U.S. DEPARTMENT OF THE INTERIOR

U. S. GEOLOGICAL SURVEY

ANNOTATED BIBLIOGRAPHY: MARINE GEOLOGIC HAZARDS OF THE HAWAIIAN ISLANDS WITH SPECIAL FOCUS ON SUBMARINE SLIDES AND TURBIDITY CURRENTS

By

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Open-File Report 93-551C

Prepared in cooperation with the
U.S. Department of Energy

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This annotated bibliography has been compiled to highlight the submarine geology of the Hawaiian Islands and identify known and potential marine geologic hazards with special emphasis on turbidity currents, submarine slides and tsunamis. Work that is described only in published abstracts is not included because it is generally impossible to evaluate the applicability of the material in an abstract to the problem at hand. This report will not attempt to duplicate the work of Wright and Takahashi (1989) and Wright and others, who are producing an annotated Hawaii Bibliographic Database covering the period from 1779-1992 (written communication, 2 November 1992) that includes abstracts on all literature pertaining to the geology of Hawaii. Their works include the offshore area around the Hawaiian Islands and can be used to provide additional background. This report includes some references that are not specific to Hawaii but are needed to understand the geologic processes that can affect the integrity of submarine cables and other man-made structures.

Any references noted in the annotation texts will be found in this report but not necessarily within the same section. Those entries based on observations of turbidity-current flow, submarine mass failures, and tsunamis specific to the Hawaiian Island area are shown in bold type.

1. TURBIDITY-CURRENT PROCESSES

The references selected for this section relate to the initiation processes and flow characteristics of turbidity currents, especially with respect to the potential for destruction of man-made structures on the sea floor. Turbidity currents are density flows capable of transporting large volumes of clastic sediment to deep water. The higher density of these fluid flows, relative to sea water, is caused by suspended sediment, but turbidity currents can transport large volumes of sediment as bedload and are capable of causing significant erosion on slope gradients much less than those of the submarine flanks of the Hawaiian volcanoes.

Turbidity currents can be generated by submarine landslides, storm surge disturbance of sediment, slope instability resulting from earthquakes, and other oceanographic phenomena such as internal waves and deep water currents that can be expected in the Hawaiian Islands region. The resulting turbidity-current flow characteristics are affected by slope angle, sediment grain size, topographic control of flow paths, and the volume of sediment involved in the flow. Visual observation of turbidity currents of a physical scale (flow over tens to hundreds of kilometers) typical of oceanic island slopes has not been accomplished. Thus it is difficult to forecast the flow velocity, duration, and potential destructiveness of a turbidity current that might be generated in the Hawaiian offshore area using *only* data available from the area of interest. For this reason, we include references from continental margin areas because an understanding of the processes involved must be based on available model and laboratory-flume studies, serendipitous measurements of some flow parameters of small-scale turbidity currents in lakes and fjords, and derivation of flow properties for a few large-scale turbidite events inferred from studies of the sediment deposited and the morphologic constraints along the sediment flow path. For a limited number of examples, the destruction of submarine telecommunication cables and other manmade objects provides more direct data on current speeds.

Bagnold, R.A., 1962, Autosuspension of suspended sediment: Proceedings Royal Society London, Series. A, v. 265, p. 315-319.

Describes the concept of autosuspension, which refers to the transport of fine-grained sediment in turbulent flows. When the settling velocity of the grains in suspension is insufficient to allow them to settle out of the fully turbulent flow, the net result of the gravitational pull on the grains is to impart energy to the flow. The paper applies this concept to turbidity currents to explain both the high velocities deduced from cable-break studies and the long transport distances observed even in areas of low slope angles.

Bowen, A.J., Normark, W.R., and Piper, D.J.W., 1984, Modelling of turbidity currents on Navy submarine fan, California Continental Borderland: Sedimentology, v. 31, p. 169-185.

The flow characteristics of a late Holocene turbidity current are derived from knowledge of the total volume, areal distribution, and grain-size distribution of the sediment deposited, and from the morphological constraints of the turbidite channels and basin slopes. The analysis uses the standard equations commonly used for depth integrated flow of turbidity currents as summarized in Komar (1977). By considering the conservation of momentum and mass, the evolution of the flow is derived. This dominantly muddy turbidity current reached velocities of 0.75 ms^{-1} on low slopes (1:100) and the flow duration was between 2 and 9 days. An earlier turbidity current that transported coarser sediment reached velocities of 1.5 ms^{-1}. Both the slope angle and the volume of sediment involved are small compared to potential turbidity currents off the Hawaiian Ridge.

Chamberlain, T.K.. 1964, Mass transport of sediment in the heads of Scripps submarine canyon, California, *in* Miller, R.L., ed., Papers in marine geology, New York, Macmillan, p. 42-64.

This report documents 12 years of observation using echo-sounding and SCUBA-diving techniques that recorded periodic deepening of the tributary heads of Scripps submarine canyon. The catastrophic removal of sediment from the heads of the canyons could occur within a period of a few days. Although some episodes of sediment loss corresponded to earthquakes, there was no general correlation with earthquakes events or to any single type of initiation process. Local storms tended to result in sediment filling the canyon heads through the effect of rip currents, but mass sediment loss was observed after some storms. The report noted that decay of organic (plant) matter within the sediment accumulating in the canyon heads produced significant gas that tends to weaken the sediment column.

Clague, D.A., Moore, J.G., Torresan, Michael, and Lipman, Peter, 1988, Shipboard report for Hawaii GLORIA ground-truth cruise F2-88-HW, 25 Feb.-9 March, 1988: U.S. Geological Survey Open-File Report 88-292, 54 p.

This cruise data report includes descriptions of turbidite layers in cores from the Hawaiian deep as far as 50 km from the base of the volcanic slopes of Hawaii.

Dengler, A.T., Noda, E.K., Wilde, P., and Normark, W.R., 1984a, Slumping and related turbidity currents along proposed OTEC cold-water-pipe route resulting from Hurricane Iwa: Proceedings of 1984 Offshore Technology Conference, OTC 4702, p. 475-480.

Dengler, A.T., Wilde, Pat., Noda, E.K., and Normark, W.R., 1984b, Turbidity currents generated by Hurricane Iwa: Geo-Marine Letters, v. 4, p. 5-11.

These two papers present data documenting sediment transport and turbidity-current flow resulting from the passage of Hurricane Iwa between the islands of Oahu and Kauai on 23 November 1982. Self-contained current meters moored in water depths between 100 m and 760 m moved downslope as much as 2.4 km as a result of 4 discrete episodes of high-velocity flow. Measured velocities within the flow ranged from 0.3 to 2.2 ms^{-1} with the higher values from intermediate water depths. The speed of the front of one of the flow episodes reached 3 ms^{-1} between two of the moorings. Additional current-meter moorings in the array were never recovered, and telecommunication cables in the area downslope from the array (depths of 1000 to 2000 m) were damaged or buried with sediment. Timing of the flow episodes suggests that they were initiated by storm surge associated with wave heights of up to 9 m during the passage of the center of Hurricane Iwa.

Dengler, A.T., and Wilde, Pat., 1987, Turbidity currents on steep slopes: application of an avalanche-type numeric model for ocean thermal energy conversion design: Ocean Engineering, v. 14, p. 409-433.

This paper discusses the data from the Dengler et al. (1984a,b) using a two-dimensional avalanche model for the turbidity currents. This model is only applicable to slopes greater than 5°, which is typical of much of the Hawaiian Island submarine slopes. Tables and graphs of the relations between many turbidity-current parameters are presented in an appendix. The model is developed with assumptions that limit its usefulness for predictive purposes, and it does not cover initiation processes.

Dolan, J.F., Beck, Christian, Ogawa, Yujiro, and Klaus, Adam, 1990, Eocene-Oligocene sedimentation in the Tiburon Rise/ODP Leg 110 area; an example of significant upslope flow of distal turbidity currents: Proceedings of the Ocean Drilling Program, Scientific Results, v. 110, p. 47-83.

This paper is included in this report because it provides unequivocal documentation of upslope turbidity-current deposition at distances far from the initiation site (more than 1000 km). In this example from the Atlantic Ocean, turbidity currents deposited sediment as much as 800 m above the surrounding sea floor traversed by the currents. The turbidity currents were either capable of moving upslope or were thick enough to reach the observed height; in either case, the initial velocities implied are significant. [Current research by W. R. Normark on geophysical records from the Hawaiian EEZ that suggest similar sized turbidity currents may be common.]

Dziewonski, A., Wilkens, R., Firth J., et al., 1992, *Proc. ODP, Init. Repts.*, 136: College Station, TX (Ocean Drilling Program), 156 p.

The sediment cores obtained at Ocean Drilling Program (ODP) site 842 include volcanic "ash" layers that probably are deposits of large-scale turbidity currents derived from mass-wasting events on the slopes of Hawaii; the ash layers described (e.g., Fig. 2, p. 41) exhibit the classic sharp basal contact and fining-upward (graded) character typical of turbidite deposits. The site is about 300 km from the base of the slope of Hawaii and lies 370 m above the floor of the Hawaiian Deep suggesting that the turbidity currents were at least this thick at this distance from the volcano. An average sedimentation rate for the sediment recovered was determined from comparison of the magnetic polarity stratigraphy of the cores with the geomagnetic polarity time scale. This sedimentation rate indicates that the youngest volcanic ash layer may relate to the latest major debris avalanche.

Fukushima, Yusuke, Parker, Gary, and Pantin, H.M., 1985, Prediction of ignitive turbidity currents in Scripps submarine canyon: Marine Geology, v. 67, p. 55-81.

This paper applies the concept of *ignition*---the acceleration of turbidity currents through the entrainment of sediment from the sea floor---by using data from the well-known Scripps submarine canyon (see Inman et al., 1976). The paper presents numerical models that are then tested with the specific flow conditions measured in the Scripps canyon. The authors note that the best evidence for ignition from Inman's data is that the highest sustained velocities (1.9 ms^{-1}) occurred when the head of the canyon was filled with sand, which was then observed to be flushed out after the storm. They further note that Inman et al.'s (1976) data show that, during similar storm conditions when the canyon head is not filled with sediment, no sustained (ignitive) flow occurs because there is no "fuel."

Garcia, M.H., and Parker, Gary, 1989, Experiments on Hydraulic Jumps in Turbidity Currents Near a Canyon-Fan Transition: Science, v. 245, p. 393-396.

This paper uses flume experiments to model the effect of hydraulic jumps on the transport of sediment by subaqueous density currents. The decrease in slope as a current moves from the slope to the basin area is associated with a relatively abrupt increase in flow thickness and decrease in flow velocity. There is also a rapid decrease in bed-shear stress on the downstream side of the hydraulic jump and much of the sediment in the flow can move farther seaward before deposition. This experimental work provides support for observations of depositional patterns described for many modern and ancient turbidite systems with large flows.

Hallworth, M.A., Phillips, J.C., Huppert, H. E., and Sparks, R.S.J., 1993, Entrainment in turbulent gravity currents: Nature, v. 362, p. 829-831.

This paper presents the results of laboratory experiments to examine the evolution of turbidity-current flow properties for events generated by slumping. The results obtained have implications for cable routes in deeper water areas where turbidity currents move from the steep volcano slopes onto more gently sloping deep basinal areas. These laboratory results can be used to evaluate some of the theoretical flow models that are cited elsewhere in this section.

Hampton, M.A., 1972, The role of subaqueous debris flow in generating turbidity currents: Journal of Sedimentary Petrology, v. 42, p. 775-793.

