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Seismic stratigraphy of the Hawaiian flexural moat

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ABSTRACT

Approximately 4,400 km of single-channel seismic reflection data were collected over the northern Hawaiian flexural moat between Hawaii and Kauai. These data include eight cross-moat profiles and three ~600-km-long moat-parallel lines. The thick (>2 km) sedimentary section filling the Hawaiian flexural moat is composed primarily of the products of large-scale mass wasting from massive slope failures on the adjacent Hawaiian islands. The observed stratigraphy can be described by four main lithostratigraphic units: (1) a basal unit of relatively constant thickness that we interpret as pelagic sediment predating the formation of the flexural moat; (2) a thick wedge of lens-shaped units onlapping the flexural arch, each with highly chaotic internal reflectivity that we interpret as buried landslide deposits; (3) a sequence of highly reflective, continuous horizons that offlap the flexural arch and are tilted down toward the islands; and (4) a ponded unit confined to the deepest part of the moat representing the youngest sediments transported to the moat. This distinctive stratigraphy—onlap of the flexural arch in the lower moat section (landslide unit), offlap migrating back toward the islands in the upper moat section (offlapping unit), and ponding of the youngest sediments in the deepest parts of the moat (ponded unit)—can be explained in terms of the competing effects of sediment influx to the moat from large-scale mass wasting and distributed subsidence due to the progressive loading of a purely elastic plate by each successive volcano. The role of large-scale mass wasting in the sedimentation history of the Hawaiian flexural moat is expected to characterize the moats of other large subaerial oceanic volcanoes.

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INTRODUCTION AND BACKGROUND

The Hawaiian Islands lie at the southeastern end of a chain of large shield volcanoes that stretch nearly 6,000 km across the North Pacific. The loads associated with these massive volcanoes bend the underlying lithosphere, resulting in a moat-like depression around the islands and a peripheral bulge seaward of the moat (Fig. 1). Known as the Hawaiian Deep (Hamilton, 1957; Menard, 1964), this flexural moat parallels the Hawaiian Ridge and forms a trough surrounding the southeastern end of the island chain with a radius of about 140 km. The moat, which is partially filled with transported volcanic material derived from the adjacent islands, has sea-floor depths ranging from 4,000–5,000 m. The flanking flexural bulge, known as the Hawaiian Arch (Menard, 1964), is located ~250 km from the islands and consists of a broad shoaling of the sea floor to depths of <4,000 m (Fig. 1). Both the flexural moat and arch are superimposed on a much-longer-wavelength (~1,200 km) bathymetric high, the Hawaiian Swell, which surrounds the younger part of the Hawaiian Ridge (Detrick and Crough, 1978).

The large mass of the Hawaiian Ridge and its location in the interior of the Pacific plate have made it ideally suited for studies of the response of the oceanic lithosphere to long-term ($>10^6$ yr) surface loads. Several studies have found a good overall agreement between gravity anomalies in the vicinity of Oahu and a model in which the mechanically strong part of the lithosphere has an effective elastic plate thickness (T_e) of 25–30 km (Watts, 1978; McNutt, 1984). Seismic refraction studies (Watts and others, 1985; ten Brink and Brocher, 1987) have documented an increase in depth to Moho from about 6–7 km on the arch to 12–14 km beneath the moat and ~18 km beneath the Hawaiian Ridge that is in general agreement with the predictions of the flexural model of Watts and others (1985).

The sedimentation history of the moats flanking large oceanic islands is of interest as a record of short-term ($<10^6$ yr) changes in lithospheric strength (ten Brink and Watts, 1985). Simple rheological models of oceanic lithosphere (Goetze and Evans, 1979; Bodine and others, 1981) suggest a rapid thinning of the mechanically strong part of the lithosphere to its long-term (elastic) thickness by thermally activated creep in the lower lithosphere over a relatively short time period (10^4–10^5 yr) immediately following emplacement of the load. These models predict that the shape of the moat should change in the first ~1 Myr after the load is emplaced as the moat deepens and the peripheral bulge migrates toward the load (Bodine and others, 1981). If the moat is continuously fed up to some reference level, ten Brink and Watts (1985) showed that a distinctive stratigraphic pattern of onlap is predicted on cross-moat profiles, particularly if the mechanical strength of the plate progressively weakens with time. Watts and ten Brink (1989) extended this model by showing the potential importance on moat stratigraphy of the progressive loading of a purely elastic plate by new volcanoes. In their model, as each new island is formed, it affects the subsidence history of the adjacent, older islands, tilting once-horizontal surfaces by as much as 2° in the direction of load migration. This leads to a stratigraphic pattern of onlap in cross-moat profiles (Fig. 2A) and downdip thickening and increasing dip toward the young end of the chain in along-moat profiles (Fig. 2B) that does not require long-term viscoelastic behavior of the lithosphere.

A multichannel seismic reflection profile across the Hawaiian Deep north of Oahu published by ten Brink and Watts (1985) revealed a thick wedge of stratified material in the moat, with reflectors tilting and diverging toward the islands. The overall stratigraphic pattern seen in this profile was one of progressive onlap of the flexural arch in the lower moat section, offlap migrating back toward the islands in the upper section, and ponding of sediment near the surface in the deepest part of the moat. Ten Brink and Watts (1985)

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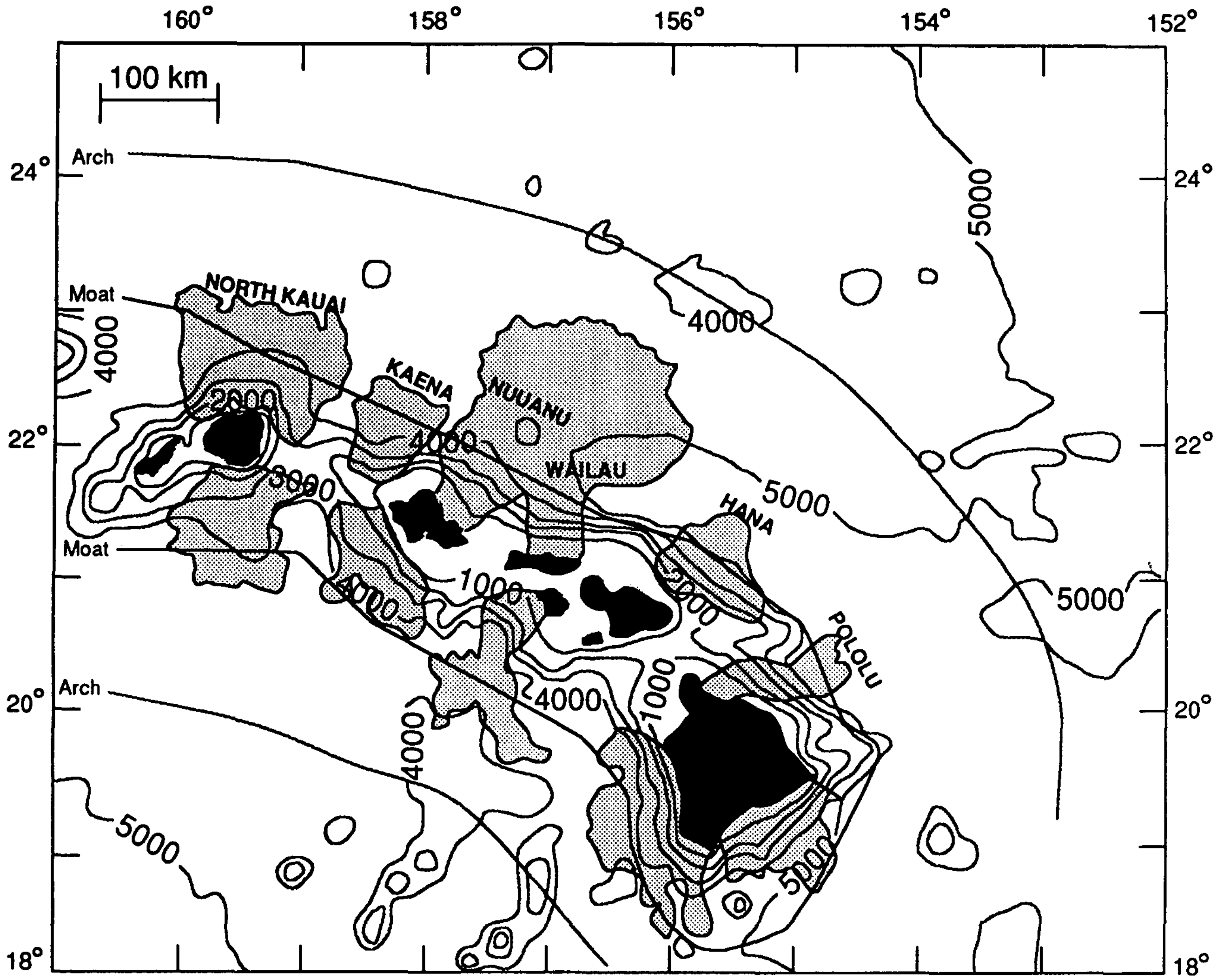

Figure 1. Map of the Hawaiian area showing the location of the islands and the flexural moat and arch. Bathymetry is 1,000-m contours from the DBDB5 data set. Gray shaded areas show the extent of the large-scale mass-wasting deposits identified from GLORIA side-scan sonar data by Moore and others (1989). Names of significant features are used in text.

argued that some additional long-term (>1 Myr) weakening and subsidence of the plate is required in order to explain the systematic backtilting of moat reflectors toward the islands seen on this profile. The alternative progressive loading model of Watts and ten Brink (1989) could not be tested with these data since long reflection profiles oriented along the axis of the moat, where the clinoform structures predicted by this model should be best developed (Fig. 2B), were unavailable.

A new perspective on sedimentary processes in the flexural moats of large volcanic islands has recently come from the discovery of spectacular submarine landslides on GLORIA side-scan sonar images collected by the U.S. Geological Survey near Hawaii (Moore and others, 1989). These surveys showed that mass-wasting deposits cover more than 100,000 km^2 of sea floor from Hawaii to Kauai (Fig. 1). The dimensions of individual submarine landslides in this area are huge; some are >200 km long and have estimated volumes of >5,000 km^3.

