoelastic
Other use avoidance	None known	None known

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