This paper combines observations of the transition from landslide to debris flow in the subaerial environment with laboratory flume experiments to study the generation of turbidity currents from debris flows in a subaqueous setting. This work is one of the classic studies of the processes involved and suggested that turbidity currents can form by erosion of material from the head of the debris flow; the weaker the debris flow, the more material that could be mixed to form a turbidity current. The paper also suggests, but without experimental observations, that instability on the upper surface of the debris flow can lead to mixing with the overlying water and the formation of turbidity currents. Subsequent work has shown that the transition from submarine slides to turbidity currents is probably the most common initiation process for large turbidity currents, especially if noncohesive sandy sediment is readily available..

Hay, A.E., 1987a, Turbidity currents and submarine channel formation in Rupert Inlet, British Columbia; I. Surge observations: Journal of Geophysical Research, v. 92, p. 2875-2882.

Hay, A.E., 1987b, Turbidity currents and submarine channel formation in Rupert Inlet, British Columbia; II. The roles of continuous and surge type flow: Journal of Geophysical Research, v. 92, p. 2883-2900.

Hay, A.E., Burling, R.W., and Murray, J.W., 1982, Remote acoustic detection of a turbidity current surge: Science, v. 217, p. 833-835.

These three papers report direct acoustic detection of turbidity-current flow in a fjord environment. The Hay et al. (1982) paper is basically the discovery of the technique using acoustic backscatter mapping at several different frequencies. This technique provides determination of the longitudinal profile of the upper surface of the turbidity current together with an estimation of the changes in density within the body of the flow. The results suggest that for surge-type turbidity currents, as might be expected for currents generated through submarine slumps caused by earthquakes, equations for steady-state flow that are commonly used to determine velocity and related characteristics of density flows may not be strictly applicable.

Heezen, B.C., and Ewing, Maurice, 1952, Turbidity currents and submarine slumps, and the 1929 Grand Banks Earthquake: American Journal of Science, v. 250, p. 849-873.

This is the first paper to relate the disruption of submarine telecommunication cables to turbidity-current flow and to deduce the speed of the current. In addition, they concluded that the turbidity current following the 1929 Grand Banks earthquake on the Atlantic margin of Canada was generated by a submarine slump. Their analysis suggested speeds well in excess of 20 ms^{-1} although later authors, using the same cable-break sequence but possessing more recent knowledge of the flow path and area of initiation, suggested top speeds equal to or less than this value.

Heezen, B. C. and Hollister, C. D., 1971, The Face of the Deep: Oxford University Press, New York, 659 pp.

Chapter 8 in this book summarizes all of the submarine cable-break data available at the time to review what is known about the speeds, frequencies, and sediment transported by turbidity currents from a variety of settings.

Hine, A.C., Wilber, R.J., Bane, J.M., Neumann, A.C., and Lorenson, K.R., 1981, Offbank transport of carbonate sands along open, leeward bank margins: northern Bahamas: Marine Geology, v. 42, p. 327-348.

This paper documents that significant transport of carbonate-reef sediment occurs during storms and other "non-background" oceanic events. The importance of this observation is seen by comparing this study with the results of Tsutsui et al. (1987), who document the transport of sediment from the reef to deeper water off Oahu during Hurricane Iwa in 1982.

Hughes Clarke, J.E., Shor, A.N., Piper, D.J.W., and Mayer, L.A., 1990, Large-scale current-induced erosion and deposition in the path of the 1929 Grand Banks turbidity current: Sedimentology, v. 37, p. 613-629.

This paper presents the results of new studies on the turbidity current that was generated by the 1929 Grand Banks earthquake using multibeam echosounding and deep-towed side-looking sonar observations. Their analysis shows that the 1929 event was ignitive and resulted in substantial flushing of the sediment that was on the floor of the tributary channels and main valley floors prior to the earthquake. They demonstrate from the chord lengths of gravel waves on the main valley floor that the 1929 turbidity current accelerated over a distance of 100 to 200 km (for more details, see Piper et al., 1985, 1988, and Shor et al., 1990).

Inman, D.L., Nordstrom, C.E., and Flick, R.E., 1976, Currents in submarine canyons: An air-sea-land interaction: Annual Review of Fluid Mechanics, p. 275-310.

> This work extends the understanding of sediment loss from Scripps canyon heads (see Chamberlain, 1964) with direct measurement of downcanyon flow and accompanying sediment removal. The observations begun in 1964 include synoptic measurement of pressure and currents in the canyon and of wind, wave conditions, and tides on the adjacent shelf. Initial attempts to measure canyon currents invariably resulted in the loss of the instruments when velocities exceeded 1 ms^{-1} at water depths of 44 m. Later, instruments at 20 m depth successfully recorded sustained flow of 1.9 ms^{-1} for 2.5 hr for one of the episodes; in all episodes of sustained flow at 20 m depth in the canyon, the instruments at 44 m depth were lost. The authors show that the autosuspension criteria (Bagnold, 1962) are probably satisfied. The episodes of sustained downslope flow are associated with high waves and onshore winds during the passage of storm fronts that cause a complex interaction of water setup, longshore currents, vortex-induced downslope flow, and edge waves. Eventually, discrete down-canyon flow events become more intense and transport sediment downslope.

Kirwan, A.D., Jr., Doyle, L.J., Bowles, W.D., and Brooks, G.R., 1986, Time-dependent hydrodynamic models of turbidity currents analyzed with data from the Grand Banks and Orleansville events: Journal of Sedimentary Petrology, v. 56, p. 379-386.

> This paper reviews the theory of gravity-induced mass movement to develop two models of turbidity-current flow. The models are used to estimate both velocity and distance vs time for a turbidity current initiated in the area of the 1929 earthquake on the Grand Banks. Their results suggest that the turbidity current was generated lower on the continental slope than was assumed by Heezen and Ewing (1952), as later confirmed by Hughes Clarke et al. (1990).

Komar, P.D., 1969, The channelized flow of turbidity currents with application to Monterey deep-sea fan channel: Journal of Geophysical Research, v. 74, p. 4544-4558.

Komar, P.D., 1971, Hydraulic jumps in turbidity currents: Geological Society of America Bulletin, v. 82, p. 1477-1488.

Komar, P.D., 1975, Supercritical flow in turbidity currents: a discussion: Journal of Sedimentary Petrology, v. 45, p. 747-749.

Komar, P. D., 1977, Computer simulation of turbidity current flow and the study of deep-sea channels and fan sedimentation: in, The Sea: Ideas and Observations of Progress in the Study of the Sea, edited by Goldberg, E. D., Wiley, New York, p. 603-621.

Komar, P.D., 1986, Reply,'Breaks' in grain-size distributions and applications of the suspension criterion to turbidites: Sedimentology, v.33, p. 438-440.

> The five references above are selected to emphasize the long-term research activities related to turbidity-current flow as well as the broad approach taken by Komar. The earliest paper used channel morphologic characters and the autosuspension concept (Bagnold, 1962) to develop flow parameters for steady-state flow conditions. The subsequent papers (and others not included here) examine the importance of hydraulic jumps, interface frictional drag, and suspension criteria for sediment in the flow. Most workers attempting to develop turbidity-current flow models start with reference to these works.

Krause, D.C., White, W.C., Piper, D.J.W., and Heezen, B.C., 1970, Turbidity currents and cable breaks in the western New Britain Trench, Geological Society of America Bulletin, v. 81, p.2153-2160

> The paper reviews evidence from two episodes of disruption of submarine telecommunication cables durine the 1960s in the western Pacific Ocean. Similar to the earlier studies of the 1929 Grand Banks event, the authors suggest that the flows were induced by earthquakes and used the available data on timing of cable damage to deduce maximum velocities of as much as 8.5 and 14 ms^{-1} for the two events.

Lambert, A.M., Kelts, K.R., and Marshall, N.F., 1976, Measurement of density underflows from Walensee, Switzerland: Sedimentology, v. 23, p. 87-105.

This study provided one of the first sets of measurements of turbidity-current flow that included velocity, flow density, and suspended sediment load. Peak velocities for the observed hyperpycnal flow were only 0.3 ms^{-1}, but these were at 1.5 m above the lake floor (maximum velocity will occur just above the bed); sand-sized sediment was observed to be transported by and eroded by currents of these velocities. They also observed that flow velocities show marked oscillations in strength that were interpreted as evidence for supercritical flow.

Lowe, D.R., 1979, Sediment gravity flows: their classification and some problems of application to natural flows and deposits: Society of Economic Paleontologists and Mineralogists Special Publication No. 27, p.75-82.

Lowe, D.R., 1982, Sediment gravity flows II: depositional models with special reference to the deposits of high-density turbidity currents: Journal Sedimentary Petrology, v. 52, p. 279-297.

These two papers update the work of Hampton (1972) and others to distinguish between the types of gravity-driven sediment flows. The rheology and the mechanisms that maintain sediment in suspension are used to classify flow types and to review the evolution of flow from debris flows into turbidity currents. Although the paper focuses on characteristics of the deposits, it is a good review of the processes involved and thus would bear on the development of predictive flow models.

Luthi, Stefan, 1980, Some new aspects of two-dimensional turbidity currents: Sedimentology, v. 28, p. 97-105.

Certain conditions of turbidity-current flow are examined using a theoretical two-dimensional momentum model, which is then tested through flume experiments. The results support the concept of autosuspension as a special condition of a general momentum equation, which can be applied to conditions for hydraulic jumps in turbidity currents. The paper is useful in developing models for density-current flow.

Malinverno, A., Ryan, W.B.F., Auffret, G., and Pautot, G., 1988, Sonar images of the path of recent failure events on the continental margin off Nice, France: Geological Society of America Special Paper 229, p. 59-76.

Deep-towed side-looking sonar images document the effects of the passage of a turbidity current generated by a small submarine slump (not associated with an earthquake). The turbidity current transported sand- and boulder-sized sediment and created bedforms as high as 5 m. Where the flow path widened into an area of lower slope angle, conditions under which the current can go through a hydraulic jump, large-scale erosive scours up to 70 m deep are observed. Disruption of two telecommunication cables downslope from the scour area suggests that current velocities were still as high as 11 ms^{-1}. The significance for the Hawaiian Ridge area is that the size of the submarine slide and the slope angles along the transport path for this Nice example are both significantly smaller than observed features on the submarine flanks of Hawaiian volcanoes. Large-scale scours indicate high turbulence in currents that transport coarse sediment and are capable of major destruction.

Middleton, G. V., 1966a, Small scale models of turbidity currents and the criterion for auto-suspension: Journal Sedimentary Petrology, v. 36, p. 202-208.

Middleton, G. V., 1966b, Experiments on density and turbidity currents, I. Motion of the head: Canadian Journal of Earth Sciences, v. 3, p. 523-546.

Middleton, G. V., 1966c, Experiments on density and turbidity currents, II. Uniform flow of density currents. Canadian Journal of Earth Sciences, v. 3, p. 627-637.

Middleton, G. V., 1967, Experiments on density and turbidity currents, III. Deposition of sediment: Canadian Journal of Earth Sciences, v. 4, p. 475-505.

Middleton, G. V., and Hampton, M. A., 1973, Part I. Sediment gravity flows: mechanics of flow and deposition: *in* Middleton, G. V. and Bouma, A. H., eds. Society Economic Paleontologists and Mineralogists Pacific Section Short Course Notes, 38p.