Moore and others (1989) identified two distinct types of mass-wasting features on the GLORIA images. Using the descriptions and terminology of Varnes (1978), they called these features "slumps" and "debris avalanches." The first type, "slump," includes broad failures that have a steep scarp at their toe, are cut by transverse faults into a few large blocks, and are thought to have moved slowly and intermittently downslope. A representative example of this type of deposit on the GLORIA images is the Hana slump off the northeast of Maui (Fig. 1). The second type of failure, "debris avalanche," identified by Moore and others (1989), is narrower and longer, displaying a well-developed amphitheater in its upper part, and large broken blocks and broad aprons of distinctly hummocky terrain in its distal end. These debris avalanches are assumed to represent a single episode of rapid failure. The Nuuanu debris avalanche northeast of Oahu is a spectacular example of one of these features (Fig. 1). It covers 23,000 km^2, crossing the flexural moat and extending another 140 km up the flank of the Hawaiian Arch. Individual blocks carried downslope in this debris avalanche are as much as tens of kilometers in dimension and rise 0.5–1.8 km above the regional elevation (Moore and others, 1989). The ages of these

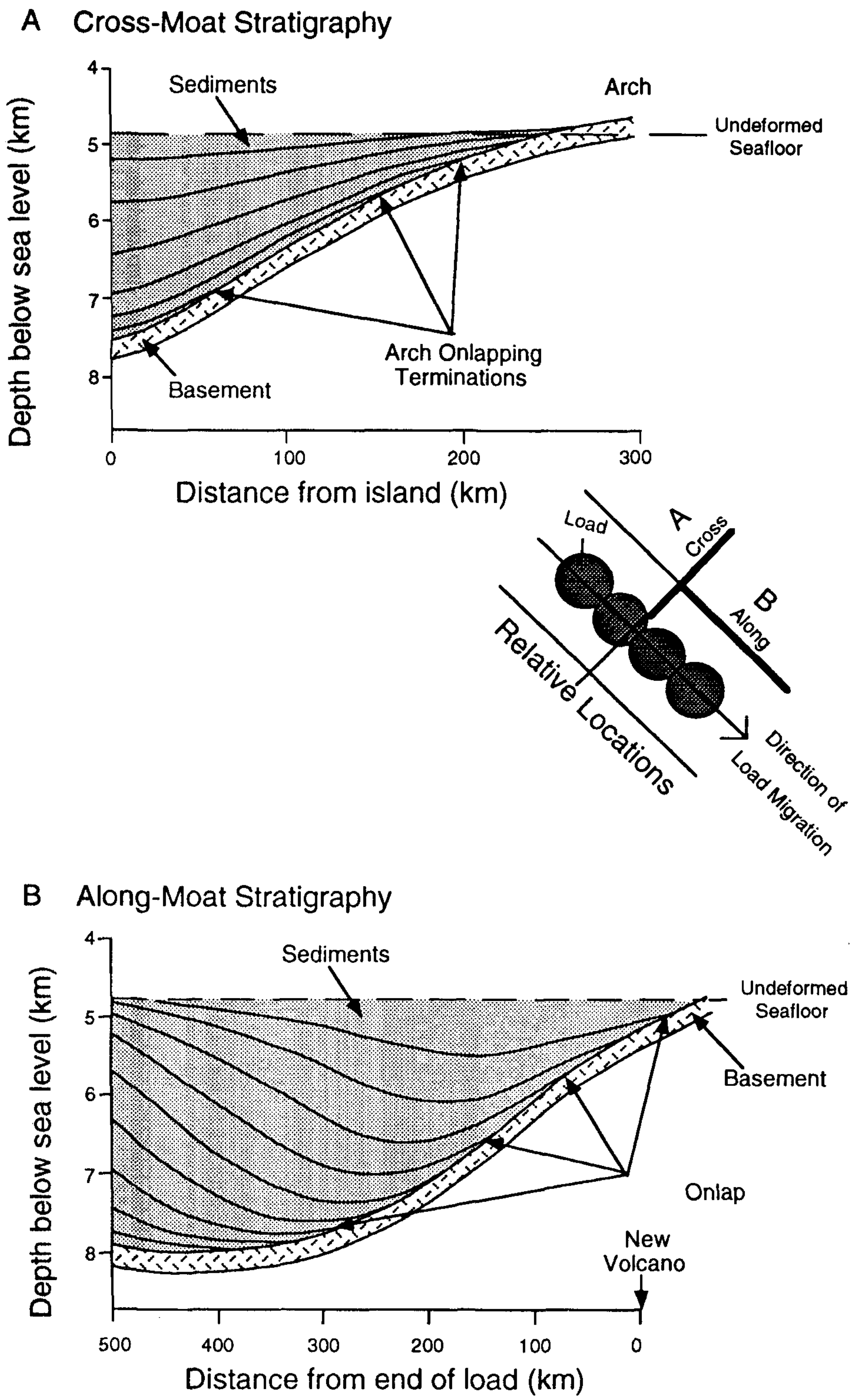

Figure 2. Synthetic seismic stratigraphy of sediments in the Hawaiian flexural moat predicted by modeling the effect of a circular load on the surface of an elastic plate, assuming a constant sedimentation rate (from Watts and ten Brink, 1989). Location of profiles A and B relative to the island chain are shown in the inset. (A) Cross-moat profile showing the predicted onlap of sediment on the flexural arch. (B) Along-moat profile showing predicted stratigraphy on seismic lines running parallel to the island chain. As the load migrates progressively to the southeast, offlap is predicted in the upper moat section, and onlap, in the lower moat section.

various slumps and debris avalanches are still poorly constrained. It appears that slope failures begin early in the history of individual volcanoes, perhaps culminate near the end of subaerial shield building, and may continue long after the volcanoes become dormant (Moore and others, 1989).

This large-scale mass wasting has been the primary sediment source for the Hawaiian flexural moat. Many of the large debris avalanche deposits mapped by Moore and others extend outward across the axis of the flexural deep and up onto the flanking arch. Huge volumes of massive or poorly bedded volcanic rock have been transported into the moat by these mass-wasting events. The largest deposits (for example, the Nuuanu and Wailau avalanches north of Oahu and Molokai) overfill the flexural moat, producing low ridges that divide the moat into a series of discrete basins and block along-moat sediment transport, particularly in the deepest portion of the moat.

The existing side-scan imagery in the Hawaiian area, although documenting the surficial expression of mass wasting, provide few constraints on the subsurface extent of these deposits or their role in the overall development of the distinctive moat stratigraphy originally identified by ten Brink and Watts (1985). In this paper, we present the results of a single-channel seismic reflection survey of the Hawaiian flexural moat. The objectives of this study are threefold: (1) to define the major stratigraphic units of sediments infilling the flexural moat, (2) to determine how the sedimentation history of the moat varies along the island chain, and (3) to identify the critical processes that affect moat sedimentation. Our results show that the Hawaiian flexural moat is filled with a stratified sedimentary section >2 km thick dominated by the products of large-scale mass wasting of the adjacent islands. The distinctive stratigraphy observed in the moat reflects the interplay between volcanic accretion, which constructs the islands; mass wasting and erosion, which destroy the islands; and distributed, regional subsidence due to the progressive loading of a strong lithosphere by the newly forming volcanoes.

DATA ACQUISITION AND PROCESSING

This study is based on ~4,400 km of single-channel seismic reflection data collected in May/June 1988 aboard the R/V *Thomas Washington*. The reflection data were obtained using two different sources: a 1.3-l watergun and a 23-l airgun array comprised of six

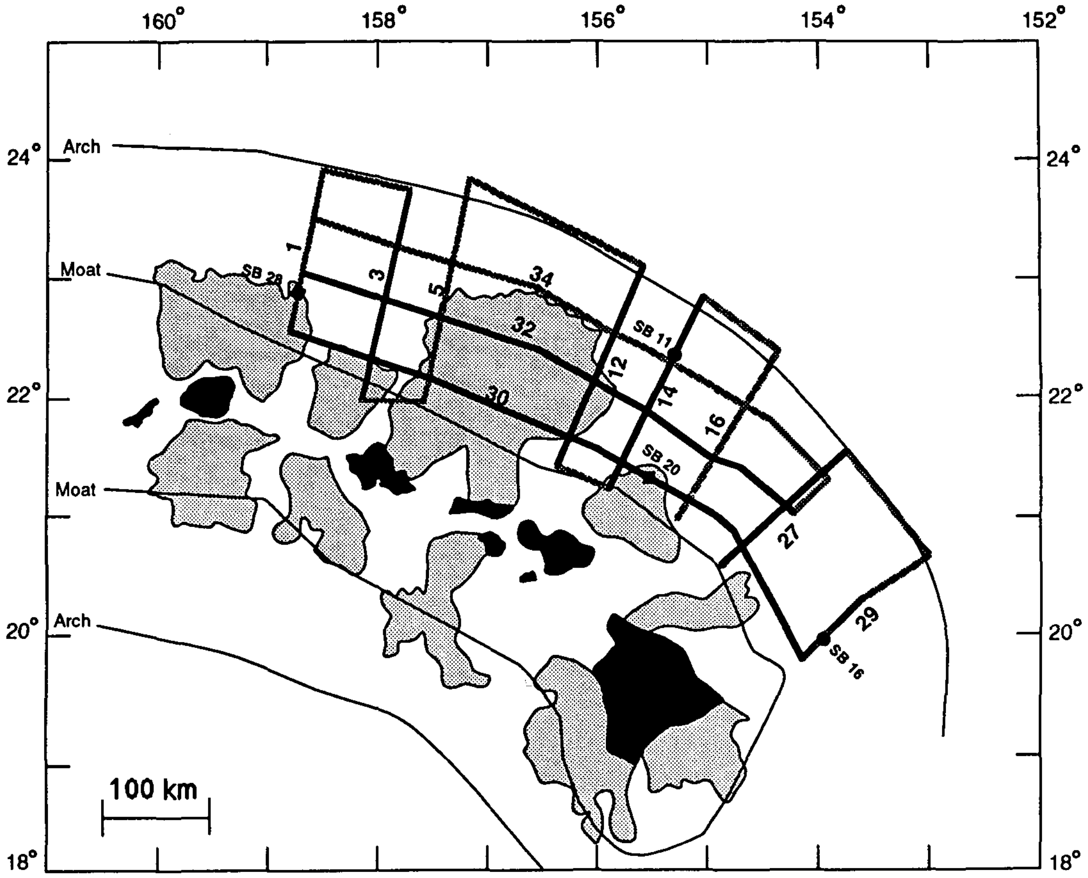

Figure 3. Locations of single-channel seismic reflection profiles collected in this study. Black lines are profiles that are shown in subsequent figures. Gray shading shows the location of the slumps and debris avalanches mapped by Moore and others (1989). Sonobuoy locations (SB) are also shown; square symbols indicate thick, high-velocity sediment solutions; circles represent thin, low-velocity sediment solutions. See text for discussion.

1900C Bolt airguns with chamber sizes of 1.3, 2.0, 2.5, 3.3, 4.9, and 9.0 l. The guns were towed ~20 m behind the ship and suspended ~10 m below the sea surface from Norwegian floats. The reflection data were received on a 50-m Teledyne single-channel streamer with 50 active elements towed ~200 m behind the ship and digitally recorded on a Scripps VAX 11/730–based digital recording system. The watergun was fired every 10 sec, and 2-sec records were recorded at a 1-msec sample interval. The airgun array was shot with either a 14- or 20-sec repetition rate and 5-sec records were recorded with a 2-msec sample interval.

On the northern side of the island chain between Hawaii and Kauai, eight ~200-km-long cross-moat profiles and three ~600-km-long moat-parallel lines were obtained (Fig. 3). The cross-moat lines were run from the foot of the Hawaiian Ridge, across the moat, and up onto the crest of the flexural arch, ~250 km from the islands. This suite of cross-moat profiles between the islands of Hawaii and Kauai were located so as to observe the development and infilling of the flexural moat during the first 5 Myr of its existence. Moat-parallel lines were located along the axis of the deepest part of the moat (line 30), approximately midway between the moat and arch (line 32), and about two-thirds of the way from the islands to the crest of the flexural arch (line 34).

Data processing was limited to bandpass filtering (15–75 Hz), spherical divergence corrections, and redisplay at a variety of scales using a time-variable gain with a 20-msec automatic gain control operator. Sediment thicknesses range from <0.1 sec two-way travel time on the arch to >1.0 sec in the deepest parts of the moat. Although a clear basement reflector is not apparent on some lines where the moat sediments are quite thick, maximum sediment thicknesses are comparable to those reported by ten Brink and Watts (1985) from multichannel reflection data north of Oahu.

We have divided the sedimentary section in the flexural moat into a series of units based on stratal terminations. The cross-moat profiles were each interpreted independently, then the unit boundaries were tied using the moat-parallel lines. The principal unit boundaries were digitized, merged with cruise navigation, gridded using an ~8-km grid interval, and machine contoured to construct maps of the major units. The isopleth maps presented here are contoured in time and referred to as "isochrons" after Sheriff (1991). These isochron maps are estimated to have an uncertainty of ±10 msec; unit thicknesses of <10 msec were set to zero.

