dune, and allows upward growth of the plant to keep pace with sand deposition. Vehicle and foot traffic that damage the vegetation can greatly diminish dune stability.

f. Dune fauna. Dunes may appear to be harsh and inhospitable environments, but they are hosts to many species of animals. A wide variety of invertebrates are present, including species as large as crabs. Numerous shorebirds and upland birds use the dune zone for foraging and nesting. Other vertebrates, such as rabbit, fox, deer, etc., frequent the dune in search of food.

g. Classification. Dunes can be described or classified on the basis of physical description (external form and internal bedding) or genetic origin (mode of formation). Smith (1954) devised a descriptive classification system that has been widely used. It established the following types (Figure IV-2-11):

(1) Foredunes. Mounds or ridges directly by the beach. Serve as storm buffer.

(2) Parabolic dunes. Arcuate sand ridges with the concave portion facing the beach. Rare; often form downwind of pools or damp areas.

(3) Barchan dunes. Crescent-shaped dunes with the extremities (horns) extending downwind (caused by the horns migrating more rapidly than the central portions). Sometimes show incomplete sand cover moving over a nonerodible pavement.

(4) Transverse dune ridges. Ridges oriented perpendicular or oblique to the dominant winds. Their form is asymmetrical with steep lee and gentle upwind slopes.

(5) Longitudinal (seif) dunes. Dune ridges elongated parallel to the wind direction and symmetrical in profile. Occur in groups over wide areas; feature sinuous crestlines.

(6) Blowouts. Hollows or troughs cut into dunes; may be caused when vehicles or pedestrians damage vegetation (Figure IV-2-12).

(7) Attached dunes. Formations of sand that have accumulated around obstacles such as rocks (Figure IV-2-13).

h. Shoreline protection. In many areas, dunes serve a vital role in protecting inland areas from storm surges and wave attack. As a result, many communities require that buildings be erected behind the dunes or beyond a certain distance (a *setback*) from an established coastline. Unfortunately, the protection is ephemeral because severe storms can overtop and erode the dunes, and changes in sediment supply or local wind patterns (sometimes caused by structures and urban development) can leave them sand-starved. If dunes are cut for roads or for walkways, they become particularly vulnerable to erosion. However, compared with hard structures like seawalls, many communities prefer the protection provided by dunes because of aesthetic considerations.

i. Dune restoration. Historically, sand dunes have suffered from human pressure, and many dune systems have been irreversibly altered by man, both by accident or design. Many coastal areas in Europe, North America, Australia, and South Africa, which had once-stable forested dunes, have been deforested. The early settlers to New England in the 1600's severely damaged the dune vegetation almost immediately upon their arrival by overgrazing and farming. Dune rebuilding and revegetation have had a long history, mostly unsuccessful (Goldsmith 1985). Recent restoration practices have been more effective (Knutson 1976, 1978; Woodhouse 1978). The two main methods for rebuilding or creating coastal dunes are artificial planting and erecting sand fences. Hotta, Kraus, and Horikawa (1991) review sand fence performance.