This set of papers provides one of the best introductions to the theory of turbidity-current processes evaluated through the results of laboratory experiments; an explanation of the criteria for realistic scale models is very useful and is an area that is generally ignored in more recent papers on model experiments. The results presented in this series of papers should be used together with those of Komar (1969, 1971, 1975, 1977, 1986) if an attempt is made to develop predictive models for the Hawaiian area.

Middleton, G. V., 1992, Sediment deposition from turbidity currents: Annual Reviews of Earth and Planetary Sciences, v. 21, p. 89-114.

This review of turbidity current processes, although written at the same time as the review by Normark and Piper (1992), takes a quite different perspective. As such it makes a good starting point to understand turbidity currents because it gives the historical development of research in this subject including the significance of the early experimental work by Middleton (1966a,b,c; 1967). The paper clearly defines the terminology and basic hydraulic concepts before reviewing laboratory experimental studies. The paper finishes with discussion of some of the theoretical aspects, including autosuspension, and limitation of different model approaches.

Morgenstern, N.R.,1967, Submarine slumping and the initiation of turbidity currents, *in* Richards, A.F., ed., Marine geotechnique: Urbana, University of Illinois Press, p. 189-220.

This reference is included for historical perspective of the initiation of turbidity currents. It is a good introduction for understanding the role of consolidation state and strength of marine sediment in the initiation of submarine slumps.

Normark, W.R., 1989, Observed parameters for turbidity-current flow in channels, Reserve Fan, Lake Superior: Journal of Sedimentary Petrology, v. 59, p. 423-431.

Normark, W.R., and Dickson, F.H., 1976, Sublacustrine fan sedimentation in Lake Superior: American Association of Petroleum Geologists Bulletin, v. 60, p. 1021-1036.

These two papers document turbidity-current flow resulting from tailings discharge in a deep water lake. The 1976 paper showed that turbidity-current overflow across natural channel levees was at least 5 m thicker than the flow necessary to fill the channel, and flow episodes lasted for up to two weeks. This work suggested that, within the channel itself, turbidity currents were continuous as long as tailings discharge was occurring; this allowed an experiment to directly measure flow properties, including velocity, density, thickness, and vertical sediment distribution within the flow. This experiment confirmed the estimates of the drag coefficient, as estimated by Komar and others (see above references) for deep marine settings. The results further show that the flow properties as measured are consistent with the flume experiments of Parker and others (see below) and allows determination of layer-averaged velocity and volume concentration of sediment within turbidity-currents.

Normark, W.R., and Piper, D.J.W., 1991, Initiation processes and flow evolution of turbidity currents: Implications for the depositional record, *in* Osborne, R.H., ed., Shepard Memorial Volume, Society of Economic Paleontologists and Mineralogists Special Publication number 46, p. 207-230.

Normark, W.R., and Piper, D.J.W., 1992, Turbidity current processes, *in* Magoon, L.B., ed., The Petroleum System---Status of Research and Methods, 1992, U. S. Geological Survey Bulletin 2007, p. 22-31.

These papers provide a literature review of turbidity-current research during the last 25 years together with a synthesis of current ideas on flow initiation and changes in flow characters moving from slope to basin area. The 1992 paper is basically an outline to the initial paper and the references are divided topically. Because of the additional focus on deposit characters resulting from turbidity currents in different environments, these two papers provide many references not included in this report. Among several initiation processes discussed, the 1991 paper considers both storm-generated and slump-generated currents including the Hawaiian examples of Dengler and others (above). The growing evidence for large-scale erosion by turbidity currents is emphasized as is the difference in flow characters reflecting both grain size of the sediment transported and the initiation processes.

Parker, Gary, 1982, Conditions for the ignition of catastrophically erosive turbidity currents: Marine Geology, v. 46, p. 307-327.

The paper explains the conditions for ignition, i.e., for a self-sustaining flow, in which the autosuspension criteria (Bagnold, 1962) are met but insufficient to define the flow state. The key point of this work is that ignition involves entrainment of erodible sediment on the sea floor along the path of the turbidity current and does not require large-scale submarine mass failure. This provides an alternate process to generate highly destructive flow, especially if ignitive conditions prevail on steep slopes such as those of the submarine flanks of the Hawaiian Islands.

Parker, Gary, Fukushima, Y., and Pantin, H.M., 1986, Self-accelerating turbidity currents: Journal of Fluid Mechanics, v. 171, p. 145-181.

This paper provides a full mathematical model for describing the conditions for self-sustaining turbidity currents as described by Parker (1982). The ideas presented would be very useful to evaluate conditions for ignitive flow occurring on the flanks of the Hawaiian Islands.

Parker, Gary, Garcia, M., Fukushima, Y., and Yu, W., 1987, Experiments on turbidity currents over an erodible bed: Journal of Hydraulic Research, v. 25, p. 123-147.

This paper presents the results of flume experiments to examine the turbidity-current flow conditions for erosion and deposition of sediment. The measurements of vertical profiles of velocity and sediment concentration fit quite well with limited observations of turbidity currents in lakes, e.g., Normark (1989). The results of this experimental work can be used to help guide the application of the mathematical models given in Parker et al. (1986).

Pickering, K.T., Underwood, M.B., and Taira, Asahiko, 1992, Open-ocean to trench turbidity-current flow in the Nankai Trough: Flow collapse and reflection: Geology, v. 20, p. 1099-1102.

This paper uses core samples from a deep ocean turbidite environment to document that turbidity currents can be reflected off major bathymetric relief. The paper's focus is to indicate potential problems for interpretation of turbidity-current transport paths in ancient turbidite sequences, but the significance for the Hawaiian area is that destructive turbidity currents can be deflected/reflected off the Hawaiian arch back toward the island ridge and *cause damage to submarine cables from sources not directly upslope from the cables.*

Piper, D.J.W., and Aksu, A.E., 1987, The source and origin of the 1929 Grand Banks turbidity current inferred from sediment budgets: Geo-Marine Letters, v. 7, p. 177-182.

Piper, D.J.W., Shor, A.N., and Hughes Clarke, J.E., 1988, The 1929 Grand Banks earthquake, slump and turbidity current: Geological Society of America Special Paper 229, p. 77-92.

Piper, D.J.W., Shor, A.N., Farre, J.A., O'Connell, Suzanne, and Jacobi, Robert, 1985, Sediment slides and turbidity currents on the Laurentian Fan: Sidescan sonar investigations near the epicenter of the 1929 Grand Banks earthquake: Geology, v. 13, p. 538-541.

Shor, A.N., Piper, D.J.W. , Hughes Clarke, J., and Mayer, L.A., 1990, Giant flute-like scour and other erosional features formed by the 1929 Grand Banks turbidity current: Sedimentology, v. 37, p. 631-645.

These four papers present new data concerning the source area, initiation process and erosional and depositional features related to the 1929 Grand Banks turbidity current. The Piper, Shor, and Hughes Clarke (1988) reference provides a complete overview of the event and is based on the data in the other two references and other cited works they have co-authored. These works document one of the best examples of ignitive conditions for a turbidity current that resulted from an earthquake. The 1929 flow was highly erosive and about 300 m thick as observed from the scouring of the walls of the Laurentian fan channels. Extensive fields of sediment waves formed of gravel (granule to cobble size) extend for more that 50 km along the path of the turbidity current. The Shor et al. (1990) reference is included here to emphasize the importance of scouring caused by this turbidity current; isolated depressions along the channel path are several tens of meters deep and one scour that is over a kilometer long reaches a depth of 100 m. Their work has also discovered segments of one of the telecommunication cables that was broken during the 1929 event. The turbidity current was not initiated by failure of a huge section of the upper continental slope as suggested by previous workers but rather from multiple failure of the surficial sediments on the slope around the epicenter of the earthquake.

Piper, D.J.W., and Normark, W.R., 1983, Turbidite depositional patterns and flow characteristics, Navy Submarine Fan, California Borderland: Sedimentology, v. 30, p. 681-694.

The primary aim of this paper is to document the different behavior of turbidity currents that follow the same path and deposit in the same basin but transport different amounts of coarser sediment in suspension. Thicker, mixed-sediment currents tend to overtop channel margins; the authors introduce the term *flow stripping*, which occurs when the lower part of turbidity current can be stopped by a topographic barrier while the upper part of the flow (where the flow thickness exceeds barrier height) can keep advancing in the original flow direction. The paper also documents the effect of the Coriolis force in deflecting turbidity current flow against a basin slope resulting in a pronounced upward tilt of the top of the current against the slope. For the Hawaiian Ridge area, for example, a turbidity current flowing down the western side of the volcanoes would be deflected to the right and begin to flow parallel to the ridge, perhaps even tilting up against the base of the Ridge for the larger, long-distance flows.

Prior, D.B., Bornhold, B.D., and Johns, M.W., 1986, Active sand transport along a fjord-bottom channel, Bute Inlet, British Columbia: Geology, v. 14, p. 581-584.

Prior, D.B., Bornhold, B.D., Wiseman, W.R.,Jr., and Lowe, D.R., 1987, Turbidity current activity in a British Columbia fjord: Science, v. 237, p.1330-1333.

The Prior et al. (1986) paper presents detailed observations on the channel system and evidence for sand deposition in a deep (>600 m) fjord fed by two rivers. Sandy lobe deposits with evidence for current scours up to 50 m across indicate sand is transported at least 50 km along the fjord. The second paper reviews the monitoring of turbidity currents along a 26 km section of the channel system for a yearlong period beginning in 1985. The velocity of flow between current meter moorings during one episode exceeded 3.3 ms^{-1} over a gradient less than 1^{o} and exceeded 1 ms^{-1} at 32 m above the channel floor at the upstream meter. Sediment trap records showed sand in suspension in the flow at 6 to 7 m above the fjord floor. On three occasions, entire moorings were displaced by the flows and damaged instruments thus indicating even higher velocities. The larger events probably experienced flow stripping and spread across the entire fjord floor. Slumping of the delta sediments is suspect for most flow events, but one turbidity current was caused by high discharge during river flooding.

Reimnitz, Erk, 1971, Surf-beat origin for pulsating bottom currents in the Rio Balsas submarine canyon, Mexico: Geological Society America Bulletin, v. 82, p. 81-90.

This work records observations made by SCUBA divers in the head of a steep-floored (26^{o}) submarine canyon. Downslope current pulses with velocities of about 1ms^{-1} transported suspended sand in flows at least 3 m thick. The downslope pulses were associated with fluctuating longshore current speeds that were up to 2 ms^{-1}. These observations support the more quantitative study by Inman et al. (1976).

Reynolds, Suzanne, 1987, A recent turbidity current event, Hueneme Fan, California: reconstruction of flow properties: Sedimentology, v. 34, p. 129-137.

The flow properties of a turbidity current are reconstructed from knowledge of the volume and particle characteristics of the resulting deposit. The relatively fine-grained deposit (sandy silt) is inferred to have been deposited during a flow of up to 10 days duration with flow speeds of 0,1 to 0.9 ms^{-1}. This paper is one of several included in the bibliography (e.g., Bowen et al., 1984) that provide methods to determine flow properties of turbidity currents; applicable techniques will depend on the amount and type of information about the deposit. There are numerous documented turbidite deposits adjacent to the southeastern Hawaiian Islands whose physical characters are still under study; in the future, it may be possible to determine flow properties of currents generated on the Hawaiian submarine volcanic slopes.

Shepard, F.P., and Marshall, N.F., 1973, Storm-generated current in La Jolla Submarine Canyon, California: Marine Geology, v. 15, p. M19-M24.

Shepard, F.P., McLoughlin, P.A., Marshall, N.F., and Sullivan, G.G., 1977, Current-meter recordings of low speed turbidity currents: Geology, v. 5, p. 297-301.