Thirty-three SSQ-41B sonobuoys were deployed throughout the survey to provide velocity control on the sedimentary section, and independent estimates of total sediment thicknesses (Fig. 3). The sonobuoys were digitally recorded using 15-sec record lengths and a 4-msec sample interval. The sonobuoy records were filtered 5–80 Hz and then interpreted using the tau-sum inversion method (Diebold and Stoffa, 1981). The solutions fall into two main groups. The sonobuoys shot near the flexural arch (for example, SB11; Fig. 4A) are characterized by a thin sediment section (<0.3 km), with relatively low seismic velocities (<2–3.8 km/s) overlying oceanic basement (V_p 5–6 km/s). We interpret these low-velocity solutions to be the result of a sediment layer composed predominantly of pelagic sediments, with some small component of mass-wasting (island-derived) sediments. In contrast, sonobuoys shot over the axis of the moat (for example, SB20; Fig. 4B)

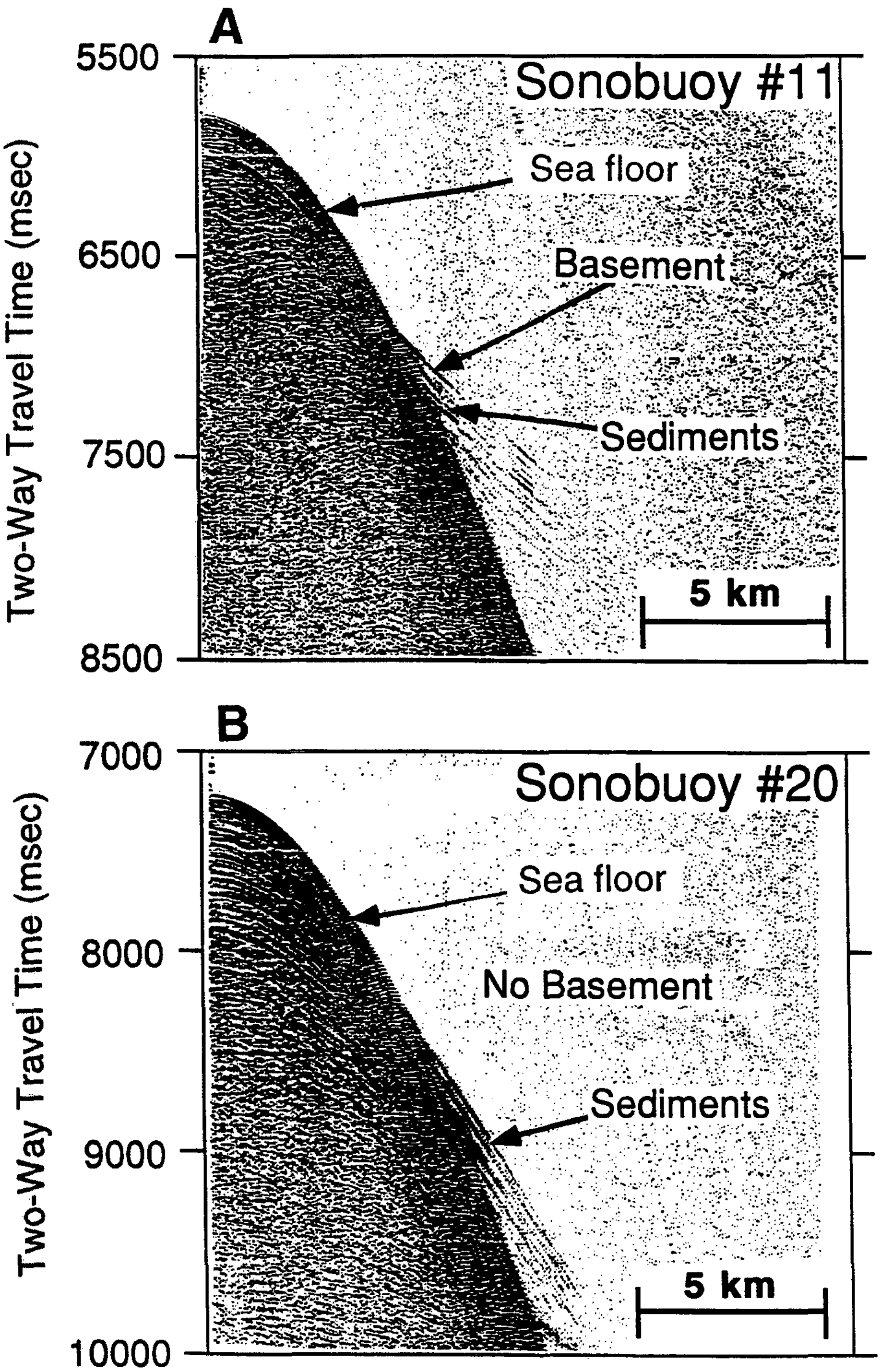

Figure 4. Examples of sonobuoy data from the Hawaiian moat. For locations, refer to Figure 3. (A) SB11, showing thin veneer of low-velocity sediments. (B) SB20, showing thick, high-velocity sediment cover. No basement refractor is apparent on this sonobuoy, indicating the presence of a thick sedimentary section.

reveal higher sediment velocities, increasing from about 3.7 km/s at the sediment/water interface to ~4.7 km/s in the deeper part of the sedimentary section. Similarly high seismic velocities (3.5–4.4 km/s) were also reported by ten Brink and Watts (1985) within the flexural moat. These high velocities suggest the presence of volcanic material in the more-proximal portions of the moat. Using these velocities, and the observed two-way travel times to basement, the total sediment thickness within the moat exceeds 2 km.

DESCRIPTION OF MOAT STRATIGRAPHY

Figures 5 and 6 show representative examples of four cross-moat profiles (lines 27, 14, 12, and 3) and a moat-parallel line (32). For purposes of description, we have divided the moat sediments into four major lithostratigraphic units based on their reflection character (Fig. 7): (1) a basal unit of relatively constant thickness that predates the formation of the flexural moat; (2) a unit of layered, continuous reflectors, interbedded with chaotic sequences, that onlaps the flexural arch and thickens toward the islands; (3) an offlapping unit composed of highly reflective continuous horizons that is backtilted toward the islands; and (4) an upper, distinctly layered unit that is ponded in the deepest parts of the moat.

Various terms (debris avalanches, debris flows, slides, slumps) have been used to describe the products of massive slope failures or landslides (Nardin and others, 1979; Varnes, 1978; Hansen, 1984). Classically, these features are defined in terms of their grain size, internal structure, or the mass-transport processes by which they formed. In contrast, the features described in this paper are defined seismically in terms of reflection character and stratal terminations (discordant chaotic units with no internal structure, onlapping or offlapping layered units, acoustically transparent units, etc.). Using only reflection data, we cannot easily differentiate between the various products of mass wasting in a genetic sense. We therefore use the general term "landslide unit" to describe the lenticular, chaotic reflector sequences and bounding concordant bundles of reflectors that we believe are the product of large-scale submarine mass wasting along the Hawaiian Ridge. Genetically, these features may be the product of debris avalanches, flows, slides, slumps, or some combination of these processes. This usage is consistent with that of Moore and others (1989).

Basal Unit

A clear basement reflection from the top of oceanic crust is not observed in the deeper parts of the moat on our single-channel profiles. Where basement is imaged, the lowermost unit is of approximately constant thickness, appearing to drape and infill the rough basement topography. We interpret this unit

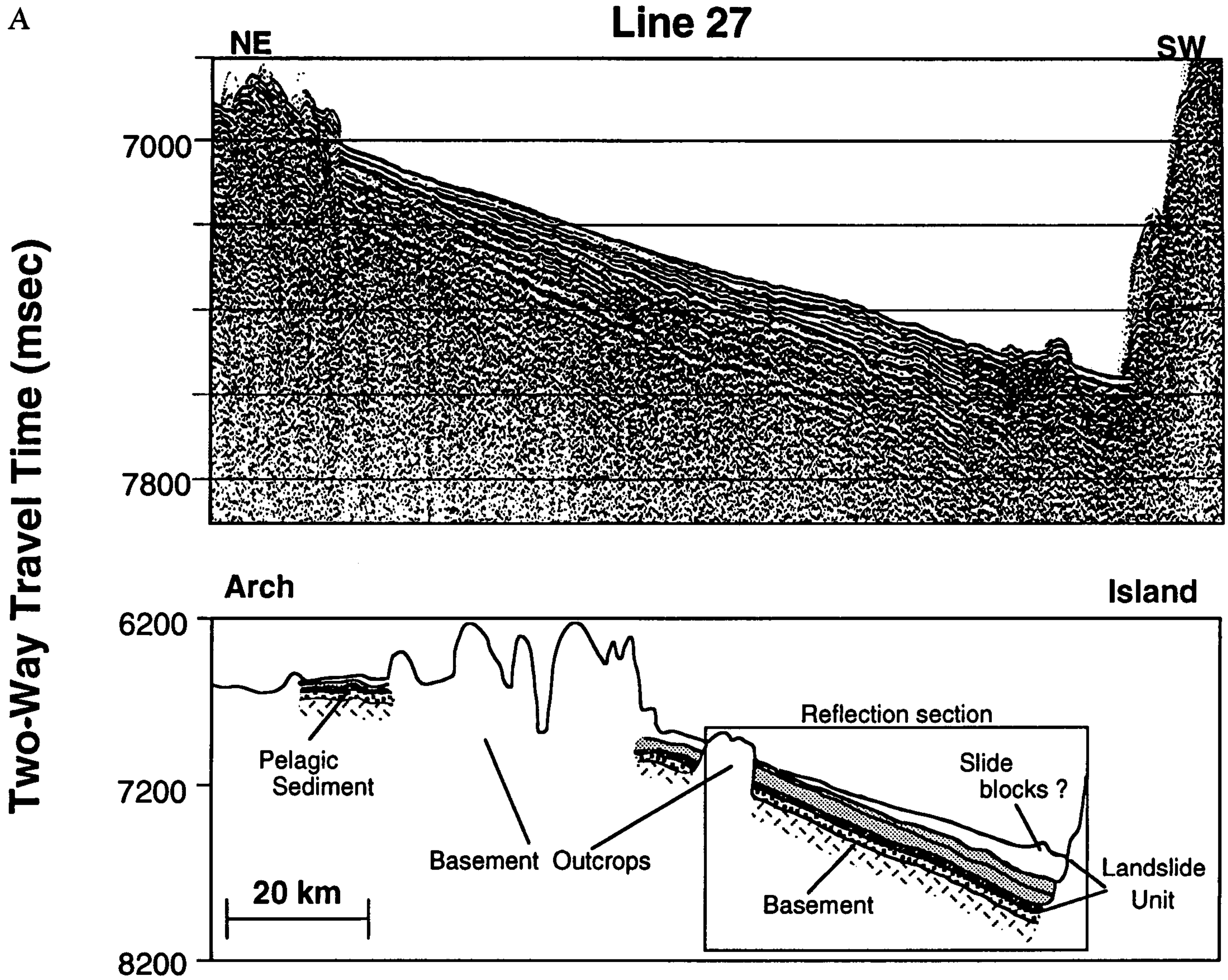

Figure 5. Cross-moat reflection profiles and interpretations for (A) line 27, (B) line 14, (C) line 12, and (D) line 3, shown in order of increasing age. For location of lines see Figure 3. An interpretive section is shown in the lower panel for the entire line. The upper panel shows a portion of the original seismic data (indicated by the box in the lower panel) plotted at an expanded scale. In the lower panel, horizontal lines represent the ponded unit; light-gray pattern represents the offlapping unit; white and darker shades of gray represent sub-units within the landslide deposit; dot pattern represents pelagic sediments; dash pattern represents basement. Blank areas under diffractions represent areas where no coherent reflections can be traced.

as pelagic sediment that predates the formation of the flexural moat. Its thickness is typically less than 200 m (Winterer, 1989).

