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ALASKAN OUTER CONTINENTAL SHELF SEISMOLOGY AND EARTHQUAKE ENGINEERING WORKSHOP

March 26--29, 1979

Boulder, Colorado

Editors

Carl Kisslinger
CIRES, University of Colorado
Boulder, Colorado

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Sponsored by

The Outer Continental Shelf Environmental Assessment Program
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SUMMARY RECOMMENDATIONS

A large number of specific recommendations for future studies emerged from the Workshop. These are presented in detail in the text. The objective of the proposed program is to prepare meaningful seismological and geotechnical evaluations of the Alaskan OCS for use by BLM and USGS in their prelease and predevelopment decision. The following general recommendations represent a consensus of the participants with regard to the major needs in seismology and related areas for achieving the objectives of OCSEAP in Alaska.

1. Develop the seismotectonic framework of the Alaskan outer continental shelf. Existing data concerning the locations of earthquakes and the causative geological structures must be supplemented by additional observations and field work in sufficient detail to establish the relationship between earthquakes and local and regional tectonics. Data sets (both historical and geological) relative to recurrence rates of major earthquakes must be made as complete as possible.

2. Expand the network of strong ground motion instrumentation. Additional land-based and offshore strong-motion instruments are required to optimize the opportunities for acquiring vitally needed data on the properties of ground motion generated by earthquakes affecting the Alaskan outer continental shelf. The ultimate purpose is to develop reliable techniques for estimating the expected values of ground motion parameters for future earthquakes, at least on a regional basis. Over a period of time, expanded strong ground motion networks may also provide valuable data for further improving seismotectonic models.

3. Assess the potential hazard due to earthquake loading on unstable sea floor sediments. Estimates on a regional basis of the possibility of hazards arising from ocean-bottom instabilities, such

as submarine landslides, liquefaction and turbidity currents, must be developed from the geological and geotechnical data and updated as new data become available.

4. Synthesize existing information and develop products needed by the ultimate users in making decisions related to leasing and operations. The best existing seismological, geological and geotechnical information should be assembled in the near future into geological and seismic hazard maps and other forms. These syntheses must be updated regularly as new information is obtained, so that research results are available to decision makers in a timely fashion.

INTRODUCTION

A workshop on Alaskan Outer Continental Shelf Seismology and Earthquake Engineering was held in Boulder, Colorado, March 26-29, 1979. The general purpose of the workshop was to assist the Outer Continental Shelf Environmental Assessment Program (OCSEAP), NOAA, by providing a review of the status of current projects in its seismology program, an overview of the state of the art of relevant basic science, and an outline of the requirements and goals for necessary future work. Although the workshop focussed on the seismology program, the discussions were held in the context of the specific applications for which the results are needed, so that the geological, geotechnical and structural engineering aspects were given careful attention.

OCSEAP is not a program for basic research. It has well-defined goals in terms of the national needs for development of hydrocarbon resources in the Alaskan outer continental shelf. The workshop recognized that the knowledge required to provide well-founded answers to the relevant questions is not available in some cases. Therefore, the group addressed the total needs for further research in pursuit of OCSEAP goals, including basic research that may very well have to be supported by other agencies. The Workshop participants took the responsibility for looking at the total problem as a national concern and did not limit discussion to those things that fall within the charter and present financial resources of OCSEAP. It is fully expected that important results from programs underway in the U. S. Geological Survey, National Science Foundation, Department of Energy and other programs in NOAA will be incorporated into the work of OCSEAP in a timely way.

The agenda for the workshop is presented in Appendix III. A session of papers by present contractors informed the participants of the present content and direction of the seismology program. Then a series of state-of-the-art papers provided background on: the national program of earthquake hazards reduction, current approaches to probabilistic hazard assessment, the geology of earthquake hazards and earthquake engineering design criteria in the marine environment. Some new techniques in use by the National Ocean Survey/NOAA for revealing details of the tectonics of the sea floor were also described.

There followed small group discussions of the program from the viewpoint of engineering, geology and seismology. Each group was asked to discuss the problems from the viewpoint of a particular discipline, but with a broader concern for the fundamentally interdisciplinary nature of the question. Excellent interaction among the groups and individuals led to a sound, overall approach to the subject. The heart of the material reported here was developed in these sessions and a consensus concerning the key recommendations was reached during a final plenary session on the fourth day.

The discussions resulted in the formulation of a list of needs and research required for the satisfactory achievement of the OCSEAP goals. These may be broadly categorized as: immediate needs for additional observations and analysis, individual research problems, and syntheses. The list reads as follows:

1. Immediate needs for additional observations and analysis.

    New or additional sensors (seismometers, strong-motion sensors, tide gauges, etc.)

    Data transmission and recording facilities

    Geotechnical boreholes

    Geodetic observations

    Surveys (sub-bottom profiles, bathymetry, refraction lines for velocity structure, etc.)

    Age determinations - terraces and other geomorphic features, tephrochronology.

2. Individual problems.

Identification, location and geometry of active faults

Determination of recurrence rates

Attenuation and characteristics of ground motion, treating source regions and receiving positions in pairs

Evaluation of seismic potential of gaps

Estimate stress in source regions

Classification of seismic zones by type (main thrust, Benioff zone, back-arc, etc.)

Model of soil behavior for improved slope stability analysis

Distribution of volcanic ejecta in Deep Sea Drilling Program (DSDP) Logs - to understand extent of volcanic hazard

3. Syntheses.

Geologic map of the Outer Continental Shelf

Seismotectonic model

Seismic hazard analysis:

Ground shaking maps

Ground failure potential maps

Refined catalog of Alaskan earthquakes, $M \geq 6$

Systematic review of tsunami data in old tidal data

Catalog of Alaskan volcanic episodes

More details of these proposed efforts are presented in the body of the report, with an attempt to suggest priorities. It is re-emphasized that all of the suggested work is needed to accomplish the program goals, but it is not implied that OCSEAP alone should or could do all of this.

THE GOALS AND APPROACHES OF THE OCSEAP SEISMOLOGY PROGRAM

The overall purpose of the Outer Continental Shelf Environmental Assessment Program is to develop the technical basis for decisions related to the impact on the environment due to development of hydrocarbon resources in the Alaskan outer continental shelf and to the expected impact on operations from hazards presented by the environment. The assessment of geologic hazards (of which the seismology program is an integral part) is, thus, only one element of a much broader effort. The emphasis of the program is sharply focussed on the acquisition of the information required by decision-makers in the Bureau of Land Management, the Conservation Division of the U. S. Geological Survey, various agencies of the State of Alaska, and industry. This statement of the goals of the program is based largely on the results of the discussions within the engineering sub-group, the members of which are concerned primarily with the ultimate application of the research results to planning and operations.

