Coral Reefs (1997) 16, Suppl.: S33–S38

Coral Reefs

Paleoceanography of coral reefs in the Hawaiian-Emperor Chain – revisited

R. W. Grigg

Department of Oceanography, University of Hawaii, Honolulu, Hawaii 96822

Abstract. This paper is a review of the present knowledge of coral reef ecology and paleoecology in the Hawaiian-Emperor Chain during the last 70 Ma. Research on fossil coral deposits throughout the H-E Chain has played a major role in producing information concerning the subsidence, uplift and drowning of individual islands, as well as the paleocirculation of the North Pacific Ocean during Tertiary time. The origin of the Hawaiian Islands and seamounts over the Hawaiian hotspot and their subsequent subsidence and transport by plate motion to the north and northwest are reviewed and new data concerning uplift of the central high Hawaiian Islands caused by lithospheric flexure and the effect of sea level change on the geological evolution of individual islands are presented. The Darwin Point, where atolls drown to form guyots, is redefined in dynamic terms as a function of climate and sea level history. The absence of coral reefs during the first half of Hawaiian history is evidence for a major change in ocean circulation in the north Pacific about 35 million years ago during the Middle Tertiary.

Introduction-Origin of the Hawaiian-Emperor Chain

The Hawaiian-Emperor ridge of islands, seamounts and banks in the north Pacific Ocean is the longest, oldest and best studied volcanic chain on the surface of the earth. Almost 150 years ago, James Dana (1849) observed a gradient in the degree of erosion along the Hawaiian chain. Dana believed that all of the Hawaiian volcanoes originated simultaneously and attributed differences in erosion between islands to their order of extinction which he imagined as age-progressive from west to east. Interestingly, this view was consistent with early Hawaiian legends that placed the home of the Goddess Pele first on Kauai, and then progressively eastward, island by island, to the Big Island where she now resides (Bryan 1915). Other early workers envisioned the Hawaiian Chain as having developed from a linear propagating fracture, also migrating west to east (Betz and Hess 1942; Stearns 1946; Eaton and Murata 1960). All of these theories were based on the presumption of a static earth and a stationary crust. This reasoning required that the mechanism producing the islands (rather than the islands themselves) be mobile. Then in 1960, Robert Dietz (1961) and Harry Hess (1962) revolutionized earth science with their famous theory of sea-floor spreading. The Earth's crust was shown to consist of several dozen mobile plates capable of rifting islands, and even continents, great distances over the surface of the Earth. Building on this theory, John Tuzo Wilson in 1963 proposed that the Hawaiian Islands were formed by the Earth's crust moving southeast to northwest (opposite to static Earth theories) over a relatively fixed point of upwelling lava. Wilson theorized that this source of heat melted the Pacific Plate and produced a linear trail of seamounts and islands (Fig. 1). Christofferson (1968) coined the term hotspot and extended Wilson's theory to include the Emperor Seamounts and suggested that the Hawaiian-Emperor bend represented a major change in the direction of plate motion from north to northwest. Then in 1972, Jason Morgan (1972) proposed that hotspots are produced by thermal plumes originating deep within the Earth's mantle. Morgan theorized that plumes arose from thermal instabilities in the mantle causing upward convection. Morgan identified about 20 hotspots on the Earth and suggested they are fixed relative to one another and the Earth's spin axis. While other hypotheses have been advanced to explain the origin of the H-E Chain, including new versions of the propagating fracture theory (McDougall 1971; Turcotte and Oxburg 1973), the hotspot hypothesis is widely accepted today even though the exact mechanism or cause of the hotspot is still not well understood (Clague and Dalrymple 1987). Some of the most compelling evidence in support of the hotspot hypothesis is as follows: (1) age progression: islands and seamounts along the ridge progressively increase in age with distance away from the hotspot, (2) paleomagnetism: the paleolatitude of Midway Island and the Emperor Seamounts, Ojin, Suiko and Meiji, all closely agree with the latitude of the present hotspot (Jackson et al. 1980), and (3) geochemistry: the petrology and geochemistry