Landslide Unit

Overlying the basal pelagic layer is a thick wedge of sediment that progressively onlaps the flexural arch and thickens toward the islands (Fig. 7). This unit, which comprises the bulk of the sediment in the flexural moat, consists of a series of stacked lens- or wedge-shaped sub-units. Each sub-unit has a central chaotic zone characterized by diffractions showing little or no coherent internal structure on the seismic profiles. Above, below, and extending away from this chaotic zone are relatively thin, highly reflective, continuous horizons (Fig. 8). In areas where the lens is shallow in the section, it is often associated with rough, diffractive, hummocky sea-floor topography (Fig. 5A, line 27). Moat-parallel profiles (Fig. 6) show that major sub-units can extend for as much as 200 km along the moat. The largest sub-units are as much as 700 m thick near their axis, pinching out along the moat.

We interpret these features as the subsurface expression of older, buried slumps and debris avalanches, like those mapped at the sea floor on GLORIA side-scan sonar records around Hawaii (Moore and others, 1989). The incoherent, diffractive energy in each lens is believed to result from large basaltic blocks (hundreds of meters or more on a side) embedded in a matrix of poorly sorted volcanic debris. The continuous reflectors extending out from this chaotic zone may represent finer-grained, better-sorted turbidities that form the distal facies of these landslide deposits.

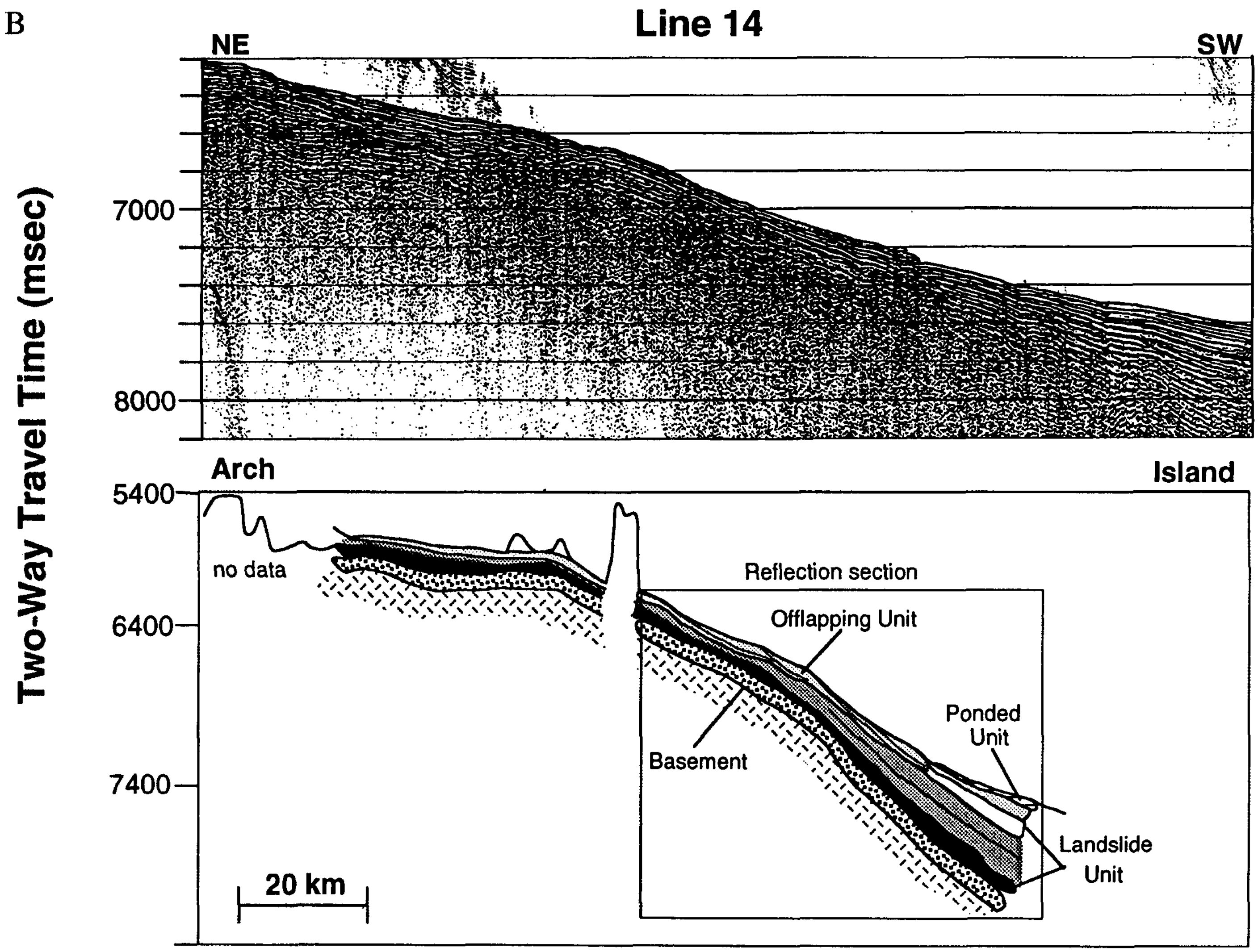

Figure 5. ***(Continued).***

Similar seismic sequences have been reported associated with slope failure and mass wasting along sedimented continental margins (Coleman and Prior, 1988).

Figure 9 shows an isochron map for this landslide unit. It has an overall wedge shape in cross section, indicating that the islands are the source of these deposits. Along moat, the unit thins to the southeast, in the direction of decreasing island age. The landslide unit is thickest north of Oahu, to the west of the Nuuanu/Wailau debris avalanches. In this area, the flexural moat is almost completely filled. Northwest of Oahu, we see four distinguishable sub-units (Fig. 5D) that cover the entire sub-basin. North of Molokai and Maui, only three sub-units are present, one of which is of limited extent (Fig. 5B). Farther east, near the island of Hawaii, the landslide unit consists of three relatively thin sub-units (Fig. 5A). These units may actually be the distal ends of debris avalanches off older islands that have flowed down the axis of the moat toward Hawaii.

Offlapping Unit

Overlying, and sometimes interbedded with, the landslide unit is a sequence of highly reflective, continuous horizons that offlap the flexural arch (Fig. 10). This unit thickens and tilts down toward the moat, indicating continued subsidence of the moat and the adjacent islands. The isochron for this unit shows that the unit is thickest in the basins between major surficial mass-wasting deposits (Fig. 11), for example, in the relatively narrow basin between the Wailau and Hana events, and directly off the northeastern flank of the Hana slide. The unit generally thins to the southeast, where the moat is still developing and large-scale mass wasting from the younger islands is just beginning. We also interpret the offlapping unit as a product of large-scale mass wasting, either the distal facies of the landslide deposits or turbidites associated with smaller-scale slope failures.

Ponded Unit

The youngest sediment in the section is ponded in the deepest portions of the flexural moat. This unit, which we call the ponded unit (Fig. 7), is comprised of sediments that infill

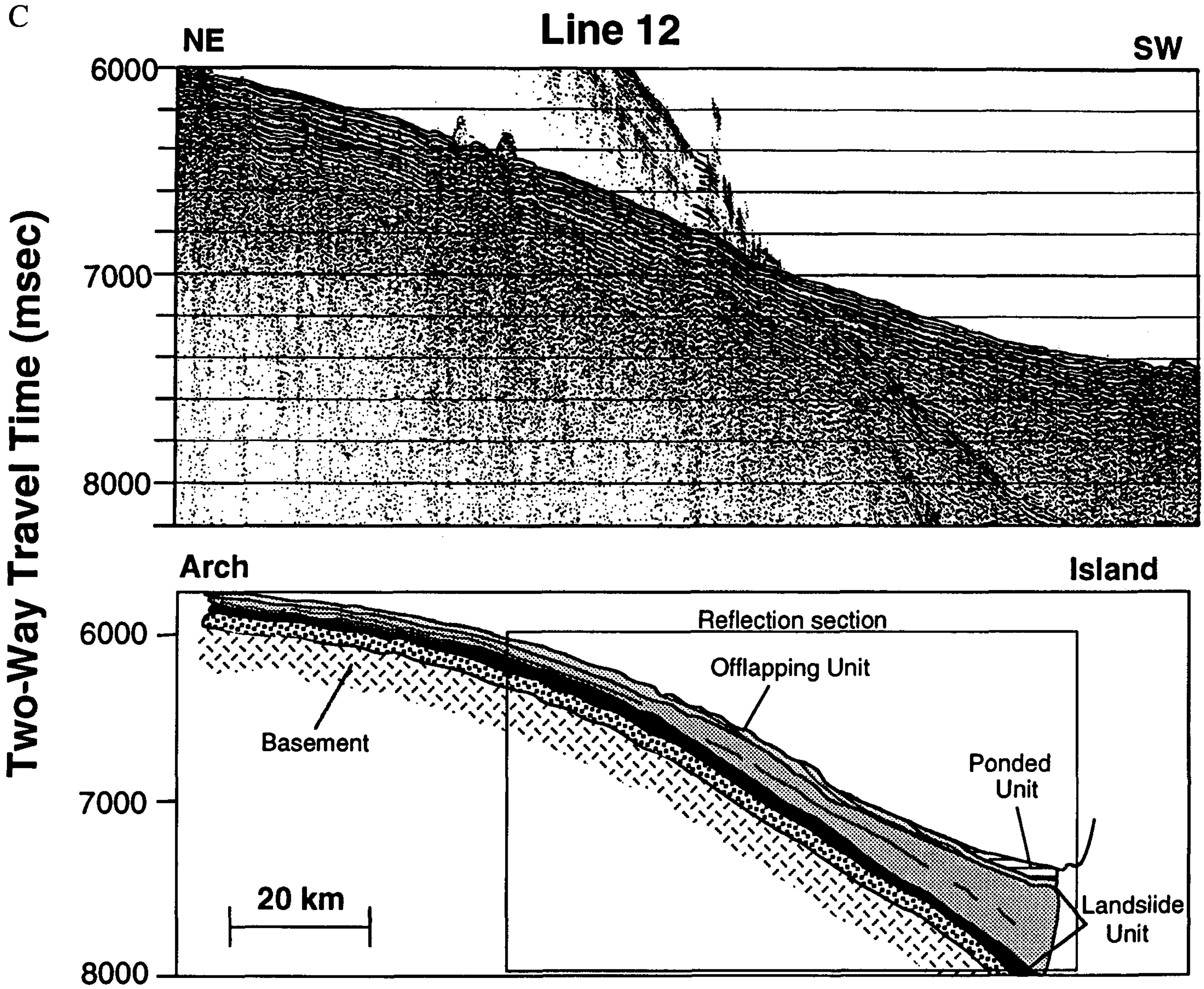

Figure 5. (*Continued*).

local depressions. These strong, coherent events are discordant with the underlying moat reflectors (Fig. 12) and do not extend more than one quarter of the distance between the moat and arch (Fig. 5). The reflectors in the ponded unit are nearly horizontal, indicating little or no post-depositional tilting, in contrast to the older offlapping unit, which lies below. The ponded unit is quite variable in thickness. It reaches a maximum thickness of 100 msec (~185 m) in the local depression between the North Kauai and Nuuanu avalanches and between the Wailau and Hana deposits (Fig. 13). The ponded unit pinches out against the broad ridges formed by these large-scale landslide deposits (Fig. 13). The easternmost lines (for example, Fig. 5A) do not show the type of localized depression that is filled by the ponded unit on the other, older lines.

An isochron map of the overall sediment thickness in the northern Hawaiian flexural moat is shown in Figure 14. The sediments are thickest north of Oahu and thin to the southeast. Sediment two-way travel times of >1 sec, given the average sediment velocities of 4 km/sec derived from sonobuoys 20 and 28, give an overall thickness of >2 km for the thickest sediments in the moat. These results are in good agreement with the ten Brink and Watts (1985) estimate of 2.2 km of sediment in the deepest portions of the moat near Oahu. The overall volume of sediment within the moat is in excess of 90,000 km^3.