The general objective of the regional data-gathering program should be to obtain more complete seismological and geological data to describe the hazard from potentially damaging earthquakes, of magnitudes generally greater than 6. Table 1 lists information of primary significance to decisions regarding the design of offshore platforms, pipelines and onshore facilities. Source parameters, attenuation characteristics, character of shaking, surface faulting, recurrence times, and seismic gaps are examples of what needs to be known. In addition, there must be sufficient geological and geotechnical information to assess the potential hazard of different types of soil instabilities such as slides, slumps, liquefaction and turbidity currents.

As a prelude to planning future OCSEAP activities, it is useful to review the present program in terms of its intended uses. Many of the needed data are currently being collected but there appear to be serious gaps in the analysis and interpretation of the data, and, in some cases, the types of data that are collected.

Table 1

INFORMATION NEEDS FOR THE EARTHQUAKE RESISTANT DESIGN OF OFFSHORE STRUCTURES

I. Severity of shaking

- amplitude
- frequency content
- duration
- regional variations
- variations with depth
- likelihood of occurrence

II. Surface Faulting and Crustal Deformation

- amount of expected movement
- nature and style of movement
- spatial description
- likelihood of occurrence

III. Sediment Instability

- depth and extent of influence
- ocean bottom topography
- properties of unstable soils and soils at the site
- rate and amplitude of movement
- likelihood of occurrence

IV. Seismic Sea Waves

- wave characteristics
- likelihood of occurrence

V. Volcano Hazards

- projectiles; gas; ash; lava
- areal extent of influence
- likelihood of occurrence

Two critical categories where greater emphasis is required are:

1. A major effort in future OCSEAP programs should be devoted to synthesis of available data in a timely fashion. Seismological and geological data must be interpreted to develop seismotectonic models which can be used to develop hazard maps for pre-lease decisions and can be used as a tool to estimate strong ground motion.

2. In view of the fundamental importance of the occurrence and severity of earthquake shaking, the program should place greater emphasis on the continued collection and processing of strong ground motion data. Effort should be concentrated in southern Alaska where shaking is an important hazard. The data gathering effort should be concentrated onshore with a limited, complementary offshore program.

<u>Uses of OCSEAP Results.</u> The planning of a mission-directed research program begins with a review of the intended use of the findings. OCSEAP is difficult to categorize in this respect because the results are used by many agencies for many purposes. The following are the two major uses recognized:

1. <u>Pre-lease sale decisions.</u> The Bureau of Land Management (BLM) uses OCSEAP information to evaluate the seismic hazard of each region of potential oil development and to prepare the Environmental Impact Statement for each sale. The U. S. Geological Survey (USGS) evaluates the geologic hazards, including seismicity of the tracts in the sale area, and makes recommendations concerning tract withdrawal or stipulation if the hazards warrant. The information can also be used by the USGS in the preparation of OCS orders and by industry for economic evaluations.

2. Pre-development decisions. The regional data base of OCSEAP provides a logical framework for the site-specific studies needed by the USGS for platform verification and by industry for design.

Recommended Program. The recommended research program is summarized in Table II. The various tasks have been subdivided into the functional steps of a seismic hazard analysis. For each task the desired information is specified, a method of obtaining the data is suggested, and the end product is described. Finally, comments concerning the scope of the task are provided. The tasks are discussed in greater detail in later sections.

Table II

RECOMMENDATIONS FOR THE OCSEAP PROGRAM

Information	Method	Product	Comment
Source Characterization			
1. Location and geometric delineation of seismic source zones (Benioff Zone, Faults).	. Geologic mapping . Better hypocentral locations (improved data, analysis and interpretation, correlation with geologic data) . Geophysical surveys	. Synthesis of available information into tectonic framework (geological maps, cross-sections, etc.)	1. High Priority. Existing arrays and analytical models must be upgraded to provide data of the desired quality. As higher quality data are collected, they should be used to update and improve a regional seismotectonic model suitable for engineering applications.
2. Recurrence rates and estimates of maximum magnitude	. Geologic investigations of faults and terraces . Source parameters of current and historical earthquakes . Statistical analysis of earthquake catalogs (seismicity patterns and gaps)	. Average recurrence intervals for earthquakes of given magnitudes, by region	2. High priority.
Strong Ground Motions			
3. Strong ground motion (SGM) characteristics and attenuation studies	. Extensive onshore SGM program . Complementary offshore SGM program	. Geotechnical characterization of near field motions (modulation, period, amplification, duration) . Attenuation relations	3. High priority

4. Characteristics of SGM produced by earthquakes in the subduction zone	. Onshore SGM program . Comparison with existing data from other regions	. Accelerograms and spectra; other characteristics of the shaking	4. High priority. Instruments should provide continuing broad coverage from Unalaska Island to Yakutat Bay, with concentration in recognized "seismic gaps". It is recommended that an additional thirty or more accelerographs be installed, on a variety of site conditions. At selected sites, additional intermediate gain instrumentation should be provided to record motions too strong for existing seismographic instruments and too weak to trigger standard accelerographs.
5. Modification of motion by regional occurrence of deposits of deep, soft sediments	. Limited offshore SGM program . Geophysical and geotechnical survey . Site description of key SGM records . Utilization of Isopach maps of unconsolidated sediments	. Guidelines for deep sediment effects	5. High priority. An offshore program should consist of an array of at least 8 strong motion instruments located in deep soft sediments, such as near the Copper River delta. Deep geotechnical boreholes (200-300 ft) are required to calibrate geophysical surveys.
<u>Ground Failure</u>			
6. Sediment instability due to seismic overload	. Geological mapping, drilling and sampling, <u>in situ</u> measurements, lab measurements, modeling . Utilization of Isopach maps of unconsolidated sediments.	. Regional maps of areas likely to be affected . Quantitative characterization of possible effect and likelihood of occurrence Estimated age (and estimated error) of most recent ground failure/movement	6. High priority. Understanding of sediment instability can be enhanced by studies of the seismic, geologic and depositional history of the area.
7. Sediment instability due to decrease of strength	. Geological mapping, drilling and sampling, <u>in situ</u> measurements, lab measurements, modeling . Utilization of Isopach maps of unconsolidated sediments	. Regional maps of areas likely to be affected . Quantitative characterization of possible effect and likelihood of occurrence Estimated age (and estimated error) of most recent ground failure/movement	7. High priority. Need to develop criteria relating geology to liquefaction potential as a function of hypocentral distance and magnitude and sediment type.