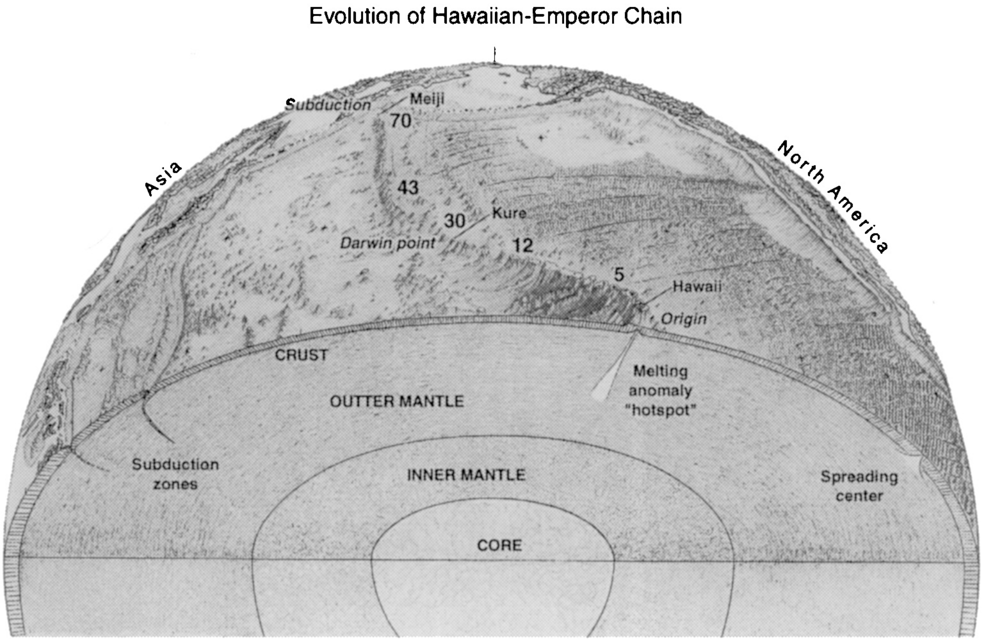

Fig. 1. Map of the Hawaiian-Emperor Chain showing a cut-away of the Earth showing the core, mantle and crust and the location of the hotspot situated below the Big Island of Hawaii. The H-E Chain streaches almost 6 000 km across the Pacific. Its formation spans 70 Ma of earth history

of the basalts of the Emperor Seamounts are virtually the same as the Hawaiian Islands (Jackson et al. 1980).

Subsidence history of the H-E Chain

The Hawaiian-Emperor Chain consists of over 100 individual volcanoes ranging from Hawaii, situated over the hotspot ($\sim$ 19°30′N × 155°15′W), to Meiji guyot (near 51°N × 168°30′E) approximately 6000 km to the northwest and about 68–70 Ma (Jackson et al. 1980). From their inception over the hotspot, all Hawaiian volcanoes have followed a similar history of primarily subsidence and subaerial erosion as they move to the north or northwest on the Pacific Plate. The largest and highest island, Hawaii, is presently 4481 m above sea level. Islands to the northwest of Hawaii are progressively smaller, lower and more eroded. At present, these volcanoes reach sea level at a latitude approximately 24°N (near French Frigate Shoals) where they form atolls. From this point to the end of the chain, the atolls (or coral islands) undergo continued subsidence; however, their position at sea level is maintained by the upward growth of coral. The Hawaiian Archipelago ends at Kure Island at a latitude of 29°N where accretion due to coral growth is offset by losses in $CaCO_3$ due to subsidence and bioerosion. Given no change in sea level, this latitude in the north Pacific represents a threshold for atoll formation (or extinction) and has been termed the Darwin Point (Grigg 1982). An accretion rate less than the threshold value at the Darwin Point leads to drowning or extinction. An accretion rate greater than the threshold value results in atoll formation. Northwest of the Darwin Point, the chain continues as a series of drowned guyots which gradually deepen due to continued subsidence. The most northwesterly and last guyot in the Hawaiian-Emperor is Meiji. Meiji is over 3000 m deep and is presently undergoing subduction beneath the Asian Plate.

Initially, subsidence along the Hawaiian ridge is extremely rapid. Moore (1987) has calculated that by the time Hawaiian volcanoes reach sea level, they have already subsided 2–4 km. Subsidence results from an isostatic response to volcanic loading over the hotspot. Cooling and thickening of the lithosphere as the volcanoes are transported by plate motion ($\sim$ 10 cm/y) away from the hotspot leads to further subsidence (Parsons and Sclater 1977). After leaving the hotspot, the rate of subsidence decreases exponentially and the depth of the plate increases approximately proportional to the square root of the age of the underlying reheated crust (Crough 1979; Schlanger et al. 1981) not withstanding small deviations due to lithospheric flexure and asthenospheric bumps (Jackson et al. 1980). An important process regarding the subsidence of Hawaiian volcanoes is reheating of the crust as it passes over the hotspot. Reheating elevates the lithosphere by about 1000 m and is responsible for producing a broad feature known as the Hawaiian swell. Reheating is significant because it appears to reset the process of subsidence of Hawaiian volcanoes (Fig. 2). Hence, after islands are transported off the hotspot, subsidence follows a path similar to the Parson-Sclater curve except, as noted already, for some deviations due to lithospheric flexure and possibly asthenospheric bumps.