STRUCTURE OF THE LANDSLIDE UNIT

Large-scale mass wasting has played a major role in the sedimentary history of the Hawaiian flexural moat. Its effects are twofold. First, massive debris avalanches and slumps from the adjacent islands have carried huge volumes of volcanic material into the moat episodically throughout the history of the islands. In essence, the moat stratigraphy can be considered as a series of stacked landslide deposits. Large-scale mass wasting has also played a key role in controlling along-moat sediment transport. The largest debris avalanches extend completely across the moat, well up onto the flanking arch, forming deposit lobes that segment the moat into a series

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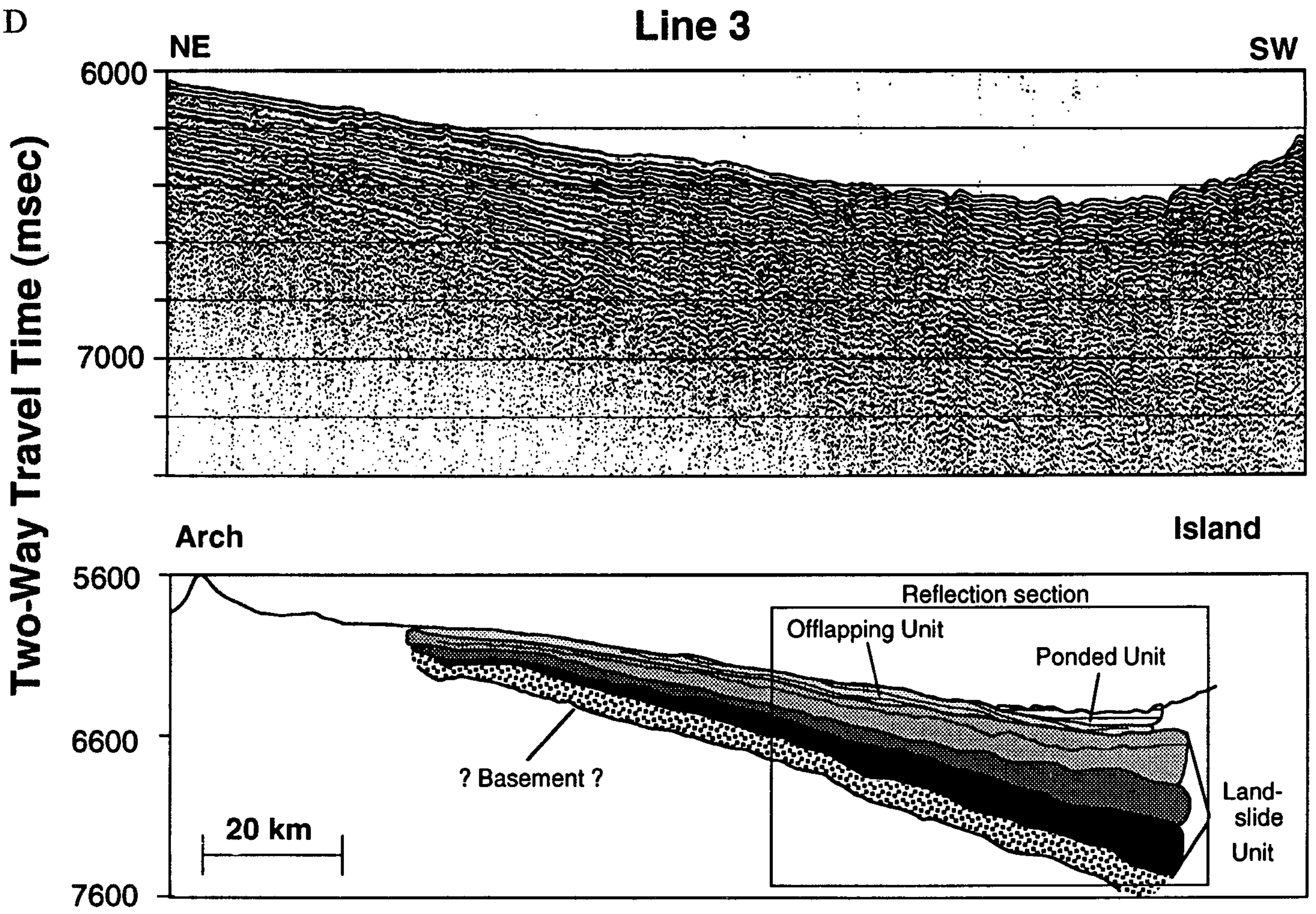

of isolated sub-basins (Fig. 1). Each successive landslide unit travels down and extends on a continuous slope from the source on the islands. Younger events have thus been channeled and limited by topographic barriers constructed by earlier, larger events.

The distribution and shape of the sub-units within the landslide deposits suggest that the main locus of mass wasting moves from west to east as the Pacific plate moves northwest relative to the Hawaiian hotspot. It is important to note, however, that we have no absolute age data on any of the units within our study. Therefore, all age assessments are made based on stratigraphic superposition and termination geometry. In the following section, we suggest island sources for the various subsurface landslide units. These interpretations are based on a comparison of the shapes of the units with the locations of the slumps and debris avalanches mapped at the sea floor by GLORIA.

Figure 15 summarizes the structure of the landslide unit in the western portion of our study area on the basis of our interpretation of the seismic reflection data obtained in this study. There are five major sub-units that can be identified in this area. The lowermost one, L1 (isochroned in Fig. 15A) is the oldest landslide unit we have defined. It covers ~130,000 km^2 and has a volume of ~20,500 km^3. It is visible in both the Kauai deep and the Maui deep. Line 32, midway between the moat and the arch, defines the continuity of this unit (Fig. 6). The thinning of this deposit to the east, particularly in the Maui deep, suggests that it originated from the western, older portion of the island chain.

A second landslide sub-unit, L2, is shown in Figure 15B. This deposit is confined to the western portion of our study area, the Kauai deep. Within the study area, this flow covers 83,000 km^2; it potentially could also cover a large area west of our data set. Although the eastern termination of this event is visible on line 32, this unit is not discernible in the deepest portion of the moat, where the recent Nuuanu/Wailau deposit masks the stratigraphy of the underlying section.

Above L2 are two sub-units, L3 and L4, which cover approximately the same 100,000 km^2 area north of the islands of Oahu and Molokai. They have, therefore, been isochroned together in Figure 15C. Their combined volumes are about 34,000 km^3. The western portion of these two enormous mass-wasting deposits almost totally fill the Kauai deep. The shapes of these sub-units suggest that they may have originated from Oahu and Molokai, the same islands that were the source of the younger Nuuanu and Wailau debris avalanches mapped in the GLORIA data.

The uppermost sub-unit, L5 (isochroned in Fig. 15D) appears to have originated from Maui, similar to the recent Hana slump. This small deposit covers 63,000 km^2 and is about 7,300 km^3 in volume; markedly smaller than any of the older events. The onlap and thin-

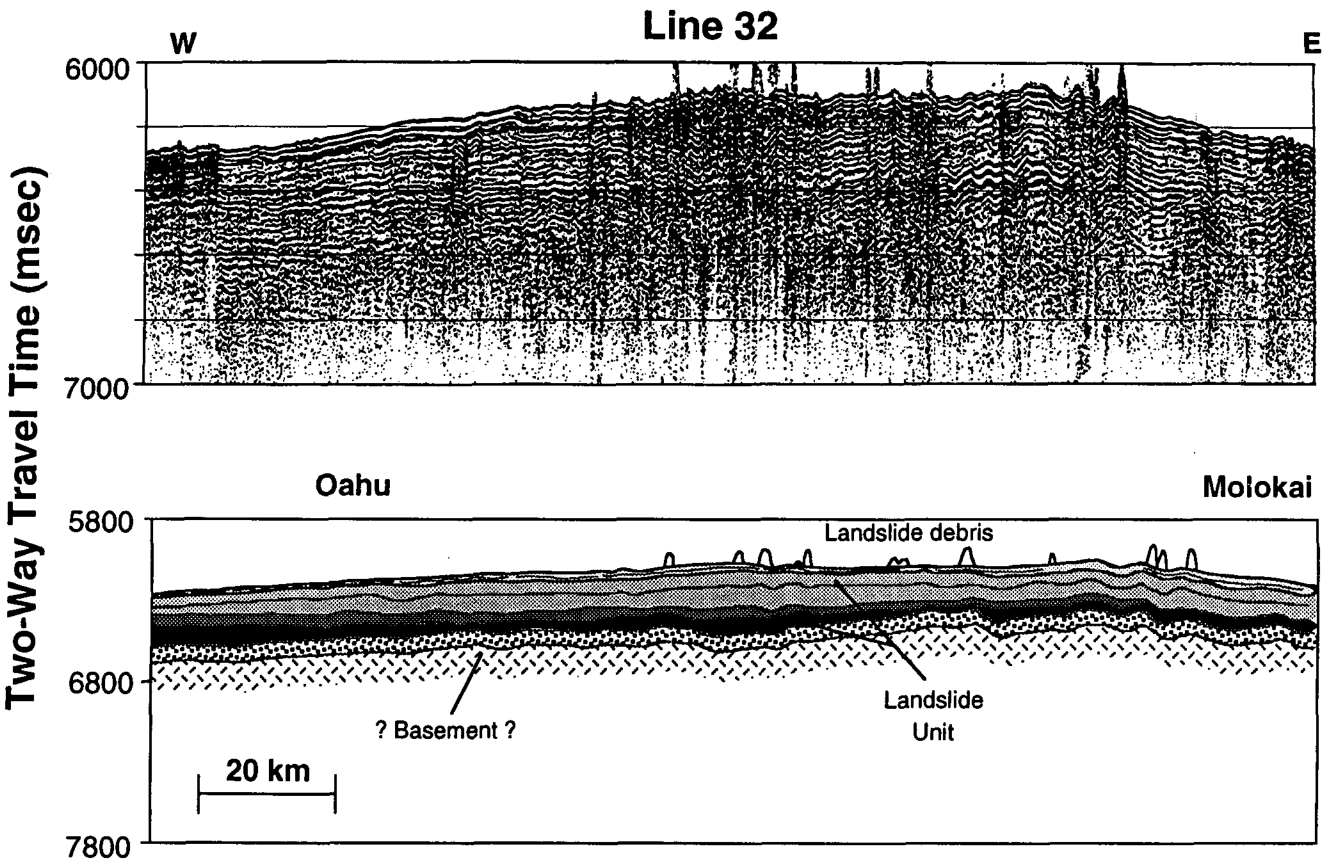

Figure 6. Moat-parallel section and interpretation of line 32, located midway between the moat and arch. For pattern descriptions, refer to Figure 5 caption.

ning of this sub-unit onto the bordering Wailau deposit at the eastern edge of the Maui deep is an excellent illustration of how older mass-wasting deposits can affect the paths of younger landslides (Moore and others, 1989).

Note that the locus of large-scale mass wasting has generally moved from northwest to southeast over time. The older lenses within the landslide unit appear to have originated no farther east than Molokai. In comparison, the younger mass-wasting events have their major expressions east of the Maui Deep.