Shepard, F.P., Marshall, N.F., McLoughlin, P.A., and Sullivan, G.G., 1979, Currents in Submarine Canyons and Other Seavalleys: AAPG Studies in Geology No. 8, American Association of Petroleum Geologists, Tulsa, Okla., 173pp.

The first two papers are examples of studies by these authors on low speed, oscillatory currents in submarine canyons; the 1979 book of Shepard et al. provides a fairly exhaustive review of a decade of measurements made in 25 different submarine canyons and related channels from around the world. These low speed (generally less than 0.5 ms^{-1}) flows are observed to move sediment within the canyons and are typically related to tidal oscillation and internal waves. **On pages 147 to 158 of the 1979 book, the authors review the results of their measurements off Kauai and Niihau, their only measurements from the Hawaiian area.** Their discussion also includes three areas where low-speed turbidity currents (0.7 to 1.0 ms^{-1}) were observed; they argue that such low speed currents are common and result in substantial movement of sand to deeper water over time.

Siegenthaler, C., and Buhler, J., 1985, The kinematics of turbulent suspension currents (turbidity currents) on inclined boundaries: Marine Geology, v. 64, p. 19-40.

This paper involves a fairly rigorous numerical evaluation of turbidity-current hydraulics, in which the authors look at the conditions for an "equilibrium state" of flow and define a dimensionless product termed the *sedimentation number*, which is proportional to the rate at which buoyancy is lost by the flow. Some experimental work is also presented to determine the value of the sedimentation number. It is not easy to relate this approach to the other modeling studies discussed in this section.

Stacey, M.W., and Bowen, A.J., 1988a, The vertical structure of density and turbidity currents: Theory and observation: Journal of Geophysical Research, v. 93, p. 3528-3542.

Stacey, M.W., and Bowen, A.J., 1988b, The vertical structure of turbidity currents and a necessary condition for self-maintenance: Journal of Geophysical Research, v. 93, p. 3543-3553.

Stacey, M.W., and Bowen, A.J., 1990, A comparison of an autosuspension criterion to field observations of five turbidity currents: Sedimentology, v. 37, p.1-5.

The first paper in this set develops a numerical model that is used to evaluate the application of the Richardson number (and other hydraulic parameters) in laboratory small-scale models and in natural flows. The next paper models the effect of suspended sediment, which can have a strong vertical gradient with the turbidity current, on the hydraulic properties of the flow. This work also provides a new expression for the autosuspension criteria that were originally defined by Bagnold (1962) by attempting to account for the vertical structure within the flow. The last paper then applies their new autosuspension criteria to the field observations of five naturally occurring turbidity currents (see Dengler et al., 1984a,b; Hay et al., 1982; Inman et al., 1976; Reimnitz, 1971; and the many versions of the 1929 event). Even though the numerical model is strictly for currents with only one size of suspended grains, the results of this application suggest that their redefined autosuspension criteria best fit available data. **The results presented in these papers should be used to model flows in the Hawaiian area, especially because they included the Oahu example in the test.**

Tsutsui, B.O., Campbell, J.F., and Coulbourn, W.T., 1987, Storm-generated, episodic sediment movements off Kahe Point, Oahu, Hawaii: Marine Geology, v. 76, p. 281-299.

This work is based on sidescan-sonar mapping and sediment-core data augmented by bottom photographs and observations from manned submersible to evaluate the effects of Hurricane Iwa on sediment movement in the area where current-meter arrays where displaced and damaged (see Dengler et al., 1984a,b). The sidescan mosaic shows a clear pattern of high acoustic-backscatter bands and braiding patterns that coalesce downslope just above the damaged telecommunication cables. The high backscatter bands are coarse deposits washed from the shallow shelf (reef) area during the storm-surge generated currents. The pattern of sediment dispersal is consistent with the disruption sustained to the current-meter array.

Van Tassell, Jay, 1981, Silver Abyssal Plain carbonate turbidite: Flow characteristics: Journal of Geology, v. 89, p. 317-333.

This work documents the composition and distribution of sediment structures within a very large carbonate turbidite deposit. The calculated current velocity was about 3 ms^{-1} where the current passed onto a nearly flat basin floor over which it continued to flow more than a 100 km. The nature of this flow may be similar to flows of carbonate sediment from the shallow submarine flanks of the Hawaiian volcanoes.

Van Tassell, Jay, 1986, Discussion: The hydraulic interpretation of turbidites from their grain sizes and sedimentary structures: Sedimentology, v. 33, p. 437-440.

This paper raises several questions with regard to the work of Komar (see above); the entries under Komar include the response to this discussion. The paper is included here to indicate some concerns about our ability to use physical data from a turbidite deposit to determine hydraulic parameters of the turbidity current that deposited it.

Weirich, F.H., 1984, Turbidity currents: monitoring their occurrence and movement with a three-dimensional sensor network: Science, v. 224, p. 384-387.

This work provides a unique look at turbidity-current flow through a three-dimensional array of optical and thermal sensors. The observations are used to distinguish between continuous flow and surge-type turbidity currents.

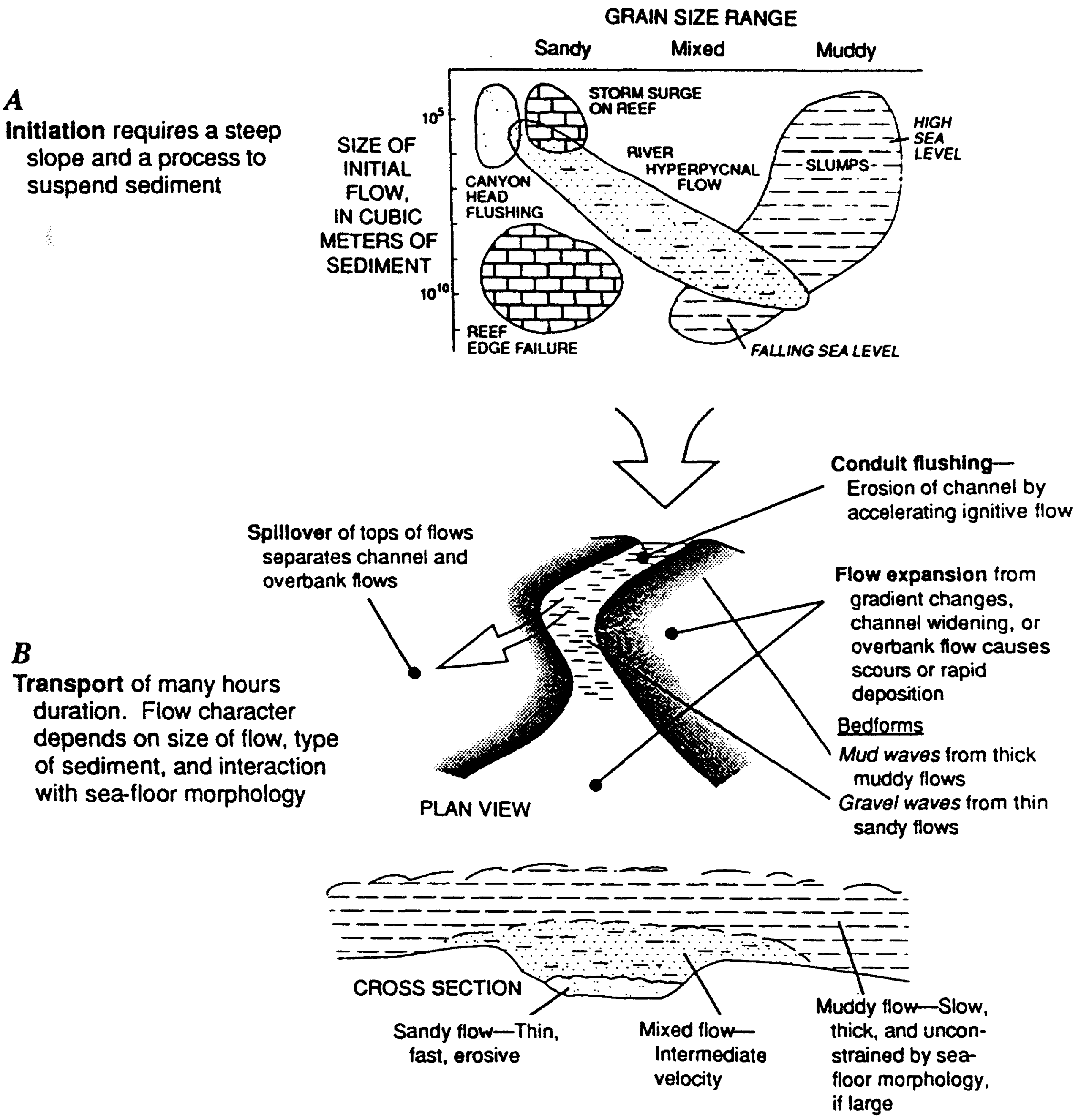
Weirich, F.H., 1988, Field evidence for hydraulic jumps in subaqueous sediment gravity flows: Nature, v. 332, p. 626-629.

The work presents a clear demonstration of both the change in flow thickness and in the rate of deposition related to a hydraulic jump in a subaqueous flow. The study allowed observation of subaerial debris flows moving into a fresh-water reservoir; both flows continued along an existing channel on the floor of the reservoir and underwent the flow transformation at the same point in the channel system. Draining of the reservoir half a year later allowed direct and simple measurement of the changes in flow parameters. This work confirms some of the suggested flow behavior for deep-water turbidity currents and can be used to provide further constraints for predictive models of flow evolution.

Zeng, Jianjun, Lowe, D.R., Prior, D.B., Wiseman, W.J., and Bornhold, B.D., 1991, Flow properties of turbidity currents in Bute Inlet, British Columbia: Sedimentology, v. 38, p. 975-996.

This study is a follow-on to the papers by Prior et al. (1986,1987) and provides an important tie between the direct measurement of recent flows (1986) and the deduction of flow properties using the depositional record of the recent past. For example, the maximum flow velocity observed was about 3.35 ms^{-1}, but estimates of maximum flow velocity using channel morphology and the grain size of sediment deposited are in the 4 to 5 ms^{-1} range. Their analyses draw on the work of Bowen, Komar, and Normark presented earlier in this section.

The figure below schematically presents the principal factors controlling initiation and transport processes of turbidity currents.



A
Initiation requires a steep slope and a process to suspend sediment

B
Transport of many hours duration. Flow character depends on size of flow, type of sediment, and interaction with sea-floor morphology

2. SUBMARINE SLIDES

As emphasized in the previous section,turbidity currents are commonly generated by submarine landslides. The Hawaiian area includes some of the largest submarine-slide deposits documented on Earth, and thus the sea floor around the volcanoes probably experienced major turbidity currents capable of traveling several hundred kilometers. The volcanoes of the Hawaiian Ridge are associated with three types of mass movement (the general term 'mass failure' is also commonly used to describe gravitationally driven movement of sediment and rock in the form of slides, slumps, and debris flows; definitions of these terms are given in a number of the included references). The largest mass failures (by aerial extent) are the result of catastrophic failure of flanks of volcanoes that are still growing. These are referred to as *debris avalanches* following similar terminology for subaerial landslides. The resulting deposits can cover 10,000 km^2 and extend as much as 200 km from the volcano that collapsed. Large submarine *slumps* are commonly half the dimensions of the largest debris avalanches; these features also involve the entire flank of a volcano but are expressed as large (tens of kilometers across) blocks that have glided and rotated away from the volcano. The third type of mass failure are those involving sediment that has accumulated on the volcano flanks.