In the case of the central high Hawaiian Islands, a departure from the normal Parsons-Sclater subsidence curve appears to have resulted from lithospheric flexure. Lithospheric flexure is produced by excessive loading on an elastic plate resulting in deformation and uplift of the adjacent sea floor. Loading of the Big Island has resulted in 4–5000 m of subsidence since inception (Watts and ten Brink 1989). This deformation has produced a moat around the Big Island consisting of a proximal trough and a distal arch (Dietz and Menard 1953). The radius of the arch or bulge is about 250 km from the hotspot. The elevation of the arch is about 500 m above the trough. Watts and ten Brink (1989) used a three-dimensional

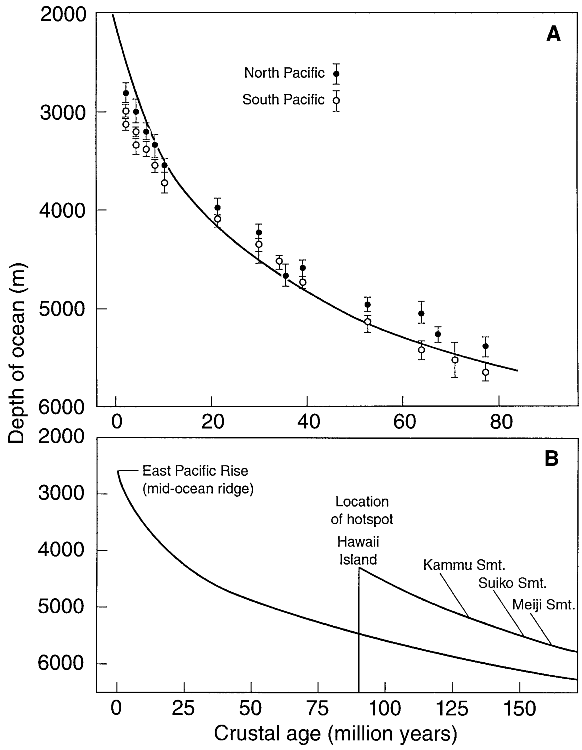

Fig. 2. **A** Age-depth curve for the Pacific. Depth increases in proportion to the square root of the age of the plate. **B** Reheating of the Pacific Plate over the Hawaiian hotspot produces about 1000 m of elevation in the seafloor (modified from Nunn 1994)

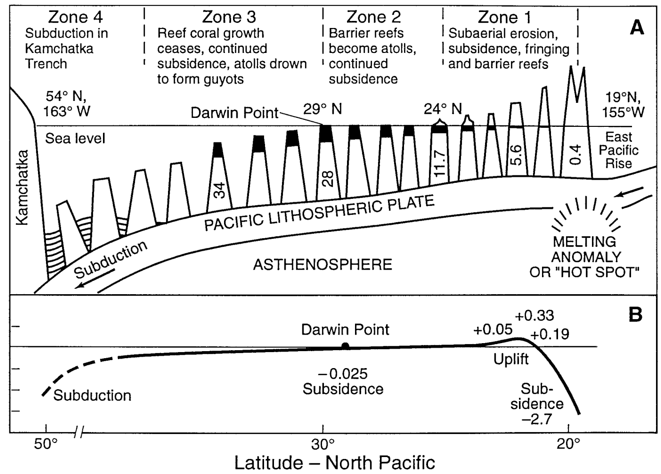

Fig. 3. **A** Schematic representation of the origin, subsidence, drowning and subduction history of the islands and guyots along the H-E Ridge. Processes are outlined in four zones. Ages of volcanic edifices are shown in Ma. Drowning of atolls occurs at the Darwin Point. **B** Schematic approximation of subsidence and uplift history in the H-E Chain. See text for explanation (modified from Grigg 1982 and Rotondo 1980)

elastic plate model to predict the bulge height and the wavelength of the deformed plate below the ridge to the northwest. Using 4–5000 m of subsidence for the Big Island, the Watts-ten Brink model predicts 56–70 m of uplift for the apex of the bulge. The model places the apex of the bulge (wavelength) 275–300 km downstream of the hotspot midway between Oahu and Molokai. The model estimates of height and wavelength are approximately supported by the elevation of uplifted coral reef deposits on Oahu, Molokai and Lanai which are + 30 m, + 85 m, and + 74 m, respectively (Grigg and Jones in press). The lower uplift on Oahu may be related to the smaller size of the Big Island 500 000 years ago when Oahu drifted over the apex of the bulge.