Other Earthquake Effects

8. Surface faulting	. Synthesis of existing data . High resolution sub-bottom profiling	. Estimates of movements . Quantitative characterization of possible effect and likelihood of occurrence Estimated age (and estimated error) of most recent movement	8. Low-to-medium priority.
9. Tsunamis	. Collection of historic records and examination of sources of tsunamis and local waves	. Catalog and general characterization of regional tsunami hazard	9. Medium priority.
10. Crustal deformation	. Geodetic surveys before and after large earthquakes	. Maps of elevation and horizontal distance changes	10. Low-to-medium priority.

GEOLOGICAL AND GEOTECHNICAL ASPECTS OF OCS HAZARDS ASSESSMENT

The approach of the soil mechanics and geologic group at this workshop was aimed at developing the geologic and geotechnical information requirements for the description and risk assessment of earthquake-related hazards in the Alaskan outer continental shelf. The assessment of these hazards should provide a rational basis for either the deletion of tracts due to unacceptable risks or the development of appropriate stipulations to selected tracts due to a presence of a greater than normal level of risk. With respect to preparation of an Environmental Impact Statement, the information developed from recommended studies will provide direct input to a general description of the area of interest and a detailed description of potential effects the environment may have on a proposed tract.

The intention of the group was to define broadly the various hazards or conditions that could affect development and then outline means to identify the hazards, assess the probability of occurrence of the hazard, and present findings of the recommended program(s) in a usable form. The various hazards or conditions are grouped under three areas: (1) Tectonic Effects, (2) Ground Failures, and (3) Ground Response. Tectonic Effects include faulting, broad-scale vertical movement, and volcanic activity. Even though there is some overlapping, ground failures are further broken down into two categories. One is related to permanent soil movement resulting primarily from overload conditions (e.g., rotational slump failures), and the other is related to loss of soil strength (e.g., liquefaction). Ground response considerations were primarily related to a general description of the seismic activity of an area with respect to sources, to duration, amplitude, and frequency content of the ground shaking and to modification of the ground motion by near surface sediments.

Early in the categorization of the various hazards it became apparent that geologic histories and comprehensive near-surface geophysical surveys (including side-scan sonar, high resolution sub-bottom profiles, sparker, and precision fathometer or their equivalents) were common requirements to all aspects of hazard identification. Therefore, a general description of such studies is included in this section as a separate item.

The following paragraphs present detailed discussions of the three categories of hazards mentioned earlier. These discussions are intended to classify the hazard, define field and laboratory data needed to assess the risk of occurrence of the hazard, define research needs to improve the risk assessment, and recommend means of presenting the results. It is recognized that because of economic constraints it will not be possible to obtain all of the recommended field data. These data needs are assigned priorities to guide in developing plans for field operations. In terms of geographic priorities based on the degree of known seismic activity, high priority should be given to plate-boundary OCS areas (Gulf of Alaska, Kodiak shelf, Cook Inlet, Aleutian shelf); moderate priority should be given to OCS areas west of Alaska (Bristol Basin, St. George Basin, Navarin Basin, Norton Sound, Hope Basin); low priority should be given to OCS areas off northern Alaska (Chukchi Sea, Beaufort Sea).

<u>Geologic Map and Related Data.</u> A geologic map of each region considered for OCS development should be prepared as a basis for identifying earthquake and related hazards, and for analyses of earthquake response characteristics. The geologic map is a primary tool for geotechnical analyses and may be useful in planning offshore drilling and sampling and in placing ocean bottom seismographs and ocean bottom strong-motion instruments. The Quaternary geology of an area provides a long-term record of tectonics, geotechnical conditions, and potential hazards; accordingly, emphasis of geologic studies should be on the Quaternary record. Information should be collected and presented in a format that is useful to the geotechnical engineer, as well as to the geologist and seismologist.

Existing data regarding the geology of the OCS areas and adjacent landward areas should be used as a framework for establishing a high quality geologic map of each OCS lease area. A knowledge of the structural geology, stratigraphy, and geologic history of each OCS area is critical in evaluating earthquake-related hazards. The capability to prepare this product exists although improvements in geophysical hardware, software, and interpretations may allow preparation of increasingly better subsea geologic maps in the future.

Field data that should be collected include precision bathymetry (narrow beam type), side-scan sonar, and very high-resolution reflection profiles that penetrate a few hundred feet or more. The geophysical data should be complemented by numerous surface samples (gravity cores) and by selected borings as deep as a few hundred feet to identify the geological and engineering properties of each stratigraphic unit important to decision making and planning. The field programs should be adequate to define the stratigraphic units in the OCS area and, for each unit, the distribution, geometry and ranges in material properties. The concentration of field programs should be upon the stratigaphic units that would be classified as soils rather than rocks by the geotechnical engineering profession, and upon the engineering properties and variations of these properties for each stratigraphic unit.

The following products should be developed as part of the study to produce a geologic map and description:

1. Geologic map of rock and soil stratigraphic units exposed at (or reasonably close to) the sea floor. The base for this map ideally would be a bathymetric map.

2. Isopach map(s) of each identified stratigraphic unit that would be classified as a soil rather than a rock; a summary isopach map of all such units should also be compiled.

3. The ranges in physical properties of each stratigraphic unit should be identified. Such properties should include textural data (grain size, grain shape, packing of grains, etc.), and for soils should include density, degree of consolidation, water content, shear strength, and other properties that are pertinent to geotechnical evaluations of earthquake response or soil stability, and whether anomalous conditions (such as organics, shallow gas, boulders, etc.) may be encountered within the unit.

4. A map that shows identified potential hazards (landslides, shallow faults, etc.)

5. A text description of each of the stratigraphic units including bedding characteristics, local and regional variations, physiographic associations, environment of deposition, age (estimated or dated, and relative to other stratigraphic units), and special or anomalous conditions that may be associated with each stratigraphic unit.