This section includes papers on examples of the volcanic slides (as defined above) from Hawaii and other oceanic islands as well as papers describing mass failures along continental margins. The latter are included because they are much better known and provide insights on the mechanisms of mass wasting and on determining the potential for future failures.

Alpha, T.R., Morely, J.M., Gutmacher, C.E., and Austin, W.A., 1982, Oblique map of the Loihi Seamount and Papa'u Landslide, Hawaii: U.S. Geological Survey Open-File Report 82-0463.

This map shows two types of landslides off the Island of Hawaii. The very steep slopes off the flanks of Loihi Seamount are examples of the effect of debris avalanches; even though this seamount is relatively young and small (compared to the volcanoes that comprise the adjacent island), several large-scale mass failures have already occurred. The Papa'u feature is a large sediment mass that has failed (Moore et al., 1989).

Booth, J.S., Sangrey, D.A., and Fugate, J.K., 1985, A nomogram for interpreting slope stability of fine-grained deposits in modern and ancient marine environments: Journal of Sedimentary Petrology, v. 55, p. 29-36.

This work attempts to provide a general model for slope stability for quantitatively evaluating the potential for mass movement and to review the factors involved that determine the stability of a sediment mass. The assumptions behind the nomogram appear to apply to the sediments on the Hawaiian Ridge volcanic slopes, e.g., a relatively constant rate of sediment accumulation, a base that is impermeable, and that generation of gas or formation of cement within the sediment is basically nonexistent.

Bugge, Tom; Befring, Stein; Belderson, R.H.; Eidvin, Tor; Jansen, Eystein; Kenyon, N.H.; Holtedahl, Hans, and Sejrup, H.P., 1987, A giant three-stage submarine slide off Norway: Geo-Marine Letters, v. 7, p. 191-198.

Bugge, Tom, Belderson, R.H., and Kenyon, N.H., 1988, The Storegga Slide: Philosophical Transactions of the Royal Society of London, A325, p. 357-388.

These two works provide a comprehensive description of one of the largest and best understood submarine slides recognized to date on Earth. The volume of sediment involved in this slide is even larger than the Hawaiian Ridge failures (see Moore et al., 1989, 1992). A key finding of these studies is that the massive slide deposits represent multiple failures that are recognized on the basis of seismic-reflection profiles, sidescan sonar images, and sediment-core data. Understanding the initiation and transport processes in large continental margin slides such as this one will help in understanding the landslide mechanisms (and the generation of tsunamis) on Hawaii; because the Hawaiian debris avalanches involve volcanic rock, it is difficult to determine the internal structure of the deposits as can be done for continental margin slides composed of sedimentary masses. See also Jansen et al. (1987).

Cochonat, Pierre; Lenat, J.-F.; Bachelery, Patrick; Boivin, Pierre; Cornaglia, Bruno; Deniel, Catherine; Labuzuy, Philippe; Le Drezen, Eliane; Lipman, P.W.; Ollier, Gilles; Savoye, Bruno; Vincent, Pierre, and Voisset, Michel, 1990, Gravity events as a primary process in the construction of a submarine volcano-sedimentary system (Fournaise Volcano, Reunion Island): Comptes Rendus de l'Academie des Science de Paris, v. 311, p. 679-686.

This paper reviews deep-tow sidescan sonar images of a debris avalanche on the flank of an active mid-oceanic volcano. Photographs and samples show that the blocks in the deposit (which are typically 50 to 100 m across) are from the subaerial part of the volcano. This work provides one of the best comparisons with the debris avalanches off Hawaii, and the higher resolution data from the deep-tow sidescan of this Reunion Island example provide more detail than exists for most Hawaiian examples (compare with Lipman et al., 1988; Moore et al., 1989). The authors suggest that fluidized flow may be responsible for transporting the large blocks into deeper water.

Crandell, D.R.; Miller, C.D.; Glicken, H.X.; Christiansen, R.L., and Newhall, C.G., 1984, Catastrophic debris avalanche from ancestral Mount Shasta volcano, California: Geology, v. 12, p. 143-146.

The debris avalanche that extends from the northwest flank of the Mount Shasta volcano is one of the best subaerial analogs to the huge submarine avalanches off the Hawaiian volcanoes. The relatively young age of this deposit (between 300,000 and 360,000 years) allows determination of the extent and volume of material involved. The avalanche traveled more that 40 km from the base of the volcano on very low slopes (1:200). The authors observe that, although debris avalanches may be "anticipated" from active volcanoes, their volume and extent probably can't. The speculations concerning the mechanism of movement are useful in understanding the deep-water Hawaiian examples.

Delaney, P.T., 1992, Volcanoes; you can pile it only so high: Nature, v. 357, p. 194-196.

This work reexamines the mechanism of failure of Hawaiian volcanoes by comparison with recent work on Mt. Etna. It is suggested that the volcano fails because of the weight of the edifice, which is resting on unconsolidated sediment on the sea floor and causing the base of the volcano to spread laterally by thrusting over the sea floor. This is fundamentally different from the more classic slump model in which the side of the edifice breaks away and glides across the sea floor; it has been suggested that the cause of slumping and sliding in Hawaiian volcanoes is the pressure associated with the injection of magma along the rift zones pushing the side of the volcano outward (Lipman et al., 1985).

Embley, R.W., 1976, New evidence for occurrence of debris flow deposits in the deep sea: Geology, v. 4, p. 371-374.

This work provided one of the first concise descriptions of debris flow deposits on the deep-sea floor and the relation of the deposit to the submarine slide from which it formed. Because of the details provided from 3.5-kHz reflection profiles, core samples and bottom photographs, this was a landmark study for our understanding of the potential for large-scale debris flows (the example described in this paper from the Spanish Sahara margin covers 30,000 km^2). The area of the submarine slide scar is just more than half that of the deposit, which involves 600 km^3---similar in size to many of the failures off Hawaii.

Embley, R.W., and Jacobi, R.D., 1977, Distribution and morphology of large submarine sediment slides and slumps on Atlantic continental margins: Marine Geotechnology, v. 2, Marine Slope Stability Volume, p.205-228.

This paper is a standard reference for the character and widespread occurrence of large-scale mass failures. The authors compare the size and morphologic features of 12 submarine slides and slumps; together with the Moore (1977) reference, it provides a good overview of submarine slides.

Fairbridge, R.W., 1950, Landslide patterns on oceanic volcanoes and atolls: Geographical Journal, v. 115, p. 84-88.

This early work recognized that landslide failure of the slopes of oceanic volcanoes might be a common occurrence and even suggested that volcanoes change from circular (=youthful) forms to a mature form with concave indentations. The observations include both islands, where the concave slide areas are fairly obvious, to the scalloped shape of the reef-fringed atolls.

Hine, A.C., Locker, S.D., Tedesco, L.P., Mullins, H.T., Hallock, Pamela, Belknap, D.F., Gonzales, J.L., Neumann, A.C., and Snyder, S.W., 1992, Megabreccia shedding from modern, low-relief carbonate platforms, Nicaraguan Rise: Geological Society of America Bulletin, v. 104, p. 928-943.

This work characterizes mass-wasted deposits from a carbonate-bank environment using high-quality seismic-reflection profiles and provides an example that may be more analogous to failures of reefs and drowned reefs with accumulated pelagic sediment on the slopes of the Hawaiian Islands. This work defines the character of megabreccias that result from bank-margin collapse and slope failure and the associated debris flows. The authors suggest that earthquakes are the most likely triggering mechanism for these mass-wasting events. Most models for sediment failure are based on terrigenous sediment accumulations of continental slopes; attempts to model failures from Hawaii should take into account the differences attributed to this carbonate source.

Holcomb, R.T., and Searle, R.C., 1991, Large landslides from oceanic volcanoes: Marine Geotechnology, v. 10, p. 19-32.

This work shows that the numerous submarine slides that have been mapped in the Hawaiian Ridge area using the GLORIA sidescan sonar system (Moore et al., 1989, 1992) are common features of many other oceanic volcanoes and volcanic islands. The paper emphasizes that these landslides are an integral part of the growth processes of oceanic volcanoes; by the end of active growth, the major part of the volcanic edifice can be the debris from repeated failures during growth. Individual failures can remove as much as half of the subaerial part of a volcano and 10 to 20% of the total edifice. The paper also notes a possible historical record for the kind of catastrophic tsunamis that result from such failures as documented in the geologic record by Moore and Moore (1984, 1988).

Jansen, Eystein; Befring, Stein; Bugge, Tom; Eidvin, Tor; Holtedahl, Hans; and Sejrup, H.P., 1987, Large submarine slides on the Norwegian continental margin: Sediments, transport and timing: Marine Geology, v. 78, p. 77-107.

This work is a companion paper to the two Bugge et al. references (1987, 1988). The focus of this paper is on the sediment samples that were obtained to define the nature of the margin sediment that failed, the character of the slide deposits and to obtain radiocarbon ages to determine the timings of the multiple failure events.

Karlsrud, K., and Edgers, E., 1982, Some aspects of submarine slope instability, *in* Saxov, Svend, and Nieuwenhuis, J.K., eds., Marine slides and other mass movements: New York, Plenum Press, p. 61-81.

This chapter provides some technical discussion of the effect of earthquakes on the stability of marine sediments. Because historical earthquakes as large as magnitude 8 have occurred in the Hawaiian region, some areas of sediment accumulation may be prone to failure.

Keefer, D.A., 1984, Landslides caused by earthquakes: Geological Society of America Bulletin, v. 95, p. 406-421.

This work is included in the bibliography because it examines the relation between landslides and the earthquakes that cause them. Even though the data are for subaerial mass-wasting events, it provides insight to the types of failures that result from earthquakes and a relation between the size of the slide deposit and the magnitude of the associated earthquake. This review of 40 historical earthquakes also includes two events from Hawaii.

Kenyon, N.H., 1987, Mass-wasting features on the continental slope of northwest Europe: Marine Geology, v. 74, p. 57-77.

This work provides an overview of the nature of mass wasting along a large segment of the eastern North Atlantic continental margin and shows that submarine slides are common and range from less than 1 km^3 to the Storegga slide, which is greater than 5500 km^3. Factors such as slope angle and sedimentation rate are examined to understand the processes involved. This paper provides an update to the earlier summaries of our knowledge of submarine slides that might be useful if predictive models are to be developed to estimate probabilities for mass-wasting events off Hawaii.

Lee, H.J., 1989, Undersea landslides: extent and significance in the Pacific Ocean: *in* E.E. Brabb and B.L. Harrod eds. Landslides: Extent and Economic Significance, Proceedings of the 28th International Geological Congress: Symposium on Landslides, Balkema, Rotterdam, p. 367-379.

This review provides a direct comparison of submarine slides from fjords, continental margins, and the Hawaiian Islands. The techniques used to map these mass-wasted deposits are described so that the effect of resolution of features can be understood in discussing the mechanism of failure and transport. This paper draws insights from many of the older papers included in this bibliography; it is one of the best updates to the summaries by Moore (1961, 1977) and Kenyon (1987), which are specific to the Atlantic Ocean.

Lee, H.J., and Edwards, B.E., 1986, Regional method to assess offshore slope stability: Journal of Geotechnical Engineering, ASCE, v. 112, p. 489-509.