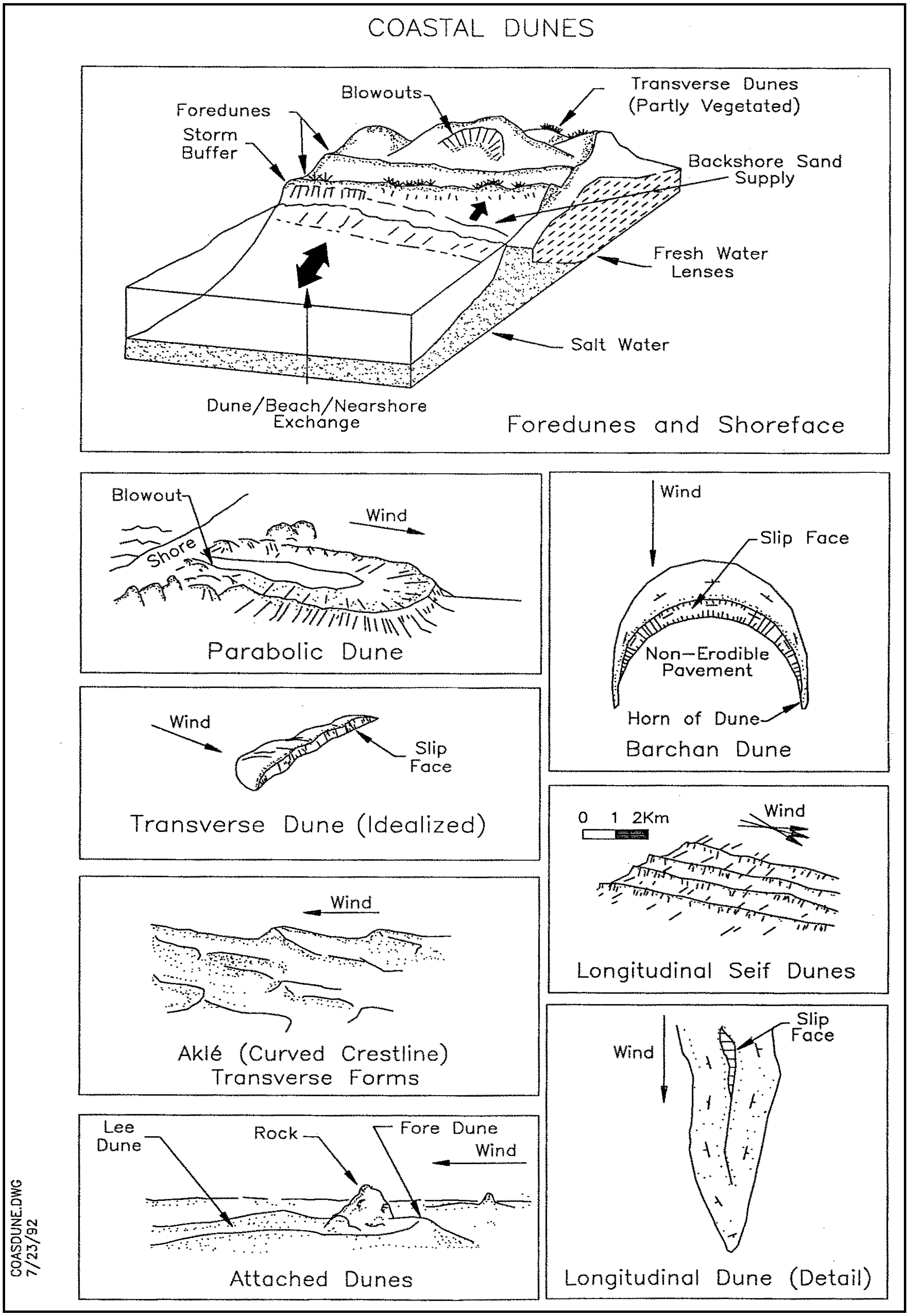

Figure IV-2-11. Variety of dune types (adapted from Carter (1988), Reading (1986), and Flint (1971))

Figure IV-2-12. Blowout in dunes. Eastern Alabama on the Morgan peninsula east of the mouth of Mobile Bay (April 1995)

Figure IV-2-13. Huge dune anchored to a rock outcrop in the eastern Sinai Desert (January 1979). The dune is more than 15 m high. Most of valley floor is hard-packed sand, although there are pockets of loose sand that impede vehicle traffic. As of 1979, many of the bedouins in this area were already using pickup trucks instead of camels

Coastal dune management and conservation practices are reviewed in Carter, Curtis, and Sheehy-Skeffington (1992).

IV-2-7. Volcanic Coasts

a. Introduction and definitions. *Volcanoes* are vents in the earth's surface through which magma and associated gases and ash erupt (Bates and Jackson 1984). Often, conical mountains are formed around the vents as repeated eruptions deposit layer upon layer of rock and ash. Therefore, the definition is extended to include the hill or mountain built up around the opening by the accumulation of rock materials.

(1) The fundamental importance of volcanism to mankind has been clearly documented around the world. The entire west coast of the Unites States is highly active tectonically and most of the continent's volcanoes are within 200 km of the coast. There are more than 260 distinct volcanoes younger than five million years in the Unites States and Canada, most of which are in Alaska and the Hawaiian Islands (Wood and Kienle 1990). Fifty-four have erupted in historic times, and distant memories of others are recounted in Native American legends.