6. A text description of the geologic history of the OCS area, with concentration upon the recent part of the history that would relate to the units classified as soils, and upon the history and development of faulting, landsliding, and other geologic hazards that may be related to or aggravated by earthquakes or other tectonic deformation. It is desirable to identify an absolute time-scale (chronology) as a basis for the geologic history; for example, an absolute chronology would provide a basis for decision making with regard to hazards through time for each area.

<u>Tectonic Effects.</u> Faults that rupture to the sea-floor surface or approach the surface, should be identified and mapped on a regional scale, and their significance should be addressed in a text to accompany the map. The goal is to identify youthful faults that have the potential to rupture during the lifetime of offshore structures.

Existing data from available sources should be compiled and evaluated to identify and locate faults. The existing data should include, but not be limited to, geologic maps and reports, geophysical data (including shallow-penetration high-resolution reflection profiles, multi-channel reflection profiles, gravity, magnetic, and seismicity data), and bathymetric data. Information from onshore areas adjacent to the offshore areas should be included in the review of existing data. In Alaska the onshore data is generally of higher quality than the offshore data.

Faulting and rates of faulting in the onshore area typically are studied by means of geologic mapping, and by identifying whether or not stratigraphic units or geomorphic surfaces are deformed or undeformed by faulting or related folding. The methods of identification differ widely but may include trenching, drilling, and geophysical studies (seismic refraction, seismic reflection, gravity, magnetics, and electrical resistivity).

In the subsea area, reflection profiling is the best single tool, with very high resolution desirable when studying the details of near surface stratigraphy and faulting. Geophysical data to evaluate faults should be collected from the same regional surveys conducted to gather shallow geologic data. Penetration and resolution of reflection profiling should be adequate to depths of at least several hundred feet, and possibly deeper in areas with thick accumulations of young deposits. In addition to reflection profiling, bathymetric and side-scan sonar data should be collected, along with gravity and magnetic data. Age dating of onshore and offshore stratigraphic units as well as geomorphic features pertinent to evaluation of fault activity should be attempted by appropriate methods that may include radiocarbon, amino acid racemization rates, and paleontology; samples for age dating should be collected during other sampling programs. Boreholes are required to collect data for the geotechnical properties studies of deeper subsurface layers.

Submarine fault locations should be mapped on a bathymetric base map, and each fault should be identified by number on the map. A catalog of all observed faults should be included to append the map; the catalog should include such data as fault length (or, because of the paucity of trackline crossings, the range of possible lengths based upon the number of crossings), orientation, maximum observed displacement, type of slip, sea floor scarp relief, age of youngest displaced stratigraphic unit or geomorphic surface, line and shot point locations, and miscellaneous notes regarding surface expressions or other pertinent observations. An interpretative report should describe the faults and identify insofar as possible the rate of fault displacement, amount of fault displacement per event, rates of uplift, subsidence or tilting, and the potential for future fault rupture. Estimates should be made not only of the earthquake potential due to fault rupture, but the recurrence and maximum earthquake expected from a given source.

Mapping and evaluating faults are within the current state of the art, although accurate fault lengths are rarely established. New and improved methods are constantly being developed and refined under other programs; accordingly, research on new techniques is not recommended as a part of OCSEAP. Integration of geological and seismological data from parallel programs in Alaska is recommended as a high priority item for OCSEAP.

Volcanic hazards are considered to be of marginal importance to many of the Alaska OCS areas, with the prominent exception of Cook Inlet. The dominant hazards usually associated with volcanoes include the locations of eruption, the type of eruption, and the area of influence of ejecta, flows and gases. These hazards should be considered as part of OCSEAP under the earthquake hazards program or as another program element.

Volcanic hazards can be subdivided into two subsets: near-field and far-field. Near-field hazards typically include lava flows, pyroclastic flows, mudflows, floods (Jökulhaups), heat blasts, shock waves, projectiles and noxious fumes. Far-field hazards include ash falls, acid rains, and volcanologic tsunamis such as those which occurred during the 1883 eruption of Augustine Volcano.

Hazard maps should be prepared for certain volcanoes that are considered hazards based on (1) the distribution and areal extent of historic and prehistoric flows and tephra, (2) ballistic calculations, (3) ash and noxious fume dispersals observed during historic eruptions, as controlled by the prevailing wind fields, and (4) historic observations of runup of volcanogenic tsunamis and floods.

Ground Response and Ground Failure. The term ground response, as used herein, means ground shaking induced by earthquakes. Ground failure means either the formation of new slides and slumps on the sea floor or the reactivation of movement of previously formed slump and slide features in response to earthquake-induced ground shaking. Ground response induces ground failure either by overloading (e.g., rotational slump failures), or by a combination of overloading and strength loss. This section is primarily concerned with ground failures induced by overloading associated with ground shaking. Both ground failure and ground response are interrelated and can be studied concomitantly.

Initially, basic geologic data are needed on the topography of the sea floor and the nature and distribution of the surficial geologic units including information on the origin of the material, the history of deposition, geometry, sedimentation rates, and gas sources. Existing slump and slide features need to be identified and delineated, and attempts must be made to ascertain the age and present activity of these features.

These geologic data need to be supplemented with field and laboratory geotechnical measurements to determine the material types in each geologic unit in terms of their composition, texture, plasticity, moisture content, density, and degree of consolidation. Each material type needs to be further analyzed for its stiffness and strength in situ and for the variation of these properties with dynamic strains associated with earthquake-induced ground shaking. Information is needed on the seismic wave velocity of the underlying geologic units, on seismic sources, and on travel paths.

In addition to the acquisition of basic data, research is needed to advance the state of the art for assessing ground response and ground failure on a regional basis. Measurements of relative ground response (i.e., acceleration as a function of time) in specific regions are needed to compare with predictions based on seismic sources and travel paths. For ground failure, specific slump features need to be investigated in detail to evaluate and improve existing technology for predicting slumping during future earthquakes. These process-oriented studies will need to be supported with basic research on topics such as: (1) the evaluation of sample disturbance by comparison of in situ and laboratory measurements of seismic shear wave velocities and various geotechnical properties; (2) the development of finite strain consolidation theory for calculating states of consolidation and pore pressures in situ; and (3) non-linear dynamic deformation theory for analyzing and predicting earthquake-induced slumping in soft gas-free and gas-charged sediments.