This paper suggests a relatively simple methodology to provide a quantitative assessment of the stability of sediment within a region. The method is based on the engineering behavior of failed and unfailed sediment obtained from gravity cores. Then the two process parameters of storm-wave height and earthquake-acceleration factor that can lead to failure are derived from normalized shear strengths, unit weights, slope angles, and water depths. Comparison of failed and unfailed areas can be used to assess the relative stability of the unfailed areas. The methodology is applied to four sites off California and Alaska. The paper also provides some description of the laboratory procedures.

Lipman, P.W., Lockwood, J.P., Okamura, R.T., Swanson, D.A. and Yamashita, K.M., 1985, Ground deformation associated with the 1975 magnitude-7.2 earthquake and resulting changes in activity of Kilauea volcano, Hawaii: U. S. Geological Survey Professional Paper 1276, 45 p.

This paper reviews the deformation of the subaerial part of the south flank of the Kilauea volcano associated with the 1975 earthquake. The southern flank of the volcano subsided as much as 3.5 m and moved seaward as much as 8 m near the epicenter. The depth of the earthquake showed the movement occurs at the base of the volcano and that it reflects gravitational slumping driven in part by the injection of magma in the rift zones of the volcano (see Delaney, 1992, for an alternative explanation).

Lipman, P.W., Normark, W.R., Moore, J.G., Wilson, J.B., and Gutmacher, C.E., 1988, The giant submarine Alika debris slide, Mauna Loa, Hawaii: Journal of Geophysical Research, v. 93, p. 4279-4299.

This paper reviews the largest of the young debris avalanche deposits and landslides on the western flank of the Mauna Loa volcano. The deposit is estimated to be no older than about 100,000 yrs, and, because its blocky relief is not smoothed by later sedimentation, it is the best example of this type of mass failure in the Hawaiian area. Most of the western flank of the

volcano was involved in the failure (thus the maximum collapse height is a minimum of 5 km), and later lava flows from the summit and southwest rift zone have buried the breakaway fault scarps except at the north and south edges. The authors compare the scalar properties of Alika slide with submarine and subaerial, volcanic and nonvolcanic landslides as a tool to evaluate the mechanisms of failure.

Moore, D.G., 1961, Submarine slumps: Journal of Sedimentary Petrology, v. 31, p. 343-357.
Moore, D.G., 1977, Submarine slides, *in* B. Voight Developments in Geotechnical Engineering, 14A, ed., Rockslides and Avalanches, v.1 Natural Phenomena, p. 563-604.

These review articles provide background on the development of the terminology for submarine mass failures; the 1977 work provides a good overview (with many examples from seismic-reflection profiles and a fairly extensive bibliography) of the types and common occurrence of slides in a variety of oceanic settings.

Moore, J.G., 1964, Giant submarine landslides on the Hawaiian Ridge: U.S. Geological Survey Professional Paper 501-D, D95-D98.

This is a landmark paper recognizing large-scale mass-failure deposits that affect the flanks of Hawaiian volcanoes. Although the evidence presented is basically only generalized bathymetry, two major slides were identified whose existence was confirmed some 25 years later with the GLORIA long-range sidescan-sonar surveys (Moore et al., 1989; 1992). Several rebuttals to this paper were written by the mid 1970's, but these are not included in this literature review because of the later confirmation of the slides's existence.

Moore, J.G., Normark, W.R., and Gutmacher, C.E., 1992, Major landslides on the submarine flanks of Mauna Loa volcano: Landslide News, no. 6, p. 13-16.
Moore, J.G., Clague, D.A., Holcomb, R.T., Lipman, P.W., Normark, W.R., and Torresan, M.E., 1989, Prodigious submarine landslides on the Hawaiian Ridge: Journal of Geophysical Research, v.94, p. 17,465-17,484.

These two papers review the evidence for large-scale slides (debris avalanches) and slumps involving volcanoes of the Hawaiian Ridge. The 1989 paper provides scalar data on 17 failures that were recognized from the GLORIA sidescan sonar images available at that time and discusses the style or mechanism of failure. It also is observed that slope areas with multiple submarine canyons tend to denote older slide scar areas. The 1989 work also notes that large-scale failures may occur about every 100,000 yrs and that the Alika slide could be responsible for the 325 m high tsunami wave that washed over the island of Lanai (Moore and Moore, 1984). The 1992 paper notes that, when the GLORIA mapping of the entire Hawaiian Ridge was completed, at least 40 separate large-scale landslides were mapped. The authors also observe that the GLORIA images and standard geophysical surveying methods detect only the largest of the mass failure deposits. Many smaller events remain undetected but have the potential for producing catastrophic tsunamis along the coastal Hawaiian Island areas.

Normark, W. R., 1974, Ranger submarine slide, northern Sebastian Vizcaino Bay, Baja California. Bulletin Geological Society America, v. 85, p. 781-784.
Normark, W. R., 1990, Return to Ranger submarine slide, Baja California, Mexico: Geo-Marine Letters, v. 10, p. 81-91.

Much of our knowledge of the processes of submarine slides is derived from mass-failure deposits of sedimentary units along continental margins. The internal structure of the blocks and debris within a slide deposit, however, generally cannot be resolved because of the lack of resolution using surface-towed reflection-profiling systems. The first paper in this pair describes the Ranger slide deposit with standard techniques; the 1990 paper uses a deep-tow geophysical system that documents that the large blocks formed during initial sliding continue to break apart and rotate as they move downslope. Many submarine slide deposits

are the result of multiple failures, but even with the high resolution deep-tow data it is difficult to distinguish the individual episodes. At this point, only a limited amount of deep-tow data is available for the Hawaiian debris avalanches (Lipman et al., 1988).

Normark, W. R., and Gutmacher, C. E., 1988, Sur submarine slide, Monterey Fan, central California: Sedimentology, v. 35, p. 629-647.

This work provides a detailed description of a typical submarine slide including GLORIA sidescan sonar and swath-sonar bathymetry. Together with core samples from several of the units within the slide mass, this paper provides additional insights to the process of conversion from slide blocks to debris flow units.

Normark, W.R., Lipman, P.W., Wilson, J.B., Jacobs, C.L., Johnson, D.P., and Gutmacher, C.E., 1987, Preliminary cruise report, Hawaiian GLORIA leg 2, F6-86-HW, November 1986: U.S. Geological Survey Open-File Report 87-298, 42 p.

This cruise data report discusses the GLORIA sidescan sonar surveying in an area that includes the slumps and debris avalanches on the west flank of the Mauna Loa volcano. The data are interpreted more fully in Lipman et al. (1988) and Moore et al. (1992).

Normark, W.R., Holcomb, R.C., Searle, R.C., Somers, M.L., and Gutmacher, C.E., 1989, Cruise report, Hawaiian GLORIA legs 3 and 4, F3-88-HW and F4-88-HW: U.S. Geological Survey Open-File Report 89-213, 56 p.

This cruise data report discusses the GLORIA sidescan-sonar surveying in an area that includes the slumps and debris avalanches on the northeast slopes of Oahu and Molokai volcanoes. The data are interpreted more fully in Moore et al. (1989).

Prior, D. B., 1984, Subaqueous landslides: IV International Symposium Landslides, Toronto, v. 1, p. 179-196.

This paper provides a review of both the style of mass-wasting episodes and the types of damage to offshore facilities. The paper attempts to clarify the use of terms for identifying the types of landslides (see figure 8 and accompanying text) and the transition between slides and subaqueous flows. The paper distinguishes two basic types of slides based on the geometry of the basal shear surface: rotational and translational. The author is one of the most active researchers in the area of mass wasting, and the papers selected represent only part of his voluminous work.

Prior, D. B., Bornhold, B. D., and Johns, M. W., 1984, Depositional characteristics of a submarine debris flow: Journal of Geology, v. 92, p. 707-727.

Prior, D.B., Coleman, J.M., and Bornhold, B.D., 1982, Results of a known seafloor instability event: Geo-Marine Letters, v. 2, p.117-122.

These two works describe one of the most detailed descriptions currently available for a submarine slide; the data from this delta-front failure in a British Columbia fjord include high-resolution reflection profiles, sidescan sonar, core samples, and observations from submersible. The transition from blocky debris at the base of the delta slope in an area of mixing and remolding of sediment to a zone of pressure ridges and then to a debris lobe is well illustrated. The most unique feature documented in these papers is the existence of *outrunner blocks* as much as 100 m across and 5 m thick that have moved up to a kilometer from the front of the debris lobe on slope gradients less that 0.5°. Shallow glide tracks observed on the high-resolution side-looking sonar images show the path of the outrunner blocks. This mass-wasting event occurred in 1975 and caused tsunami waves as high as 8.2 m. This exceptionally well-studied slide provides a good analog for larger, deeper water failures such as the Sur slide that are difficult to map with high-resolution systems because of both their depth and size (Normark and Gutmacher, 1988). *The Hawaiian debris avalanches show* *many blocks, some larger than 2 km in diameter, that may well be outrunner blocks that have moved tens of kilometers.*

Prior, D.B., Suhayda, J. N., Lu, N. -Z., Bornhold, B. D., Keller, G. H., Wiseman, W. J., Wright, L. D., and Yang, Z. -S., 1989, Storm wave reactiviation of a submarine landslide: Nature, v. 341, p. 47-50.

This paper presents data showing that existing submarine slide deposits on the slope of a major delta off China were further deformed during the passage of several major storms. Pressure sensors, tilt meters, and accelerometers did not resolve downslope movement (and the determinations of the positions of the instrument packages during the emplacement and recovery also could not resolve changes) but did suggest remolding and subsidence. These limited observations suggest that previously failed sediment is not necessarily more stable as has been commonly thought.

Sangrey, D.A., 1977, Marine geotechnology---state of the art: Marine Geotechnology, v. 2, Marine Slope Stability Volume, p.45-80.

This review paper is an excellent resource for understanding the factors that can lead to failure of marine sediments. It reviews techniques for sampling and measurements with special consideration of the main causes of submarine mass wasting: underconsolidation of sediment resulting from rapid deposition, gas in sediments from the decay of organic matter, and the effects of dynamic loading, including cyclic loading from waves and tides. The concepts reviewed apply to investigation of the possibility for failure of the sediments on the flanks of the Hawaiian volcanoes.

Saxov, Svend and Nieuwenhuis, J.K., editors, 1982, Marine Slides and other Mass Movements: Plenum Press, New York, 353 p.

The chapters in this book review most aspects of submarine landslides, including mapping techniques with examples from geophysical profiles, some aspects of geotechnology and the mechanics of failure, effect of oceanographic conditions, sedimentology and earthquakes. This book is a good starting point for an overview of our knowledge of submarine slides.

Schwab, W.C., Chase, T.E., Normark, W.R., Wilde, Pat and Seekins, B.A., 1986, Generic assessment of steep-slope seabed environments: identification of sediment cover and evaluation of swath sonar systems of OTEC site mapping: U.S. Geological Survey Open-File Report 86-333-A, 101 p.

This report was prepared on contract for the Ocean Thermal Energy Conversion (OTEC) studies of DOE to evaluate available technology that could be applied for substrate and morphologic evaluation of steep slope environments offshore from tropical oceanic islands. The report reviewed the available data on the types of marine sediment based on available samples, lists of sediment properties, and maps of seabed characteristics. Also considered were the available survey techniques that can be used to map steep-slope environments. The original need for this study was to look at stability factors that could affect a cold-water intake pipe for an OTEC plant, but the data can be applied to cable-route evaluation also.

Schwab, W.C., Danforth, W.W., Scanlon, K.M., and Masson, D.G., 1991, A giant submarine slope failure on the northern insular slope of Puerto Rico: Marine Geology, v. 96, p. 237-246.