(2) Volcanoes are important to coastal studies for many reasons:

(a) They provide sediment to the littoral environment. Material may reach the coast directly via ash fall-out and lava flows or may be transported by rivers from an inland source (e.g., Mount St. Helens).

(b) Vulcanism affects coastal tectonics (e.g., west coasts of North and South America).

(c) Shoreline geometry is affected by the formation of volcanic islands (Aleutians) and by lava that flows into the sea (Hawaiian Islands).

(d) Shoreline erodability ranges from very erodable for ash and unconsolidated pyroclastic rubble to very resistant for basalt.

(e) Volcanoes can pose a serious threat to coastal communities.

(f) Volcanic debris can choke rivers and harbors.

(3) This section briefly discusses general concepts of volcanism and describes features unique to volcanic shores. Examples from Alaska and the Hawaiian Islands illustrate the differences between composite and shield volcanoes and their associated coastlines. For the general reader, *Exploring our Living Planet*, published by the National Geographic Society (Ballard 1983), is a readable and interesting introduction to plate tectonics, hotspots, and volcanism.

b. General geology. Two classes of volcanoes can be identified, based on the explosiveness of their eruptions and composition of their lava. The ones in the Aleutians and along the west coasts of North and South America are known as *composite* volcanoes and are renowned for their violent eruptions. The paroxysmal explosion of Mount St. Helens on May 18, 1980, which triggered devastating mudflows and floods, killing 64 people, serves as a remarkable example. Composite eruptions produce large amounts of explosive gas and ash and build classic, high-pointed, conic mountains. In contrast, the Hawaiian Islands are *shield* volcanoes: broad, low, basalt masses of enormous volume. Shield eruptions are typically nonexplosive, and the highly liquid nature of their lava[1] accounts for the wide, low shape of the mountains. Volcanism affects the shore on two levels:

(1) The large-scale geologic setting of the continental margin affects sedimentation and overall coastal geology. Margins subject to active tectonism (and volcanism) are typically steep, with deep water occurring close to shore. Rocks are often young. High mountains close to shore provide a large supply of coarse sediments, and muddy shores are rare. Much sediment may be lost to deep water, particularly if it is funneled down submarine canyons. This is a one-way process, and the sediment is permanently lost to the coastal zone.

(2) Small-scale structures on volcanic shores may differ from those on clastic passive margins. Sediment supply may be frequently renewed from recent eruptions and may range greatly in size. Ash may be quickly destroyed in the sea, while basalt boulders may be tremendously resistant. Hardened shores at the sites of recent lava flows are difficult settings for harbor construction.

c. Composite volcanoes - coastal Alaska. The coastal geology of Alaska is incredibly complex, having been shaped by fault tectonics, volcanism, glaciation, fluvial processes, sea level changes, and annual sea ice. More than 80 volcanoes have been named in the Aleutian arc, which extends for 2,500 km along the southern edge of the Bering Sea and the Alaskan mainland (Wood and Kienle 1990). Over 44 have erupted, some repeatedly, since 1741, when written records began. Aleutian arc volcanism is the result of the active subduction of the Pacific Plate beneath the North America Plate (Figure IV-2-14).

(1) Volcanoes have influenced the Aleutian Arc in two ways. First, they have been constructive agents, creating islands as eruption after eruption has vented rock and ash. In some places, fresh lava or mudflows accompanying eruptions have buried the existing coast, extending the shore seaward. The eruptions of Mts. Katmai and Novarupta in 1912 produced ash layers 3 to 15 m thick. The Katmai River and Soluka Creek carried vast amounts of loose ash to the sea, filling a narrow bay and burying a series of old beach ridges (Shepard and Wanless 1971). Usually, loose mudflow and ash deposits are reworked rapidly by waves, providing sediment for beach development. In addition, for years after an eruption, streams may carry rock and ash to the coast, allowing the coast to locally prograde. The second effect has been destructive, and small islands have been largely destroyed by volcanic explosions. Bogoslof, in the eastern Aleutians, is an example in which both rapid construction and destruction have influenced the island's shape over time (Shepard and Wanless 1971).