HISTORY OF MOAT SEDIMENTATION

The observed stratigraphy of the Hawaiian flexural moat results from the competing effects of sediment influx to the moat, principally from large-scale mass wasting, and regional subsidence due to flexure of the lithosphere beneath successive loads of newly forming volcanoes. If the subsidence and sedimentation rates are equal, then as a

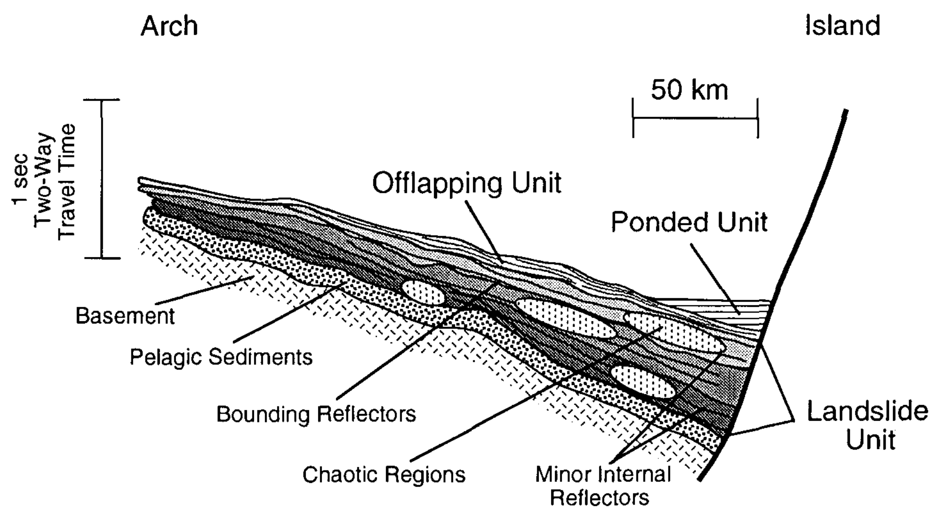

Figure 7. Idealized moat stratigraphy based on synthesis of all cross-moat lines. For pattern descriptions, refer to Figure 5 caption. For detailed descriptions of individual units, refer to text.

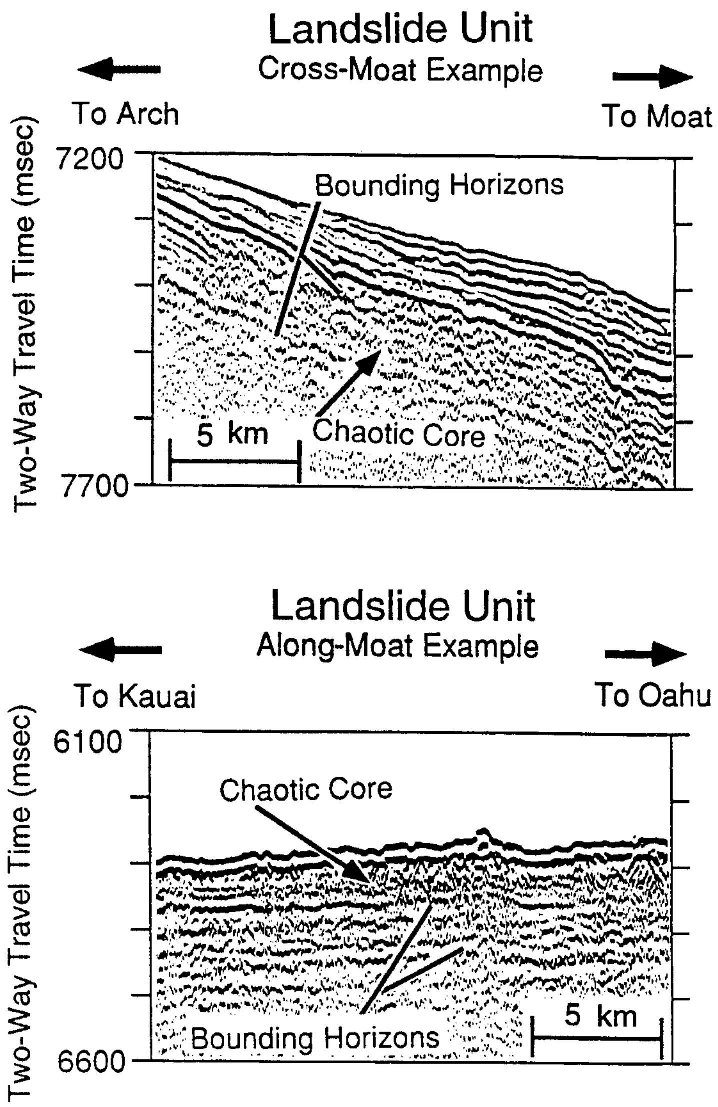

Figure 8. Examples of landslide unit. Cross-moat example from line 27. Along-moat example from line 32. We interpret the lenticular chaotic reflectors as the subsurface expression of older, buried slumps and debris avalanches like those mapped at the sea floor on GLORIA side-scan sonar records around Hawaii.

particular load ages, its flexural moat will continually be filled to the level of the adjacent sea floor and no unusual depression will be observed at any time. If, however, the subsidence and sedimentation rates are not equal, then the moat will vary in depth with time. When subsidence rates exceed sedimentation rates, the moat will deepen. We refer to the moat in this stage as being "underfilled." In contrast, when sedimentation rates exceed subsidence rates, the moat will shoal as it is gradually filled with sediment. We describe a moat in this stage as "infilling."

Subsidence rates and sediment input vary systematically throughout the development of the moat. While a new volcanic edifice is still forming, subsidence exceeds sediment input and the moat is initially underfilled. Once the island rises above sea level, erosion and mass wasting accelerate, beginning the process that eventually fills the moat. Because of the episodic nature of both the construction of new volcanoes and large-scale mass-wasting events, the stratigraphic units we have identified within the flexural moat do not represent an absolute growth cycle that the moat experiences only once. Instead, these units and their characteristic stratal patterns are markers for changes in the balance between sediment input and flexural subsidence. In the next few paragraphs, we describe the history of the moat, explain the temporal changes in sediment influx and subsidence, and describe how these changes generate the observed stratigraphy. We divide this history into four periods labeled as stages 1–4.

Stage 1

As each new volcano in the chain forms, it loads the underlying lithosphere, creating a flexural moat (Fig. 16A). At this point, only 50–100 m of predominantly pelagic sediment, identified in our sections as the "basal unit," blankets volcanic basement. The flexural moat around each new island forms very rapidly, essentially contemporaneously with the construction of the volcano (Bodine and others, 1981). Since the influx of sediment to the moat appears to significantly lag basement subsidence during this stage of island growth, an underfilled depression or moat surrounds the island and becomes the principal expression of flexural response to loading. An example of this early stage of subsidence-dominated moat development is the closed-contour topographic low around the northern and southeastern parts of the island of Hawaii (Fig. 1). Figure 5A shows a cross section of this part of the moat.

Stage 2

In this stage, the moat begins to fill with volcanic debris. Although evidence exists for significant slope failures early in the construction of Hawaiian volcanoes (for example, Normark and others, 1979; Malahoff, 1987), the primary source of material in this stage may be debris transported *along* the axis of the moat from large-scale mass wasting associated with older islands in the chain (Fig. 16B). This forms the lower part of what we have called the "landslide unit," which consists of thinner, layered units without the chaotic lenses that characterize the upper part of the section. During this stage, the new volcano continues to grow and flexural subsidence exceeds the influx of sediment, resulting in a continued deepening of the moat. Figure 5B, off the northeast coast of Maui, represents the moat near the end of stage 2, when subsidence is farthest ahead of sediment supply and the moat is the most underfilled.

Stage 3

The moat enters into stage 3 when the influx of material from mass wasting exceeds subsidence related to flexural loading of the plate. The moat begins to fill as massive

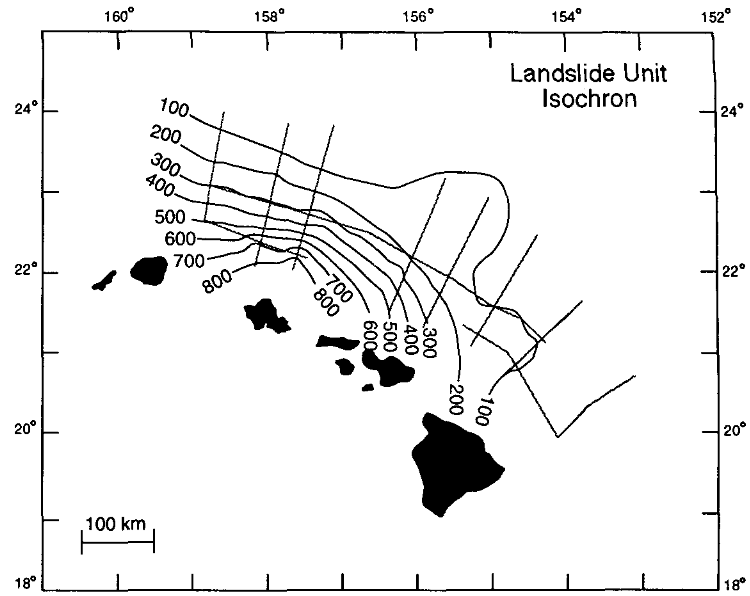

Figure 9. Isochron map of the landslide unit, contour interval is 100 msec of two-way travel time. Track lines show data distribution. The unit is wedge shaped and thins away from the island chain.

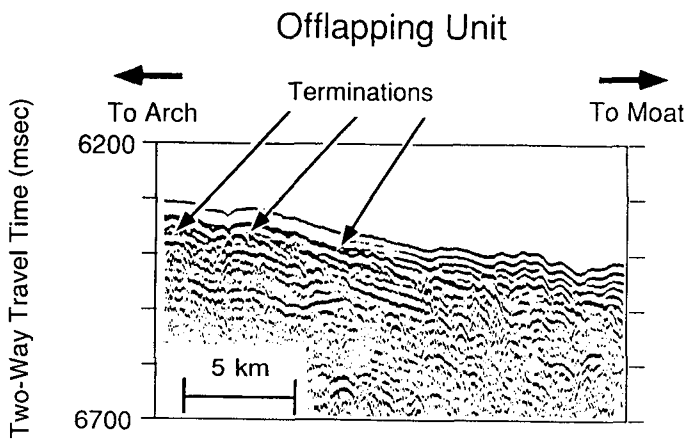

Figure 10. Example of the offlapping unit from line 3. Note back-stepping of terminations in the upper portion of the section.

slumps and debris avalanches carry huge volumes of blocky or poorly sorted volcanic rock into the moat (stage 3a in Fig. 16). These large-scale mass-wasting events may result from the instability of the unbuttressed flanks of the islands, particularly along active rift zones (Coakley and others, in press). The subaerial expression of these massive slope failures are the high cliffs along the coasts of some islands, such as the Nuuanu Pali on Oahu, the Napali coast of Kauai, and the northern shore of Molokai (Moore and others, 1989). Each event can carry several thousands to several tens of thousands of cubic kilometers of material into the moat. They represent the bulk of the material filling the

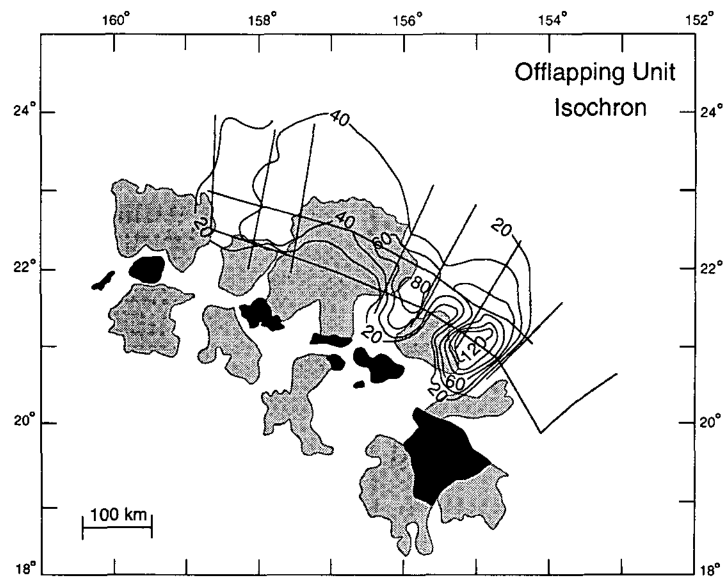

Figure 11. Isochron of the offlapping unit; contour interval is 20 msec of two-way travel time. Track lines show data distribution. Gray features are large-scale mass-wasting events from Moore and others (1989). The offlapping is thickest directly adjacent to these mass-wasting deposits.