Beyond the lithospheric bulge and the central high Hawaiian Islands, subsidence appears to resume but at a much slower rate following a path similar to the Parsons-Sclater curve. At Midway Island, near the end of the Hawaiian Archipelago, a core drilled through the reef in 1965 reached the underlying volcanic foundation at a depth of 384 m (Ladd et al. 1967). The basalt edifice of Midway is dated at 28 Ma. Assuming that Midway required about 12 Ma to subside to sea level (similar to FFS Atoll), the rate of subsidence since then is 0.024 mm/y. Beyond Midway, moving northwest, the rate of subsidence of the Emperor Seamounts is nearly constant (asymptotic) all the way to the end of the chain. A schematic figure illustrating the sequence of subsidence, uplift, continued subsidence, drowning of islands at the Darwin Point and ultimate subduction at the juncture of the Pacific and Asian Plate near Kamchatka is presented in Fig. 3.

History of coral reefs in the H-E Chain

Coral reefs presently exist on every island and shallow bank in the Hawaiian Chain. Because of this and the age progression of the islands from Hawaii to Kure Atoll (1–28 Ma) (Dalrymple et al. 1977), it is possible to use the chronological history of the Hawaiian Islands to estimate the time required for the formation of fringing reefs, barrier reefs and atolls. The youngest fringing reefs are found off the coast of west Hawaii on volcanic foundations as young as 100 years in age (Grigg and Maragos 1974). Also, drowned coral reefs exist off the coast of west Hawaii at depths to over 1300 m which are dated at 475 000 years (Ludwig et al. 1991). It is therefore reasonable to conclude that fringing reefs form in a time frame of approximately 100 to 1000 years as new islands are created over the hotspot.

The youngest incipient barrier reefs found in the Hawaiian chain exist on Oahu off Kaneohe Bay and the leeward coast of Moanalua Bay. Because these reefs have not formed complete barriers to wave energy, they could in fact be considered advanced fringing reefs (Grigg 1983). The age of this part of Oahu is about 2.5 Ma (Schlanger and Gillett 1976). Hence, 2.5 Ma serves as a minimum estimate of the time necessary for the formation of barrier reefs in the Hawaiian Archipelago. The first atoll in the Hawaiian chain is French Frigate Shoals, dated 11.7 Ma + 0.4 Ma (Dalrymple et al. 1974) (a small basalt pinnacle 41 m in elevation remains above sea level). An atoll in the Hawaiian Archipelago therefore appears to require about 10 Ma to form.