Interpretative reports and maps should be prepared to document basic data pertinent to the assessment of ground response and ground failure hazards. Examples of pertinent geotechnical and seismic data that can be mapped include states of consolidation, in situ pore pressures, shear-wave velocities, predominant periods of surface units and effective stress parameters. Insofar as the state of the art permits, interpretative reports and maps should also be prepared to assess ground response and ground failure hazards on a regional basis. This effort must interact closely with process-oriented research.

This overall approach should eventually lead to regional interpretations of hazards associated with seismically induced ground failure, and regional interpretations of the spectra and duration of ground shaking associated with each mapped unit, including the variations of these parameters with strain amplitude.

Ground Instability due to Liquefaction. Soil liquefaction is defined as the transformation of a granular material from a solid state to a liquefied state as a consequence of increased pore-water pressure and reduced effective stress. Consequences of liquefaction include: (1) flow landslides, which may develop on slopes greater than 3° (5%), flow over large distances (100's of meters), and may eventually transform into a turbidity current; (2) lateral spreads, which may develop on slopes as small as 0.3° (0.5%) and may displace from a few tenths of a meter to several tens of meters; and (3) quick conditions, which generally develop beneath flat or very gently sloping surfaces and may lead to bearing failures for structures not protected against such failure.

The primary factors controlling the development of seismically-induced liquefaction include intensity and duration of ground shaking, and the texture, density state, amount of cementation, and degree of saturation of the sediments. (Submarine sediments are assumed to be fully saturated.) Gross estimates of texture, cementation and density state can be made from geologic information such as the mode and age of sedimentation. Such gross estimates are adequate for compiling regional liquefaction susceptibility maps, but not for site-specific evaluations.

Techniques have been developed for compiling regional liquefaction potential maps for onshore areas. Such maps are useful for preliminary planning and hazard assessments, and for preliminary site selection. In the past, they have been used to stipulate types of site-specific investigations required, but not specifically to prohibit development.

Liquefaction potential maps are prepared from a composite of two maps - a liquefaction susceptibility map (essentially a map of the Quaternary geology) and a liquefaction opportunity map. The susceptibility map shows areas where geologic units may or may not contain liquefiable sediments. The opportunity map shows the likelihood of ground shaking (in terms of a parameter such as recurrence interval) capable of generating liquefaction in susceptible sediments. Thus, the liquefaction potential map shows not only where liquefiable sediments are most likely to occur, but also how often they are likely to be subjected to seismic shaking capable of causing liquefaction.

The following research needs and priorities are identified:

1. Correlations between Quaternary geologic units and liquefaction susceptibility must be developed for outer continental shelf units before liquefaction susceptibility mapping can proceed. Required research includes a review of the geologic setting of historical occurrences of offshore liquefaction, comparison of properties of offshore sediments with susceptible and nonsusceptible onshore units, and field and laboratory measurements of texture, density state and cementation at several sampling sites in some geologic units.

2. Expected locations of seismic energy sources and expected frequencies of occurrence of seismic events are fundamental data needed for evaluating liquefaction potential. Further research is needed to extend to the Alaskan OCS the correlation between liquefaction opportunity and distance from a seismic energy

source. The research would involve a more quantitative evaluation of past liquefaction occurrences than has previously been conducted, correlation with published soil property measurements (primarily penetration data), and extension of the present correlations to ground motion attenuation relationships.

Additional field and laboratory data required for evaluation of liquefaction potential include collection of soil property data from the sea floor to define the geology of the region better and also to define the soil properties of the geologic units. The requirements for defining soil properties would include collection of samples for laboratory determination of textural properties, density state and cementation. Specimens for determination of density state can be obtained only from those sampling techniques that retrieve samples in a relatively undisturbed state such as piston cores and high quality cores from drop samplers and box samplers. These samples should penetrate well into the Holocene sediment layer, and in some instances penetration into the Pleistocene layer may be required. Gas bubbles in the sediments that expand upon retrieval of the core from the ocean floor may disrupt specimens to an extent, preventing laboratory measurements of density state and cementation.

The final result of the liquefaction potential studies would be a series of maps on appropriate scales depicting liquefaction potential for pertinent segments of the Alaskan outer continental shelf. At the scale of the anticipated regional interpretative maps, only units likely to contain liquefiable materials can be delineated. The determination of whether liquefiable materials exist at any particular site will require specific geotechnical studies at that site. The regional maps are useful, however, for preliminary planning and for stipulating that such site investigations be conducted.

SEISMOLOGICAL ASPECTS OF OCS HAZARD ASSESSMENT

A multi-faceted seismology program can define a model of the OCS seismic hazard environment. This model could supply critical inputs for engineering design needed for petroleum development on the Alaskan OCS. Some of these critical inputs are:

a) delineation of active faults and regions of homogeneous seismic activity;
b) estimated source properties of probable large future earthquakes in the OCS;
c) recurrence relationships and maximum magnitude earthquakes for specific faults and regions;
d) regional attenuation relations for ground motion parameters of utility to platform design.

A preliminary seismic hazard model has been defined from data now available. This is the Offshore Alaska Seismic Exposure Study (OASES) prepared by Woodward - Clyde Consultants for the Alaska Subarctic Offshore Committee (ASOC). However, revisions based on continued and improved observations are necessary to provide the accuracy, precision and detail required for engineering purposes.

Seismic hazards studies will be influenced mostly by investigation of the attenuation properties of ground motions generated by earthquakes in the subduction and intraplate zones. This work could be pursued by the deployment of ocean-bottom strong-motion and broadband seismographs (OBS). Supporting this work would be refraction studies for velocity models and inelastic attenuation factor (Q), from which attenuation properties can be derived theoretically. The existing high gain and strong motion networks should be upgraded, not only to obtain information on regionally active faults and areas, but also because there is the possibility that these networks will enable us to anticipate the time of occurrence and source properties of the next big offshore earthquake. Finally, retrospective earthquake catalog improvements and geologic field work will enable us to better define source zones and long term recurrence estimates for the Alaska-wide tectonic environment.

Current knowledge of earth deformation processes indicates that a moderately expanded seismology program over the next few years can probably provide a practical working model of the hazard environment. However, continued observations at a lower level of effort, over the life of OCS oil production will be necessary for important updates of the hazard model.

The seismic environmental model should:

a) characterize the severity of shaking in terms of model acceleration spectra and duration of motion, which apply with specified recurrence probability to various mapped areas;
b) identify zones of active surface faulting;
c) provide shallow seismic exploration data relevant to layering, mechanical properties, and stability of sediments;
d) provide basic modeling data on generation of tsunamis; and
e) provide supporting information relevant to volcanic hazards.