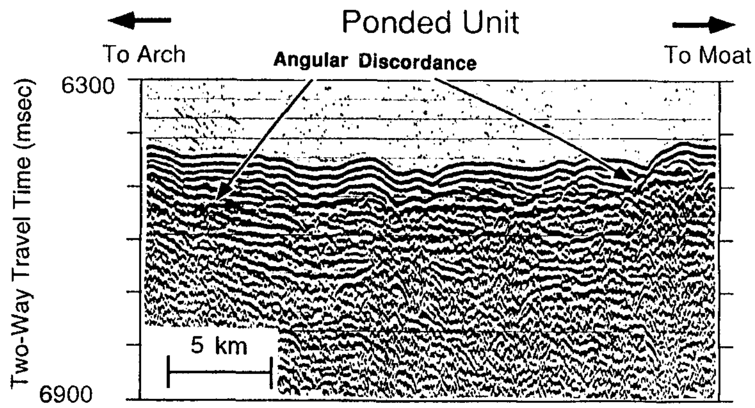

Figure 12. Example of the ponded unit from line 14. The ponded unit onlaps the flexural arch and typically terminates against basement outcrops or large slide blocks.

flexural moat. Figure 5C, which crosses the moat between Maui and Molokai, illustrates this stage of moat development.

The large-scale mass-wasting events that supply the bulk of the sediment filling the moat are, by their nature, episodic. In between these catastrophic events, the moat will continue to be filled, albeit at a much slower rate, by material eroded from the adjacent islands or transported along the axis of the moat from distant debris avalanches (stage 3b in Fig. 16). The extent to which the moat is filled depends largely on the timing and spacing of the next island. If the next island is relatively close, it will backtilt the pre-existing sediments and gradually drown the source of those sediments, leading to the formation of an offlapping sequence of reflectors. Progressive erosion and continued subsidence of the adjacent islands will gradually reduce the volume of this material carried into and along the moat, and deposition will increasingly be confined to the deeper parts of the moat. These two effects combine to create the tilted, offlapping sequence of reflectors we have called the "offlapping unit."

Stage 4

In the final, fourth stage of moat development, flexural subsidence of the moat effectively ceases, and continuing sediment influx forms what we call the "ponded unit" in the deepest part of the moat. The horizontal orientation of the reflectors in this unit indicate little post-depositional subsidence and tilting. The angular discordance at the base of the ponded unit requires a depositional hiatus between this unit and the underlying section. The origin of this rejuvenated sediment influx to the moat is unclear; it could be related to uplift of older islands as they pass over the flexural bulge of Hawaii or to a unique event such as the Pleistocene low stand of sea level. Figure 5D, the area which crosses the moat between Oahu and Kauai, is an example of the moat in this stage of development.

Presenting the stratigraphic model in a progressive, "stage" form as we have done in Figure 16 runs the risk of the model being interpreted as unidirectional. It is important to stress that although there is a general progression from stage 1 to stage 4 as the moat ages, the formation of the mass wasting and offlapping units overlap in time. Successive slope failures and landslides will send a moat in stage 3 back to stage 2. After a major episode of mass wasting, turbidites forming the

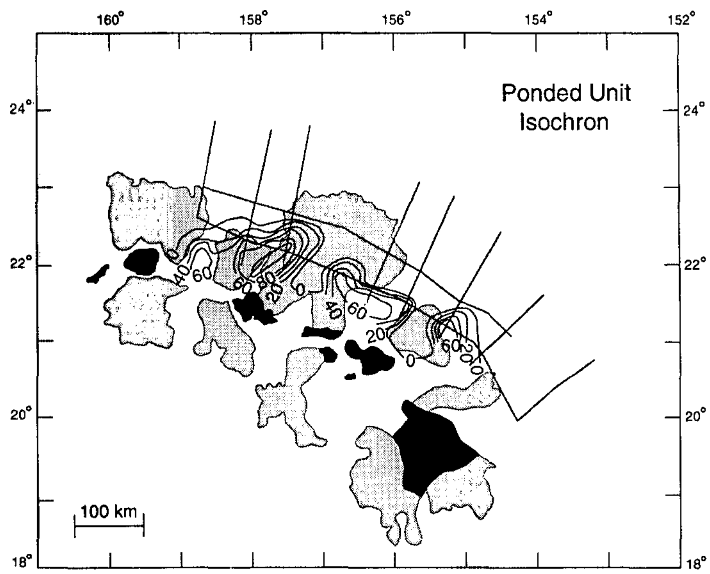

Figure 13. Isochron map of the ponded unit; contour interval is 20 msec of two-way travel time. Track lines show data distribution. Gray features are large-scale mass-wasting events from Moore and others (1989). The ponded unit is thickest in the deepest portions of the moat and in the moat between the large-scale mass-wasting deposits.

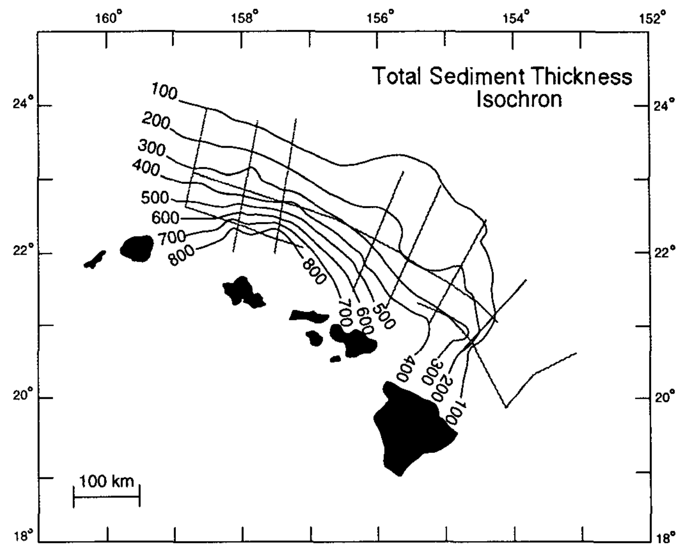

Figure 14. Isochron of total sediment thickness; contour interval is 100 msec of two-way travel time. Track lines show data distribution. On the basis of sonobuoy-derived velocities, these two-way travel times give maximum sediment thickness of >2 km. Calculated volume of sediments within the moat is in excess of 90,000 km^3.

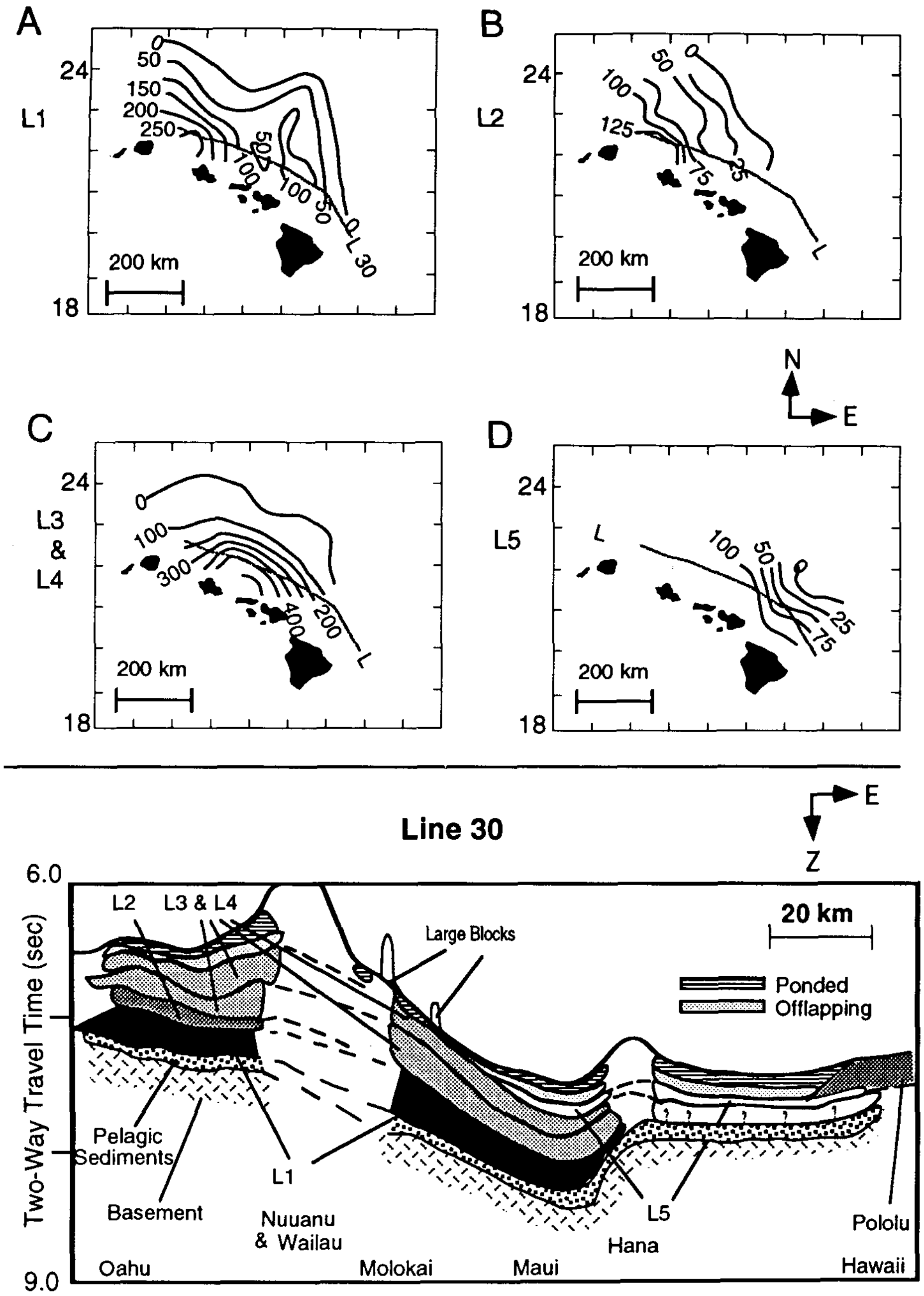

Figure 15. Structure of the landslide unit. Panels A–D are isochron maps (contours in various increments of two-way travel time) showing thickness and extent of individual deposits, from oldest to youngest, within this unit. Bottom panel is interpretation of line 30 located along the deepest portion of the moat. This interpretation shows the relative positions of the landslide sub-units labeled L1–L5 and isochroned in panels A–D.

offlapping and ponded units will gradually bury the irregular topography left by a landslide. The major stratigraphic units we have identified within the flexural moat thus do not necessarily represent individual depositional events but instead should be viewed as markers for changes in the balance between sediment input and flexural subsidence.

DISCUSSION

Large-Scale Mass Wasting in Other Contexts

Large-scale mass wasting in the Hawaiian area has been controversial since it was first suggested by Dana (1890). Over the past 30 years, the process of mass wasting has been called on to explain various localized features, such as the blocky topography on the north flanks of Molokai and Oahu (Moore, 1964), and Kilauea's nearby Papa'u seamount (Fornari and others, 1979). Surprisingly, however, until the GLORIA side-scan data were collected in the late 1980s, large-scale mass wasting was not widely accepted as an important process in the erosion of the islands and the depositional history of the flexural moat. The reflection data from this survey are limited to the northern flexural moat. However, both GLORIA side-scan sonar data (Moore and others, 1989) and the limited seismic data available across the southern moat (for example, Watts and others, 1985) indicate that slope failures are common on both sides of the Hawaiian Ridge. The results presented here show that large-scale mass wasting is an important process throughout the development and filling of the flexural moat surrounding the Hawaiian Islands.