This work is included because the failure described is similar in scale (55 km wide and about 1500 km^3 of material removed) to the Hawaiian Ridge debris avalanches; in addition, the slope gradient is closer to that of the Hawaiian volcanoes than the better known continental margin failures. The GLORIA sidescan images show that the headwall scarp area is cut by numerous submarine canyons, as also has been observed off Hawaii (Moore et al., 1989).

Schwab, W.C., Lee, H.J., Kayen, R.E., Quinterno, P.J., and Tate, G.B., 1988, Erosion and slope instability on Horizon Guyot, Mid-Pacific Mountains: Geo-Marine Letters, v. 8, p. 1-10.

This study of the sediment cap on top of Horizon Guyot at a water depth of 1600 m show that mass wasting could occur if overconsolidation of the sediment results from current reworking and local current erosion. This study has relevance to the slopes off Hawaii where similar sediment is accumulating, e. g., southwest of Oahu in the area of sediment movement during the passage of Hurricane Iwa (Dengler et al. 1984a,b; Winters and Lee, 1982).

Stoopes, G.R., and Sheridan, M.F., 1992, Giant debris avalanches from the Colima Volcanic Complex, Mexico: implications for long-runout landslides (>100 km) and hazard assessment: Geology, v. 20, p. 299-302.

This paper is included because it describes subaerial, volcanic debris avalanches, one of which is second in size only to Mount Shasta (Crandell et al., 1984), that exhibit very long-distance runout. The larger Hawaiian debris avalanches have run-out lengths as much as double the 120 km described here, but the method of analysis for both types of volcano failures are similar (Lipman et al., 1988; Moore et al., 1992). This paper can be useful for understanding the processes involved.

Torresan, M.E., Shor, A.N., Wilson, J.B., and Campbell, J., 1989, Cruise Report, Hawaiian GLORIA leg 5, F5-88-HW: U.S. Geological Survey Open-File Report 89-198, 56 p.

This cruise data report discusses the GLORIA sidescan-sonar surveying in an area on the south side of the islands of Niihau, Kauai, and Oahu. The report provides preliminary interpretation of both the sidescan mosaic and of seismic-reflection profiles to characterize multiple debris avalanches from Kauai and Niihau and a large-scale slump, which the authors term the "West Oahu Giant Landslide." These features are briefly discussed in Moore et al. (1989), in which the Oahu landslide is renamed the Waianae slump, a more accurate term for the type of failure involved.

Torresan, M.E., Clague, D.A., and Jacobs, C.L., 1991, Cruise Report, Hawaiian GLORIA cruise F12-89-HW: U.S. Geological Survey Open-File Report 91-127, 67 p.

This cruise data report discusses the GLORIA sidescan-sonar surveying in an area that includes the slumps and debris avalanches on the northwest side of the Hawaiian Ridge west of Niihau to St. Rogatien Bank. There are at least four debris avalanches and two large slumps from the volcanic edifices along the section of the Hawaiian Ridge. These features are mentioned only in passing in later literature and are included here to help define the morphologic characters of the widespread mass failures.

Varnes, D. J., 1978, Slope movement types and processes, *in* Schuster, R.L., and Krizek, R.J., eds., Landslides: Analysis and Control: Special Report Transportation Research Board, National Academy of Sciences, v. 176, p. 11-33.

This major review article is for subaerial mass movements, but it provides a good introduction to the recommended usage of many terms, many of which has been adopted and/or modified for submarine deposits. The paper also reviews the processes involved and provides an extensive reference list. This work, together with the review of submarine slides by Moore (1977), is a good starting point for evaluating the importance and widespread occurrence of submarine slides in the Hawaiian area that have been documented during the last ten years.

Winters, W.J., and Lee, H.J., 1982, Evaluation of geotechnical properties and slope stability of a calcareous ooze on the south-west slope off Oahu, Hawaii: U.S. Geological Survey Open-File Report, 82-468-B, 520 p.

This work provides geotechnical analyses of core samples of pelagic carbonate sediment that is typical for the upper submarine slopes of Hawaiian volcanoes. The sand and coarser sediment that moved from the reef to deeper water during the turbidity currents generated by Hurricane Iwa moved across this "background" sediment type (Tsutsui et al., 1987). The analyses presented are from four core samples collected before the disturbance caused by the hurricane. These data are required for developing predictive models for potential slope failures in the Hawaiian area; the data were obtained as part of a DOE-funded study to determine potential hazards for a cold-water intake pipeline for the Oahu Ocean Thermal Energy Conversion (O'OTEC) study.

3. TSUNAMIS

This section on tsunamis is included to emphasize that deformation of the submarine flanks of Hawaiian volcanoes and major submarine slides can cause destructive waves; the Moore and Moore (1984, 1988) references present compelling evidence for tsunami waves as high as 325 m. This event has been tentatively linked to the last major mass-wasting event on the west side of Mauna Loa volcano slightly more than 100,000 years ago. The Tilling et al. (1976) paper relates a discrete slump event on the south flank of Kilauea volcano with a well-documented (and destructive) local tsunami. Because there are several well-known episodes of the damage from tsunamis since the early 19th century along the Hawaiian coastal areas, this section includes not only information on the tsunamis related to local submarine failures and earthquakes offshore of Hawaii, but also those generated by distant earthquakes that have caused extensive damage (e.g., the 1946 event described by Shepard et al., 1950). In addition, we include a few articles related to modeling tsunami-wave runup.

Cox, D.C., and Morgan, Joseph, 1977, Local tsunamis and possible local tsunamis in Hawaii, Report HIG-77-14: Hawaii Institute of Geophysics, Honolulu, Hawaii, November, 1977, 118 p.

Cox, D.C., 1979, Local tsunamis in Hawaii-implications for hazard zoning, Report HIG-79-5,: Hawaii Institute of Geophysics, Honolulu, Hawaii, August 1979, 46 p.

Cox, D.C., and Morgan, Joseph, 1984, Local tsunamis in Hawaii- implications for warning, Report HIG-84-4: Hawaii Institute of Geophysics, Honolulu, Hawaii, November, 1984, 104 p.

These three reports document locally generated tsunamis and show wave-runup heights for all sections of the islands. These reports suggest that the slumps shown on the bathymetry around Hawaii represent the products of seafloor displacements that could have generated the tsunamis.

Cox, D.C., and Mink, J.F., 1963, The tsunami of 23 May, 1960 in the Hawaiian Islands: Bulletin of the Seismological Society of America, v. 53, p. 1191-1209.

This article (see also Eaton et. al., 1961) discusses the tsunami on May 23, 1960 that originated during an earthquake in Chile. Recorded wave-runup heights were 1 to 5 m in general and as high as 10 m in Hilo where sixty-one people lost their lives. The effects of this tsunami were also observed as changes in water level in wells and on tide gauges giving a comprehensive view of this event on most of the islands. The paper also looks at the history of damage in the Hawaiian Islands from 30 tsunamis since the first recorded one in 1819.

Dawson, A.G., Long, D., and Smith, D.E., 1988, The Storegga slides: evidence from eastern Scotland for a possible tsunami: Marine Geology, v. 82, p. 271-276.

This report suggests that the wave runup from a tsunami generated by the second phase (of three) of land-sliding on the Norwegian continental margin deposited a sand layer on the northern Scottish coast 500 km to the south. It is noted in this section because the Storegga failure, which is believed to be the cause, is comparable in size to the largest slides in the Hawaiian area (see Bugge et al., 1987, 1988) and gives insight to the expected size of waves from a slide off Hawaii.

Dudley, W. C., and Lee, M., 1988, Tsunami!: University of Hawaii Press, Honolulu, 132 pp.

This popular book provides a review of the history of tsunami effects in Hawaii. It contains anecdotal material and is a convenient summary of data.

Eaton, J.P., Richter, D.H., and Ault, W.U., 1961, The tsunami of May 23, 1960, on the island of Hawaii: Bulletin of the Seismological Society of America, v. 51, no. 2, p. 135-157.

This work reviews the effects of the tsunami of 1960 that originated off the Chilean coast. The authors examine the seismic character of the earthquake itself and note that a long period of ground motion was involved in the source area. A narrative of the tsunami wave arrival is given and a discussion of the effects of tsunamis in Hawaii relative to the direction of arrival of the waves (i.e., which source). See also Cox and Mink (1963).

Fraser, G.D., Eaton, J.P., and Wentworth, C.K., 1959, The tsunami of March 9, 1957, on the island of Hawaii, Bulletin of the Seismological Society of America, v. 49, p. 79-90.

This report reviews the effect of a tsunami generated by an earthquake in the Aleutian region. The differences in wave runup from this event with respect to earlier tsunamis of known origin are discussed for data from the island of Hawaii only. The study suggests that accurate prediction of the runup effects is difficult because each tsunami is unique, reflecting the size, orientation, and duration of the earthquake causing the wave and because of the orientation of the coastline with respect to the propagation direction of the tsunami.

Hammack, J.L., 1973, A note on Tsunamis: their generation and propagation in an ocean of uniform depth: Journal of Fluid Mechanics, v. 60, part 4, p.769-799.

This work presents theoretical models and experimental results looking at the generation of tsunami waves. The numerical methods presented have not been evaluated.

Harbitz, C.B., 1992, Model simulations of tsunamis generated by the Storegga Slides: Marine Geology, v. 105, p. 1-21.

This paper presents a numerical model for estimating wave characteristics for tsunamis caused by submarine slides. The author applies the technique to the Storegga slide off Norway to estimate wave-runup heights on the coasts of Scotland, Iceland and Greenland (see Dawson et al., 1988).

Iida, K., and Iwasaki, T., 1983, Tsunamis - Their Science and Engineering: Tokyo, Terra Scientific Publishing Company, 563 p.

This book presents a series of papers from an international symposium on tsunamis. In addition to historical and statistical reviews of tsunami events, papers include discussions of generation and propagation factors of tsunamis. A number of papers look at the effects of topographic features on wave propagation and numerical models are included for tsunami run-up and back-wash that might be applied to the Hawaii.

Kanamori, Hiroo, and and Kikuchi, Masayuki, 1993, The 1992 Nicaragua earthquake: a slow tsunami earthquake associated with subducted sediments: Nature, v. 361, p. 714-716.

Satake, Kenji; Bourgeois, Joanne; Abe, Kuniaki; Abe, Katsuyuki; Tsuji, Yoshinobu; Imamura, Fumihiko; Iio, Yoshihisa; Katao, Hiroshi; Noguera, Evelyn; and Estrada, Francisco, 1993, Tsunami field survey of the 1992 Nicaragua earthquake: American Geophysical Union Transactions, v. 74, no. 13, p.145,156-157.

These two papers define the characters of a "tsunami earthquake," which generates a very large tsunami relative to the size of the earthquake magnitude. A 1992 earthquake off Nicaragua generated tsunami runup of nearly 10 m (see second paper) and is the basis for these analyses. The authors relate the generation of a larger than expected tsunami to subduction along a non-accreting type of margin. This has application to Hawaii because

recent conceptual modeling suggests that the present active failure of the south flank of Kilauea volcano occurs on fault planes that behave as a non-accreting margin. If these new concepts are correct, very large tsunamis could be generated by earthquakes of magnitude 7 or larger (several of this magnitude have occurred in the last 150 years in Hawaii).

Lander, J.F., and Lockridge, P.A., 1989, United States Tsunamis (including United States possessions) 1690-1988: Boulder, Colorado, U.S. Dept. of Commerce, National Environmental Satellite, Data and Information Service, National Geophysical Data Center, 265 p.