(2) Clearly, a history of volcanic instability would be a major consideration for a coastal engineer planning a harbor or project. Most new volcanic islands are uninhabited, but harbors may be needed for refuge, military, or commercial purposes. During World War II, air fields and harbors were built quickly on formerly uninhabited Aleutian Islands. Some islands can supply stone for construction at other locations, requiring loading facilities for boats or barges.

d. Shield volcanoes - Hawaii. Each of the Hawaiian islands is made up of one or more huge shield volcanoes rising from the ocean floor. The islands are at the southern end of a chain of seamounts that extends 3,400 km to the northwest and then turns north and extends another 2,300 km toward Kamchatka as the Emperor Seamounts. More than 100 volcanoes, representing a volume of greater than one million cubic kilometers, make the Hawaiian-Emperor chain the most massive single source of volcanic eruption on earth (Wood and Kienle 1990). The submerged seamounts become successively older away from Hawaii.

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[1] *Lava* is the term used for molten rock (and gasses within the liquid) that have erupted onto the earth's surface. *Magma* refers to molten rock that is still underground.

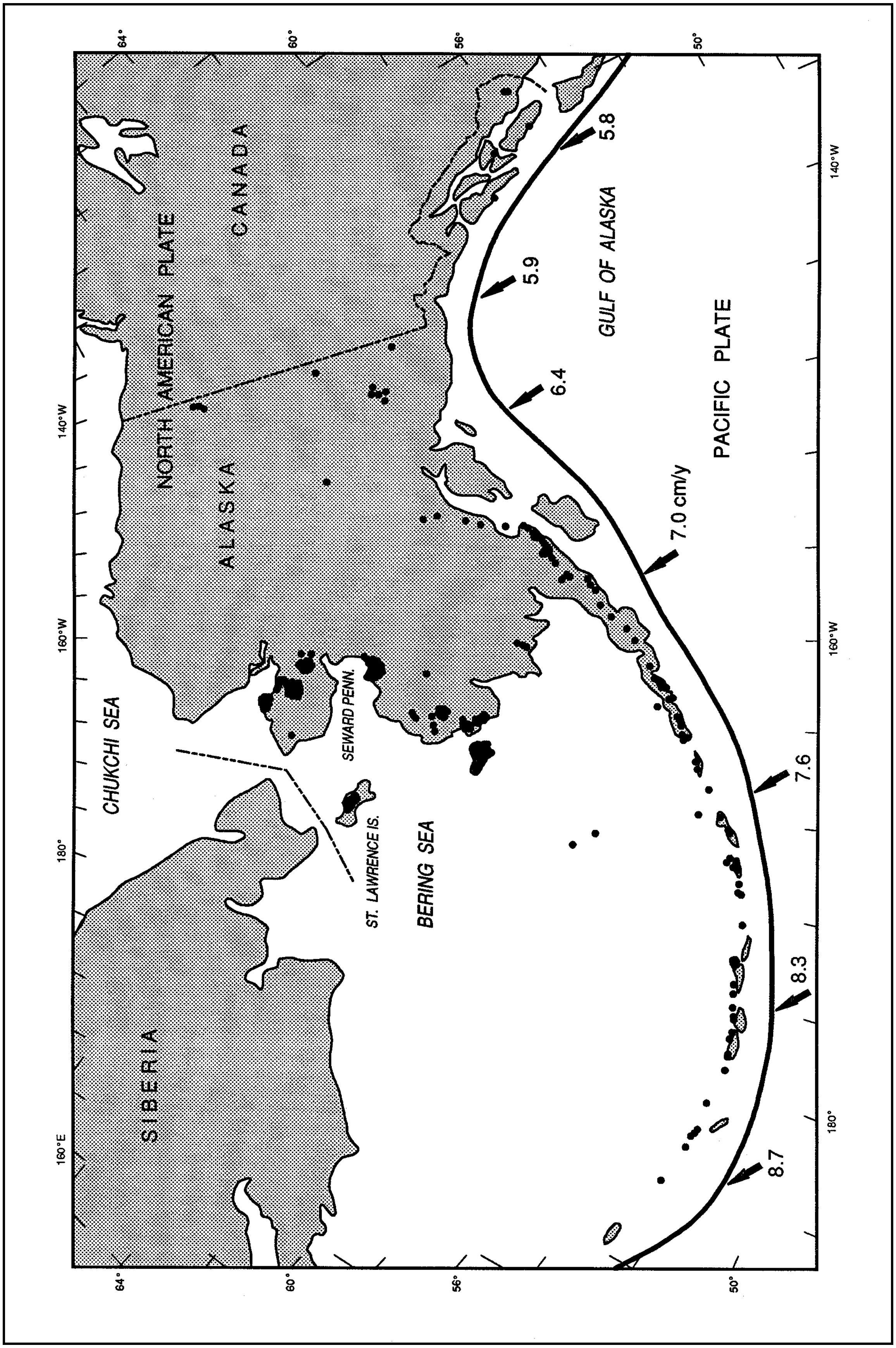

Figure IV-2-14. Alaskan volcanoes along the Aleutian Island arc, marking the boundary between the North American and the Pacific crustal plates. Arrows indicate subduction of the Pacific Plate in cm/year

Meiji Seamount, about to be subducted beneath Kamchatka, is 75-80 million years (my) old, Kilauea is only 0.4 my, while Loihi Seamount, south of the big island of Hawaii, is the newest member of the chain and has not yet emerged from the sea. The islands are found over a semipermanent "hot spot," a site where it is believed that a plume of hot, geochemically primitive material rises convectively through the mantle, interacts with the lithosphere, and vents on the seafloor (Dalrymple, Silver, and Jackson 1973). The Pacific plate is postulated to be moving over the hot spot at a rate of about 13 cm/yr, based on ages of the major vents on Hawaii (Moore and Clague 1992).