There is no reason to believe that the large-scale mass wasting associated with Hawaiian volcanoes is unique to this island chain. A Sea Beam survey around Piton de la Fournaise, the active volcano on La Reunion, provides strong evidence to support previous suggestions by Kieffer and Vincent (1978) and Duffield and others (1982) that the Grand Brule trough on the east side of Fournaise is a landslide feature (Lenat and others, 1989). Recent geophysical studies of the Marquesas island chain have shown that the archipelagic apron associated with these islands is also derived almost entirely from large-scale mass-wasting processes (Filmer and others, 1992). Like the Nuuanu Pali on Oahu, many of the Marquesas islands are truncated by massive scarps, giving the appearance that large sections of these islands have slid down into the adjacent moat. Filmer and others (1992) estimate the volume of apron sediments at ~118,000 km^3, with thicknesses reaching ~2 km in the deepest portions of the moat near the edge of the volcanic edifice. There is thus strong evidence that large-scale mass wasting is important in the history of many large sea-floor volcanoes.

Flexural and Stratigraphic Modeling

One motivation for this study was to see if the seismic stratigraphy of volcanic flexural moats, and the age and tilting of individual horizons, could be used as a record of the mechanical response of the oceanic lithosphere to the emplacement of a large surface load. Previous modeling work makes specific predictions about the patterns of onlap and

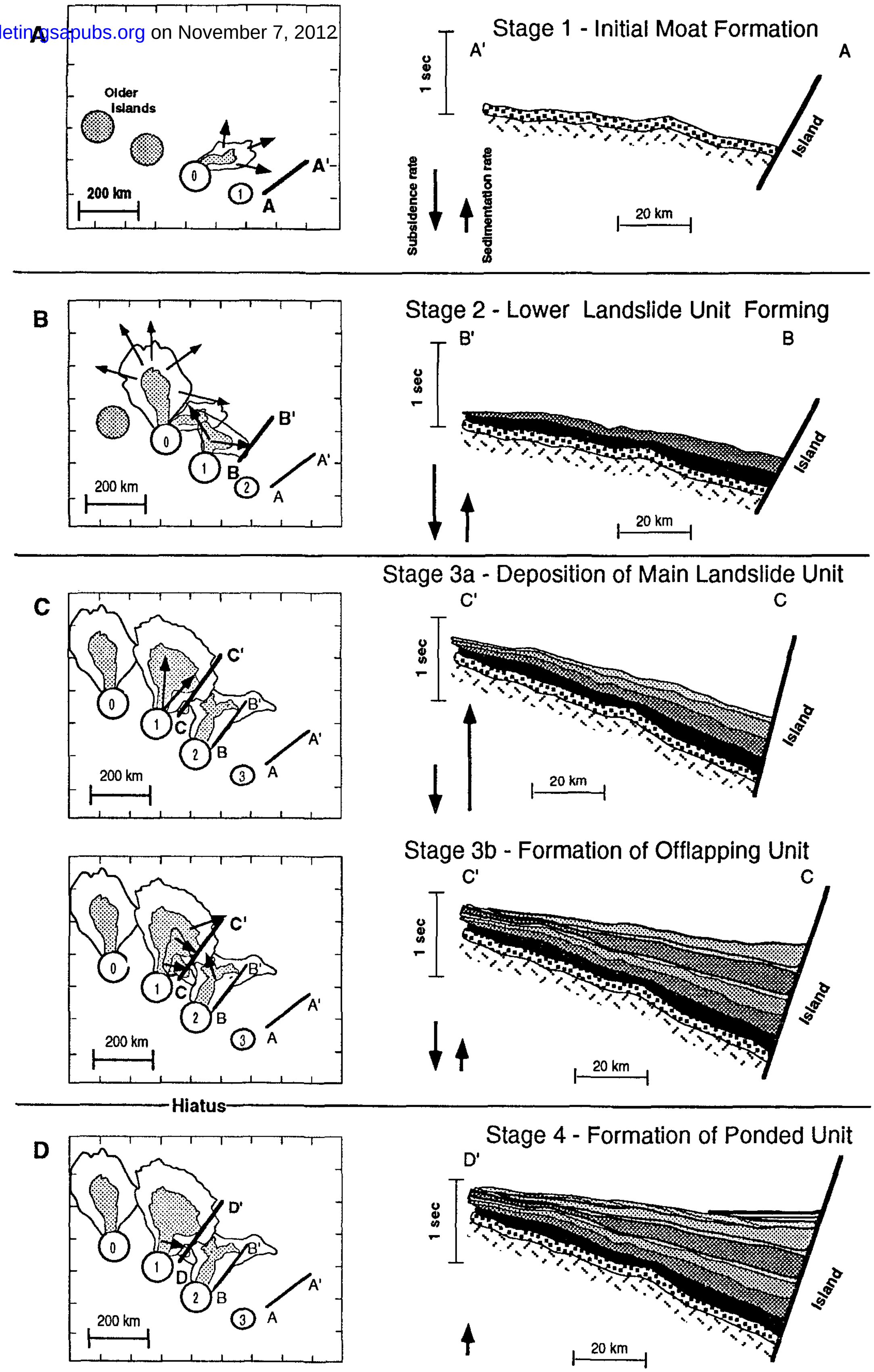

Figure 16. Schematic model showing history of moat sedimentation. Panels show a map view and idealized cross section of the moat in its four main stages of development. The relative importance of subsidence and sediment input are shown by the sizes of the downward and upward pointing arrows, respectively. Numbered circles on maps are individual volcanoes that progressively form as the plate moves across the hotspot. The same cross section (located next to island 1) is shown in each panel.

(A) Stage 1. Flexural moat begins to form; subsidence (downward-pointing arrow) is significantly larger than sediment input (upward-pointing arrow) resulting in an underfilled moat. Arrows on map represent sites of most-recent large-scale mass-wasting activity. Older events (gray) or their fringing turbidites (clear) are not yet affecting this part of the moat.

(B) Stage 2. Moat begins to fill with material transported along the axis of the moat from distant, large-scale mass-wasting events. Moat remains underfilled as subsidence exceeds sediment influx.

(C) Stage 3a. Large-scale mass wasting of the adjacent islands begins to rapidly fill the moat with huge volumes of massive or poorly bedded volcanic rock. Individual debris avalanche and slump deposits are assumed to be single episodes of massive slope failure that bury older mass-wasting deposits, and pelagic sediment deposited in the moat between these huge episodic mass-wasting events. Stage 3b. Contemporaneous with Stage 3a. Progressive erosion and mass wasting of adjacent islands gradually reduces the amount of material carried into and along the moat, forming an offlapping unit. Regional subsidence due to loading of new volcanoes along the younger part of the island chain exceeds the sediment influx, and the offlapping unit is backtilted toward the islands.

(D) Stage 4. Subsidence of the moat effectively ceases. Rejuvenation of sedimentation after a hiatus leads to the formation of a ponded unit in the deepest part of the moat.

offlap that should be observed in both the cross-moat and along-moat stratigraphy. Ten Brink and Watts (1985) argued that the progressive onlap and backtilting observed in the cross-moat profiles could only be produced by the flexure of a lithospheric plate that decreased in rigidity over time. This conclusion is based on a simple cross-moat model in which the sediments infilled the moat to an arbitrary reference level at every 0.5 Ma time interval. Watts and ten Brink (1989), in contrast, constructed a 3-D model assuming a purely elastic plate that included the effect of the progressive loading of the plate in the along-moat direction. As in the previous 2-D model, sediment infill to predeformational levels was assumed. Although sedimentation was treated the same in both sets of models, in the 3-D models a constant plate rigidity was assumed. The cross-moat stratigraphy predicted by the 3-D model is similar to that of the 2-D model that does not include a varying plate rigidity.

With the new data reported here, can we distinguish between these two different models? We now know that the influx of material to the moat is highly episodic and involves significant cross-moat and along-moat sediment transport that is controlled not only by flexural subsidence, but by the mass-wasting process itself. Moat sediments thus do not passively fill to a reference horizon or provide a continuous record of lithospheric relaxation; instead, the sedimentary record is dominated by massive, episodic slope failures on the adjacent islands. Despite this, we can identify in the reflection data the same basic stratigraphic pattern originally described by ten Brink and Watts (1985) near Oahu: onlap of the flexural arch in the lower moat section and offlap in the upper moat section due to progressive backtilting of both units toward the island chain.

The progressive loading model makes specific predictions of moat stratigraphy that can be compared to the along-moat lines in this study. As shown in Figure 2B, the along-moat synthetic profile shows offlap in the direction of the older volcanoes and onlap in the direction of load migration. Although we do see some overstepping in an eastern direction on line 32 (Fig. 6—L4 and L3 extend eastward of the termination of L2), we do not see the pattern predicted by this model. The striking observation on line 32 is the overall convex shape of the sea floor between Oahu and Molokai (Fig. 6). The shallowest portion of this profile is north of Maui and is an expression of the flexural arch resulting from the island load of Hawaii. Such an arch is predicted in the Watts and ten Brink 3-D model. Its presence demonstrates the importance of load migration on the flexural subsidence history of the moat.

We thus attribute the backtilting of the moat sediments, not to a progressive weakening of the lithosphere with time, but to regional subsidence due to the progressive loading of the plate by newly forming volcanoes as originally proposed by Watts and ten Brink (1989). Although we believe a simple elastic model for the lithosphere is adequate to explain our observations, we cannot, due to the significant primary depositional slopes and underfilling of parts of the moat, preclude the importance of longer-term viscoelastic relaxation of the plate.

CONCLUSIONS

Our results show that the Hawaiian flexural moat is filled with a well-stratified sedimentary section, as much as 2.2 km thick, consisting essentially of a series of stacked mass-wasting deposits. The moat stratigraphy is characterized by four major lithostratigraphic units: (1) a basal layer of relatively constant thickness that predates the formation of the flexural moat; (2) a series of landslide deposits that thicken toward the islands and onlap the flexural arch; (3) a unit of highly reflective, continuous horizons that offlap the flexural arch and tilt down toward the islands; and (4) a thin, layered sequence that is ponded in the deepest part of the moat.

We explain this distinctive stratigraphy in terms of the competing effects of sediment influx to the moat, principally from large-scale mass wasting and flexural subsidence due to the progressive loading of the plate by newly forming volcanoes. As each new island begins to form, flexural subsidence exceeds the influx of sediment, and the moat adjacent to the island is largely underfilled. At this stage, sedimentation is dominated by along-moat transport of material from the erosion of older islands. As the young volcano grows above sea level, massive slope failures begin forming the thick, onlapping sequence of landslide deposits that fill the bulk of the moat. The largest, most-recent deposits (for example, the Nuuanu-Wailau debris avalanche and Hana slump) segment the moat into a series of sub-basins and control the lateral transport of sediment along the moat. As the island erodes and subsides, the influx of sediment to the adjacent moat decreases, and an offlapping sequence of reflectors forms. The backtilting of this unit toward the island can be explained by regional subsidence due to progressive loading of the plate by younger volcanoes; significant long-term viscoelastic relaxation of the plate is not required (but cannot be ruled out either). As the moat continues to age, flexural subsidence effectively stops, and any sediment transported to the moat from the continued erosion of the islands ponds in the deepest part of the moat.

The large-scale mass wasting documented in this study, and in recent GLORIA surveys of this area (Moore and others, 1989), shows that the influx of material to the moat is episodic and involves significant cross-moat and along-moat sediment transport that is controlled not only by flexural subsidence, but by the mass-wasting process itself. Moat sediments thus do not record a continuous record of lithospheric deformation; instead, the sedimentary record is dominated by massive, episodic slope failures on the adjacent islands. The important role of large-scale mass wasting in the sedimentation history of the Hawaiian flexural moat is expected to characterize the flexural moats of other large subaerial volcanoes.

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