The data inputs for the above must come from seismographic networks like the ones already installed, from offshore seismographic networks which supplement land networks, from strong-motion seismographs including offshore instruments, from some new non-seismological program initiatives (e.g. marine geology and marine geotechnique), and from more intensive analysis of both existing data and new data to be acquired including an evaluation of historical information on earthquakes and tsunamis.

The following actions for continuing, adding to, and/or revising elements in the OCSEAP seismology program are recommended:

1. Selective Near-Term Refurbishing and Selective Additions to Existing Networks. Increased network reliability will close time gaps in the data base. A few relocated or additional stations are needed to close geographic gaps. Monitoring earthquakes of different magnitudes is needed to improve delineation of active local faults, to detect significant changes in the regional strain regime, and to detect episodic active centers and seismic subzones. Network operations must be sustained because seismicity patterns are not statistically stable on any known time scale. Analysis of earthquake and explosion data also helps to define structural models of the crust and mantle which, in turn, define propagation and attenuation characteristics needed to project strong motion parameters to any site of interest.

2. Major refurbishing of the Shumagin-Alaska Peninsula network. Operations and data recovery are handicapped by obsolete recording and telemetry equipment. Uniform instrumentation is also needed for improved data quality.

3. Increase density of network in Norton and Kotzebue Sound areas; move recording site from Fairbanks to Nome. Station coverage is too sparse in these areas to provide acceptable precision of epicenter locations, focal depth or magnitude determination, especially for offshore epicenters. Attenuation parameters offshore cannot be determined with the present network. Delineation of faults is promising, but quality must be improved. Present telemetry to Fairbanks is too expensive.

4. Add horizontal components to existing high-gain stations at locations where telemetry is less costly. Improved ability to identify S-wave phases and surface waves will afford more information on propagation and attenuation model.

5. Install networks in Bristol Bay-Pribilof area. In an area of lower seismicity, a longer period of time is needed to obtain a given level of seismic information.

6. Continue present OBS Programs off Kodiak and Northeast Gulf of Alaska, and deploy networks in other areas as soon as possible. Temporary offshore networks supplement land-based network to improve structural model calibration for propagation estimates. Older inland network data can then be revised to provide more accurate locations for offshore earthquakes. The Benioff zone far offshore can be delineated by small shocks detectable only from OBS networks on the slope. Future land-based network data is also better calibrated by reference to better structural models.

7. Shoot refraction profiles and large network calibration explosions in area of deployed OBS networks. Refraction profiles will provide a better structural model for correlation with active tectonic elements, especially gap boundaries and main thrust zones and for improved wave propagation models in delineated structures. Large network calibration explosions will provide ideal travel time data from known shot points to onshore and offshore stations, permitting more accurate location estimates for natural sources in the same area.

8. Examine the regional distribution of the best high gain and strong motion seismographs for feasibility of in situ stress measurements. Spectral properties, combined with hypocenter and focal plane solutions, afford a method of in situ stress estimation. Knowledge of the crustal stress field helps to define waiting time, location and length of future ruptures.

9. Develop semi-permanent offshore seismic stations. Bring coverage with offshore instruments up to onshore standards, especially with respect to long-term continuous observation by means of radio telemetered OBS's.

10. Support major increment of ocean bottom strong motion (SM/OBS) coverage, especially early instrumentation of identified seismic gap segments, followed by systematic SM/OBS coverage along entire active margin. An excellent chance exists to obtain strong motion seismograms from shallow water areas with direct applicability to platform design problems. First targets should be the Yakataga and Shumagin gaps.

11. Improve communication.

Either:

a) Dedicate a geostationary communication satellite for return of seismic data from remote sites in Alaska and elsewhere in North America.

Total OCSEAP telephone bills in Alaska for seismic data transfer is now over $250K/year while inadequate telemetry still handicaps many parts of the networks. Great simplification and improvement of network performance is possible from a common communication facility. This is a general science support proposal of broader scope than the Alaskan network requirement.

Or:

b) Investigate technological alternatives to continuous telemetry via telephone.

The goal is to reduce a major cost of operations, especially to facilitate low-cost return of data over the long term.

12. Consider geodetic methods to supplement seismic data in selected areas. Tide gauges provide useful information on vertical deformation in coastal areas at reasonable cost. Pressure-type tide gauges on

Geostationary Operational Environmental Satellite (GOES) Data Collection Platforms (DCP's) might be installed at numerous coastal points. Inexpensive technology using communications already in place provide valuable geodetic strain data and data for tsunami prediction.

Electronic distance measurement has ample precision for useful horizontal strain measurements and may be useful in some places if not too costly.

Leveling is possible, but too expensive for extensive or frequent coverage. Geodetic strain measurements are diagnostic of stress accumulations and may detect precursory changes in the deformation regime.

13. Support compilation of earthquake and tsunami information from all historical records. A more complete record of intermediate to large historic earthquakes may be available. This should be valuable for estimating rupture areas, magnitudes and recurrence times for large shocks.

A major task of seismologists is the identification of "seismic gaps" as areas of increased probability for the occurrence of a major earthquake. Intensified studies in such areas should include: history of major earthquakes; influence of geologic and tectonic features on the seismic history; spatio-temporal study of seismicity with emphasis on recognizing patterns which may be precursory to a major event.

14. Consider program feasibility of geological studies in selected areas.

    a) Field mapping to locate active faults identified only by seismology.
    b) High resolution profiling to locate active faults offshore.

c) Investigation of marine terraces, especially dating by radiocarbon.

d) Narrow-beam, multibeam and side-scan mapping on shelf.

Methods a) and b) provide data needed to verify faults of possible engineering significance; method c) extends the historic record of major earthquake uplift events and establishes prehistoric return times; method d) maps fault traces and identifies slump topography and gas eruption features on the ocean bottom.

15. Place seismic instrumentation on several additional volcanoes. Obtain distant early warning of eruptions which might endanger oil platforms or terminals. Utilize relationship between seismic and volcanic activity as possible seismic precursor.

16. Consider possible benefits of further standardization of seismic data reporting and analysis procedures. Questions to be considered are:

a) Is a uniform Alaska seismic bulletin desirable?

b) Can raw arrival time data above some magnitude threshold as well as epicenter solutions be shared? Is this desirable?