(1) Although the coastlines of the Hawaiian Islands are geologically young, wave erosion and the growth of coral reefs have modified most of the shores. Coastal plains have formed around the base of some volcanoes and between others (for example, the intermontaine plateau between Koolau and Waianae on Oahu). The plains are partly alluvial and partly raised reefs (Shepard and Wanless 1971). The greater parts of the Hawaiian coasts are sea cliffs, some as high as 1,000 m on the windward sides of the islands. There are also extensive beaches, the best of which tend to be on the western sides of the islands, protected from waves generated by the northeast trade winds. On southwestern Kauai near Kekaha, there are prograding beach ridges. Surprisingly, most of the beaches are composed not of volcanic debris but primarily of biogenic sediment. The rare volcanic sand beaches are found at the mouths of the larger rivers or along coasts where recent lava flows have killed the coral reefs (Shepard and Wanless 1971). Many beaches are undergoing serious erosion, and finding suitable sources of sand for renourishment has been difficult. This is a critical problem because tourism is a major part of the Hawaiian economy, and the beaches are among the great attractions.

(2) An example from the island of Hawaii helps illustrate the rugged nature of these volcanic shores. Hawaii, at the southeast end of the island chain, has been built up from at least seven independent volcanoes (Moore and Clague 1992). Mauna Loa, a huge dome at the southern end of the island, rises to 4,100 m above the sea (8,500 m above the seafloor). Kilauea, a low dome that rises out of the southeast side of Mauna Loa, has had a remarkable history of eruptions since 1800. Because of the porosity of the lavas, few permanent streams flow down the island, although rainfall on the windward side is heavy. The southeast coast of the island is a barren, rugged rock shore built up from hundreds of Kilauea lava flows (Figure IV-2-15). In Figure IV-2-15, the foreground is cracked, barren basalt, while the plateau in the background supports a cover of grass. The vertical cliffs are about 10 m high and in areas have been notched or undercut by the surf. Small steep pocket beaches consisting of black volcanic sands have developed in some notches. Because of the harsh wave climate and tectonic instability, coastal engineering in the Hawaiian Islands is particularly challenging (Figure IV-2-16).

e. Hazards posed by volcanoes.

(1) Introduction. Coastal projects and communities are subject to four general types of hazards caused by volcanic eruptions:

(a) Explosion-generated tsunamis that can flood coastal areas.

(b) Direct burial by lava or ash (recently experienced in Hawaii, Iceland, and Sicily).

(c) Burial or disruption by mudflows and fluvial sediment from inland eruptions, and changes in stream drainage and coastal sediment-discharge patterns.

(d) Loss of life and destruction from explosions.