Chapter 2 (p. 17-78) is on Hawaii with a complete table of the tsunamis that have affected Hawaii during recoverable history. A distinction is made between local and distant sources for the tsunamis. Brief descriptions are presented for more than 130 events with identification of probable source.

MacDonald, G.A., Shepard, F.P., and Cox, D.C., 1947, The tsunami of April 1, 1946, in the Hawaiian Islands: Pacific Science, v. 1, p. 21-37.

This work is an extensive account of the 1946 tsunami with tide gauge data and water-runup heights for the larger islands. Photographs document the damage caused, focusing on the town of Hilo, and also show changes in water level, including a bore moving upstream, in the Wailuku River.

Matlock, H., Reese, L.C., and Matlock, R.B., 1962, Analysis of structural damage from the 1960 tsunami at Hilo, Hawaii: Report of the Structural Mechanics Research Laboratory, The University of Texas, Austin, Texas, March 1962, 95 p.

This work reviews the effects of the tsunami of 1960 in Hilo and presents an extensive review of the general types of damage to man-made structures as related to exposure to the waves and the type of construction of the structures. In addition, the failure modes for specific objects are analysed in more detail.

Moore, G.W., and Moore, J.G., 1988, Large-scale bedforms in boulder gravel produced by giant waves in Hawaii: Geological Society of America Special Paper v. 229. p. 101-109.

Moore, J.G., and Moore G.W., 1984, Deposit from a giant wave on the island of Lanai, Hawaii: Science, v. 226, p. 1312-1315.

Both of these papers infer that the Hulopoe gravel deposits on Lanai were deposited by a giant-wave backwash from a large landslide in the Pleistocene that reached heights of 325 m. Despite the tremendous size implied, this wave height is not unique, i.e., in 1957 a wave 525 m high was documented in Lituya Bay, Alaska that was generated by a rockfall. Later work has suggested that the tsunami event that deposited the gravel on Lanai may have been generated by the Alika phase 2 slide off Mauna Loa volcano (Lipman et al., 1988).

Powers, H.A., 1946, The Aleutian tsunami at Hilo, Hawaii, April 1, 1946: Seismological Society of America Bulletin, v. 36, no. 4, p. 355-356.

Shepard, F.P., Macdonald, G.A. and Cox, D.C., 1950, The tsunami of April 1, 1946: Bulletin of Scripps Institution of Oceanography, University of California Press, vol. 5, no. 6, p. 391-528.

The 1946 paper is a short note that gives a simple announcement about the tsunami and its affect on the Hawaiian Islands. The 1950 article, on the other hand, is the most detailed account of the damage caused in Hawaii by the April 1, 1946 tsunami generated by the sea-floor movement on the northern slope of the Aleutian trench. The town of Hilo, Hawaii was extensively damaged where wave heights on shore were as high as 16 m above sea level.

Shepard et al. also observe that all Hawaiian shores are subject to tsunamis of local origin like that of April 2, 1968 that swept several hundred meters inland on the south coast and generated waves as high as those recorded in Hilo from the 1946 tsunami. See also Macdonald et al. (1947) for their earlier review of this event.

Tilling, R.I., Koyanagi, R.Y., Lipman, P.W., Lockwood, J.P., Moore, J.G., and Swanson, D.A.,1976, Earthquake and related catastrophic events, Island of Hawaii, November 29, 1975: A preliminary report: U. S. Geological Survey Circular 740, 33 pp.

This paper reviews the tsunami damage and observed deformation of the south flank of the Kilauea volcano based on preliminary geodetic measurements on the subaerial part of the edifice following the 1975 earthquake. More than 60 km of the coast along the southern flank of the volcano subsided (as much as 3.5 m). Tsunami wave heights locally exceeded 14 m. Because two nineteenth century earthquakes caused similar ground motion effects, the authors suggest that the long-term deformation of the south flank of the volcano is continuing and will be the source for future tsunamis (Lipman et al., 1985, provide more detailed description of the deformation associated with the earthquake).

Voit, S.S., 1987, Tsumanis: Annual Review of Fluid Mechanics, v. 19, p. 217-236.

This work reviews the basic mathematical equations for tsunamis and presents numerical models for their behavior.

Wood, H.O., 1914, On the earthquakes of 1868 in Hawaii: Bulletin of the Seismological Society of America, v. 4, p. 169-203.

This article presents numerous eyewitness accounts and news stories to describe the 1868 earthquake and resulting tsunami. Wood's review includes a detailed summary of the earthquake activity preceding the catastrophic event as well as the major aftershocks. Pages 196-199 document water-runup heights as great as 18 m (60 feet as reported).

Young, R.W., and Bryant, E.A., 1992, Catastrophic wave erosion on the southeastern coast of Australia: Impact of the Lanai tsunami ca. 105 ka?: Geology, v. 20, p.199-202.

Jones, A.T., 1992, Comment on "Catastrophic wave erosion on the southeastern coast of Australia: Impact of the Lanai tsunamis ca. 105 ka?": Geology, p.1150-1151.

Young, R.W., and Bryant, E.A., 1992, Reply on "Catastrophic wave erosion on the southeastern coast of Australia: Impact of the Lanai tsunami ca. 105 ka?": Geology, v. 20, p.1151.

The initial paper by Young and Bryant (1992, p. 199) suggest that the tsunami that produced a 325-m-high wave recorded on Lanai, Hawaii (Moore and Moore, 1984, 1988) resulted in destruction of sand barriers along the southeastern Australian coast. The timing of the wave deposits on Lanai (105 ka) are allowable for the erosion suggested for the Australian coast some 7000 km from Hawaii. The discussion by Jones (1992) and reply by the authors (1992, p. 1151) revolve around the model used for tsunami propagation; Young and Bryant prefer the model by Harbitz (1992) that is included in this section.

4. SUPPLEMENTARY DATA FOR MARINE GEOLOGY OF HAWAIIAN AREA

The references in this section are for background information on the geology of the Hawaiian Ridge to aid in the understanding the more topical subjects discussed in previous sections. In addition, several atlas compilations of marine geologic data are also included.

Campbell. J.F., 1987, Bathymetric atlas of the southeast Hawaiian Islands,: Hawaiian Institute of Geophysics, Sea Grant Miscellaneous Report UNIHI-SEAGRANT-MR-87-01.

> These bathymetric charts were compiled initially with support from the Hawaii Deep Water Electric Transmission Cable Program. The bathymetry presented is more detailed than other available maps; it is generally limited to the southwest side of the islands between Oahu and the northern part of the island of Hawaii.

Decker, R.W., 1989, The Hawaiian-Emperor chain, *in* Winterer, E.L., Hussong, D.M., and Decker, R.W., eds., The Eastern Pacific Ocean and Hawaiian Islands: Boulder, Colorado, Geological Society of America, The Geology of North America, v. N, p. 291-297.

> This is a brief but excellent review of the general seismicity, structure and age of the Hawaiian volcanoes and provides some background for understanding the nature of the major slump-type failures of the volcano flanks.

Fornari, D.J., Malahoff, Alexander, and Heezen, B.C., 1979, Submarine slope micromorphology and volcanic substructure of the Island of Hawaii inferred from visual observations made from U.S. Navy deep-submergence vehicle (DVS) "Sea Cliff": Marine Geology, v. 32, p. 1-20.

> This report summarizes observations from 44 manned submersible dives around the Hawaiian Islands. It is included in our review because it may provide some details of local microtopography depending upon the cable routes selected.

Macdonald, G.A., and Abbott, A.T., 1970, Volcanoes in the sea : the geology of Hawaii: Honolulu, University of Hawaii Press, 441p.

> This book is a classic reference work on Hawaiian volcanoes. It is included here for background information.

Makai Ocean Engineering, Inc., Ed Noda & Associates, Hawaii Institute of Geophysics, 1986, Hawaii deep water cable program bottom roughness survey of the Alenuihaha channel: Report prepared for Hawaiian Dredging and Construction Company, May 1, 1986, 76 p. with additional appendices.

> This unpublished report was prepared for the Hawaii Deep Water Cable Program to look at the area of steepest and deepest submarine slopes along the proposed route of a power cable between the islands of Hawaii and Oahu. The slope north of Kohala between 900 and 1900 m water depth averages 27° and is the steepest major gradient examined. The report includes a detailed description of the bottom-roughness sampler (a deep-tow package with a 500 kHz echosounder capable of 2 cm resolution within a 4° beam angle, a pressure sensor able to measure water depth with 15 cm resolution, and an acoustic-positioning transponder) and the survey techniques. The report also includes an analysis of the implications for cable-laying activities based on the gradients and local roughness features that were observed.

Moore, J.G., Clague, D.A., Ludwig, K.R., and Mark, R.K., 1990, Subsidence and volcanism of the Haleakala Ridge, Hawaii: Journal of Volcanology and Geothermal Research, v. 42, p. 273-284.

This work is included to emphasize that relief on the flanks of the Hawaiian volcanoes includes prominent benches that are drowned coral reefs. The weight of the growing volcanoes puts a substantial load on the oceanic crust and lithospheric plate, resulting in sustained subsidence over hundreds of thousands of years. Together with the effects of fluctuating sea level in response to glacial cycles, the continued subsidence leads to a succession of drowned reefs giving a terraced slope. Mass failure of the flanks of the volcanoes has tended to eliminate the stairstep relief in many areas.

Pacific Seafloor Atlas, 1991, Hawaii Institute of Geophysics, Honolulu, Hawaii, 25 atlas sheets.

This atlas of bathymetric, geologic (including sidescan-sonar images), and geophysical data from oceanic volcanoes does not include Hawaiian area data. The atlas, however, does provide further evidence for processes affecting oceanic volcanic islands (e.g., Samoa and the Line Islands) including slumps, debris avalanches, and turbidity currents as observed off Hawaii.

Stanley, D.J., and Taylor, P.T., 1977, Sediment transport down a seamount flank by combined current and gravity process: Marine Geology, v. 23. p. 77-88.

This work examines the interplay of gravitational processes and bottom currents in the movement of sediment and coarse debris on the flanks of a submarine volcano. Their analysis might provide insight to active processes in areas of steep slopes where strong bottom currents can be important, e.g., the Alenuihaha Channel between Hawaii and Maui.

Tribble, G.W., 1991, Underwater observations of active lava flows from Kilauea volcano, Hawaii: Geology, v. 19, p. 633-636.

Although a cable route from Hawaii to the other islands will most likely avoid areas of active lava flows entering the sea and moving down submarine slopes, this paper is included to indicate potential problems for submarine cables from active flows. For example, the report by Torresan et al., (1989) shows lava flows and vents on the seafloor between Oahu and Kauai that are directly downslope from a site of reported volcanic (?) activity in the Kauai Channel in May 1956. See discussion and figures 6b and 10 in Torresan et al. (1989). The other cruise reports included in this review note other occurrences of volcanic eruptions on the sea floor that are younger than the adjacent, and commonly dormant, Hawaiian volcanoes.

Wright, T.L., and Takahashi, T.J., 1989, Observations and interpretation of Hawaiian volcanism and seismicity 1779-1955: An annotated bibliography and subject index: University of Hawaii Press, Honolulu, Hawaii, 270 p.

This review is an excellent supplement to articles and books above that review the geology and activity of Hawaiian volcanoes. It includes eye-witness accounts of the effects of major earthquakes and tsunamis. The authors are completing an update of the volume that will cover the scientific literature, including published abstracts, through 1992. Many of the entries in this updated edition are on the submarine geology and geophysics of the Hawaiian area (draft manuscript previewed in January 1993).