The principal benefit would be a more uniform, complete and accurate earthquake catalog for seismic hazards estimates.

17. Increase emphasis on data analysis and synthesis in all programs. The seismologist interfaces with the engineer and regulator by learning their requirements and by performing analyses needed to define seismic hazard models. The seismologist makes his maximum contribution by carrying his analysis as far as possible toward the specific engineering and management design requirements.

APPENDIX I

PRIORITY OF SEISMOLOGY TASKS

The following prioritized list of tasks was determined by the seismology group and reflects the opinions of the specialists within that discipline. These priorities do not necessarily reflect a consensus of the entire workshop.

1. Deploy onshore and offshore strong motion instruments
2. Establish complementary onshore - offshore high-gain networks
3. Review historic earthquakes, including interval studies and magnitudes
4. Conduct offshore refraction surveys
5. Upgrade Shumagin high-gain network
6. Add horizontal components
7. Install onshore broad-band instruments
8. Upgrade NEGOA telemetry
9. Increase density of Norton Sound-Kotzebue seismic stations.
10. Establish gap-earthquake source mechanism estimates
11. Make geologic recurrence estimates
12. Determine gap-closing probabilities
13. Make geological investigations of terraces
14. Monitor volcanic activity
15. Measure source parameters of earthquakes
16. Develop telemetering OBS
17. Support Alaska working group meetings

18. Establish Bristol Bay network

19. Carry out crustal deformation geodesy

20. Support logistics for Shumagin geodetic work

21. Provide additional low gain channel recordings

22. Analyze historic tsunamis

23. Establish Pribilof network

EXPLANATION OF PRIORITIES FOR SEISMOLOGY TASKS

The following are detailed recommendations offered by the individual panel members who proposed each of the listed tasks:

1. Deploy offshore strong motion instruments. Construct 6-8 additional strong-motion OBS stations to bring the total available to 14. Deploy these along the outer continental shelves of the Gulf of Alaska and the Aleutian Islands. Redeploy on an annual basis until adequate data sets are obtained.

2. Establish complementary onshore-offshore networks. Install temporary OBS networks (2-3 mo.) to complement existing land networks in the following zones:

Zone	Land Net	Period (summer)*
1) Kodiak	University of Alaska	1980
2) Norton Sound	University of Alaska	1981
3) Shumagin Island	Lamont	1982
4) Northern Gulf	U.S.G.S.	1983
5) Bristol Bay	University of Alaska	1984

* Beyond 1980, the order of experimental zone is arbitrary. At least one large explosion (1-3 tons) should be planned in the vicinity of each network for calibration and refraction data.

3. Review historic earthquakes and intensity data. A careful analysis of existing historic earthquake data, including pre-instrumental, instrumental, and intensity (felt reports) information can provide a more comprehensive evaluation of possible major earthquake source areas and a better (though by no means accurate) understanding of recurrence times. This analysis would involve earthquakes of magnitude 6 or larger, and may include (but is not limited to)

estimation of magnitudes for earthquakes occurring before or about 1963, to which magnitudes have not routinely been assigned. Also, a careful study of the locations of these pre-1963 earthquakes can help define the possible areas of intraplate seismic sources. Using available historical data may help determine magnitude, focal mechanisms and other focal parameters, and improved locations for larger earthquakes in the earlier part of this century. This includes using original and published observations from Alaska and other areas.

4. Conduct offshore refraction surveys. A series of at least four reversed refraction profiles should be obtained offshore in the vicinity of each of the land-based seismographic networks. The profiles should be along strike and long enough to define the upper mantle. Where feasible (Aleutians and Adak), shots should be fired on the island ridge and recorded by the land-based stations to define the crustal structure of the island ridge. Air guns can be used for the short range portions of these lines (out to about 50 km), but explosive charges of up to 1 ton will be required at the largest ranges needed (200-300 km).

5. Upgrade Shumagin high-gain network. The PI has mentioned the need to upgrade and expand the high-gain network; to add low-gain, broad-band and strong-motion seismic stations; to deploy OBS instruments to augment onshore location ability; to obtain continued support for geodetic measurements; to obtain continued low-level support for geologic investigation of terraces; where possible, to locate regional seismic stations near volcanoes; and to utilize a seismology communication satellite. The last item represents a strong need for improved communications in the Shumagin network, especially with reference to improving the telemetry system hardware.

6. Add horizontal components. To provide S-wave attenuation, two stations (one on St. Lawrence Island and one on Seward Peninsula adjoining the coast) should be converted to three-component stations. This should be done similarly elsewhere, where needed.

7. Install onshore broad-band instruments. This requirement is primarily a need for instrumental response at frequencies below as well as above the natural frequency of the typical seismometer, which is 1 to 4 Hz. Sensitivity over the broadened frequency band is needed in order to measure acceleration and to derive source parameters such as fault length and stress drop for larger earthquakes. Strong motion instruments typically fulfill this need, except that the standard types trigger only on accelerations of 0.01g or greater. There is a need for broad-band recordings of weaker or more distant sources that would provide a more complete sample of earthquake source parameters, thereby allowing a more timely characterization of the weak ground motion to be expected from a distant earthquake.

8. Upgrade NEGOA telemetry. The ratio telemetry currently used in the NEGOA seismic network is not of adequate quality or reliability. Improved equipment would be well worth the investment.

9. Increase density of Norton Sound-Kotzebue Sound seismic coverage. Increase the density of seismic coverage around Norton (10 stations) and Kotzebue (10 stations) Sounds, and record data locally in order to: (a) improve epicenter locations, (b) delineate active structures with greater certainty, (c) determine velocity structure, and (d) determine attenuation of the propagation media. Also add one strong-motion station to the Norton Sound array to provide acceleration records.

10. Establish gap-earthquake mechanism estimates.

11. Make geologic recurrence estimates.

12. Determine gap closing probabilities. General recommendation: To assess the seismic hazard posed by the future occurrence of great thrust-type earthquakes along the northern margin of the Pacific Plate, it is essential to evaluate the relative seismic potential of segments of this margin; where the potential is high, these segments have been called seismic gaps. Two important methods (in addition to fundamental seismotectonic analysis), which contribute strongly to the evaluation of this relative seismic potential, are the measurement of stress drop in moderate sized earthquakes and the measurement of crustal strain by such techniques as leveling, electronic distance measurements, sea level monitoring with tide gauges, and systematic monitoring of volcanic activity.

13. Make geological investigations of terraces. See (5).

14. Monitor volcanic activity. Thirty-seven volcanoes lie adjacent to the Aleutian and Bering Sea continental shelves extending from Cook Inlet to the Bering Sea shelf edge. Of these, only 12 have not erupted in historic times (past 200 years) or do not show any obvious geothermal activity. The 1912 Mt. Katmai eruption ranks amongst the largest eruptions in the world in this century. Presently, single-component vertical seismic stations are located near nine volcanoes. The workshop recommends that another eight single-component vertical seismic stations be located on another eight active Aleutian volcanoes. The volcano stations provide depth control for shallow clusters of seismicity which are now being detected by the regional networks beneath certain volcanoes. The purpose of this instrumentation is twofold: (1) detection of eruption precursor seismicity, and (2) use of volcanoes as in

situ stress indicators. There is mounting evidence in Japan, Hawaii, and elsewhere around the Pacific rim that volcanic eruptions and large earthquakes are somehow linked. Some volcanic eruptions could be the result of large scale hydro-fracturing in response to building of tectonic stress in a given tectonic segment of an island arc structure.

15. Measure source parameters. See (7).

16. Develop telemetering OBS. Develop a prototype (low-cost), radio telemetering OBS station which can operate at key offshore sites for periods of one year or more. If successful, these should be installed in future years of the program to complement the existing and planned land-based station networks. It is noted that development costs might be shared with other agencies (ARPA, ONR) that have interests in developing telemetering OBS stations.

17. Support Alaska working group meetings.

18. Establish Bristol Bay network.

19. Carry out crustal deformation geodesy. Electronic distance measurements and second order (theodolite) leveling in selected seismically active regions for crustal deformation studies.

20. Support logistics for Shumagin geodetic work. See (5).

21. Provide additional low-gain recording channels. Low-gain channels to existing high-gain stations for attenuation studies in the intermediate amplitude range which is now not covered.

22. Analyze historic tsunamis. Using existing mareograms, search for records of smaller tsunamis for analysis of tsunami sources, tsunamigenic earthquake characteristics, recurrence rates, harbor

responses, and periods. The use of the older data will increase significantly the number of tsunamigenic earthquakes identified in the area and the data for determining tsunami risk. It may be possible to identify source areas.

23. Establish Pribilof network.

APPENDIX II

OTHER RECOMMENDATIONS

The preceding recommendations either deal directly with seismological methods or suggest investigation within the broader scope of the OCSEAP. There are two other areas which the seismology panel deemed important which would require participation of other agencies or programs:

1. Micromorphology-Neotectonics of the Alaskan Active Margin. It is highly desirable to run tightly controlled narrow beam, multibeam scanning surveys over the shelf trench axis and seaward rise areas of the Aleutian Trench and Eastern Alaskan margins of the Pacific Ocean. The surveys should concentrate on obtaining data over regions with "seismic gaps" where large earthquakes/ground motion are predicted. Surveys should be run before and after major earthquakes to determine degree of ground motion and association with tsunamis, if any. Surveys should also be run in conjunction with tightly controlled OBS networks located over the trench wall, axis, and rise in order to determine the association between active ocean floor surface faulting and shallow seismicity. High resolution sub-bottom profiles, with precise navigation, should be run to determine the presence of incipient submarine sediment slide flows.

2. Seismology Communications Satellite. A single communications satellite in synchronous orbit could simultaneously recover seismic data not only from Alaskan OCSEAP unmanned seismograph stations but also from many other networks elsewhere in North America. Typically, seismological observations require many entry points as in the GOES system, as well as continuous high data rates not offered by the GOES DCP's. While costly, the

single satellite system would remove the line-of-sight restriction and other difficulties and lower costs of the present communication networks. Present satellite communication costs in the Alaskan OCSEAP are now exceeding $250K, and still more satellite links are needed in some areas.

APPENDIX III

ALASKAN OUTER CONTINENTAL SHELF SEISMOLOGY AND EARTHQUAKE ENGINEERING WORKSHOP

AGENDA

Dates: March 26 - March 29, 1979

Place: Main Conference Room - Sixth Floor - Room 620
NOAA Research Building 3
Marine Street at 30th Street
Boulder, Colorado

Monday March 26, 1979

<u>INTRODUCTION</u>

Rudolf Engelmann - NOAA/OCSEAP - Welcoming Remarks

Joseph Kravitz - NOAA/OCSEAP - Seismic Program Overview

Carl Kisslinger - UNIVERSITY OF COLORADO/CIRES - Objectives of Workshop

<u>OCSEAP CONTRACTOR REVIEW</u>

John C. Lahr* and Christopher D. Stephens - USGS

Earthquake Activity and Ground Shaking in and Along the Eastern Gulf of Alaska

Hans Pulpan* and Juergen Kienle - UNIVERSITY OF ALASKA

Seismic and Volcanic Risk Studies Western Gulf of Alaska

John N. Davies* and Klaus H. Jacob - LAMONT-DOHERTY GEOLOGICAL OBSERVATORY

A Seismotectonic Analysis of the Seismic and Volcanic Hazards in the Pribilof Islands - Eastern Aleutian Region of the Bering Sea

Niren N. Biswas - UNIVERSITY OF ALASKA

Evaluation of Earthquake Activity Around Norton and Kotzebue Sounds

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*Speaker

STATE-OF-THE-ART REVIEW

Robert A. Page - USGS

National Earthquake Hazards Reduction Program

Ashok A. Patwardhan - WOODWARD-CLYDE

Framework for Probabilistic Assessment of Seismic Exposure in Alaska

George Brogan - WOODWARD-CLYDE

Geology of Earthquake Hazards as Related to the Marine Environment in Alaska

Paul C. Jennings - CALIFORNIA INSTITUTE OF TECHNOLOGY

Earthquake Engineering Design Criteria for Offshore Structures

Alex Malahoff - NATIONAL OCEAN SURVEY/NOAA

NOAA's Geodynamic Motion Program

DISCUSSION

Tuesday March 27, 1979

Workshop Instructions - Divide workshop into groups based on discipline.

Working Session - Groups will work on developing specific recommendations and prepare draft of position paper.

Wednesday March 28, 1979

Plenary Session - Each group presents results of previous day's effort, followed by discussion.

Each group reconvenes to revise draft.

Revised drafts submitted to typists.

Thursday March 29, 1979

Review of final product, and general discussion.

APPENDIX IV

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