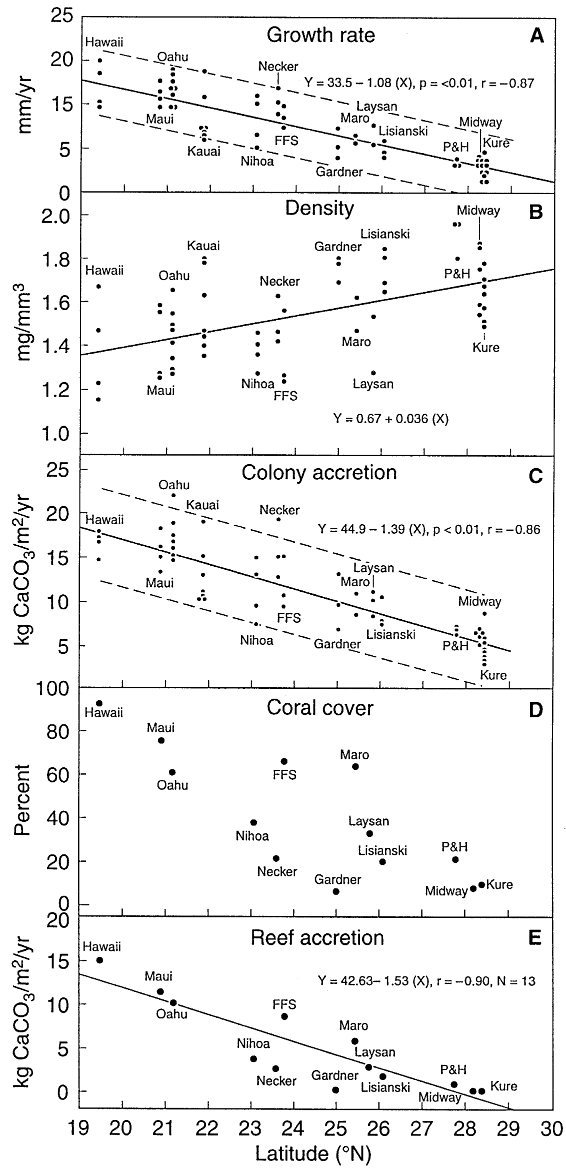

Fig. 4. **A** Growth rate, **B** density and **C** colony accretion of *P. lobata*, **D** coral cover and **E** reef accretion on seaward reefs off all major Hawaiian Islands (modified from Grigg 1982)

A comparison of rates of barrier reef and atoll formation in the Hawaiian Archipelago to the Society Islands, shows that Hawaiian rates are relatively slow. In the Society Islands, a well-developed barrier reef is present around Tahiti which is between 0.4 and 2.0 Ma (Morhange 1992). The first atoll (Motu iti) in the Society chain is only 4 Ma (Brousse 1985). These differences probably result from several factors acting in combination including initial elevation (Hawaiian volcanoes are about 2 km higher), rates of erosion (rainfall in the Society Islands is more than double that in the Hawaiian Islands) (Stoddart 1992, Fig. 7), and coral species composition and rates of coral growth (the number of species of coral in the Society Islands is about four times the number in the Hawaiian Islands (Stehli and Wells 1971)).

Rates of coral reef growth in the Hawaiian Archipelago have been shown to decline as a linear function of increasing latitude (Grigg 1982) (Fig. 4). About 2/3 of the variability in the negative regression of growth versus latitude is related to decreasing annual daylight and average sea surface temperature moving northwestward in the chain (Grigg 1982). Growth rates of coral reefs at the southeastern end average about 11 $mm/m^2/y$ or 15 $kg/m^2/y$ and are typical of coral growth rates elsewhere in the tropical Pacific (Grigg and Epp 1989). At the northwestern end of the chain at Midway and Kure atolls, the rate of reef growth is about 0.2 $mm/m^2/y$ or 0.3 $kg/m^2/y$ (Grigg 1982). While this rate is more than adequate to keep pace with the present rate of subsidence of Midway (0.024 mm/y), losses due to bioerosion on coral reefs may frequently exceed this rate (Grigg and Epp 1989). Nevertheless, the fact remains that Midway and Kure have kept pace with sea level rise at least during the last part of the Holocene transgression. Presumably both islands were elevated (makatea islands) during the early Holocene when sea level rise was very high. This must not have been true for other drowned shallow banks within the chain. Nor would it have applied to drowned guyots northwest of Kure Atoll beyond the Darwin Point now estimated to exist near 29°N.

Clearly, the Darwin Point is not an absolute threshold for atoll formation. This was recognized by Grigg in 1982 but was not resolved. In 1989, Grigg and Epp suggested that drowning of many atolls in the Pacific during the Holocene transgression was a function of the position of atoll summit elevations relative to sea level at the beginning of the last transgression about 21 000 years ago. During the transgression, sea level rise reached high rates of 45 mm/y on no less than three occasions (Branchon and Shaw 1995) for periods of time up to 1000 years. A rate of 25 mm/y existed for several periods spanning 2000–3000 years (Fletcher and Sherman 1995). These rates of sea level rise greatly exceed the capacity of coral reef growth to keep up (Grigg and Epp 1989). Rates of growth of most coral reefs in the world vary between 1–10 mm/y. The highest growth rates measured are 13–15 mm/y (Adey 1978; Buddemeier and Smith 1988) for *Acropora palmata* reefs in the Caribbean Sea. It is, therefore, not surprising that as many as 31% of all atolls in the Pacific Ocean drowned during the Holocene transgression (Menard 1984; Grigg and Epp 1989). Only those atolls that were significantly elevated (~ 100 m) at the beginning of the Holocene transgression when sea level was about 110–130 m lower than present (Grigg and Epp 1989), were able to keep pace with sea level rise. All atoll summits that "fell" much below a critical depth of 30 m drowned. Hence, many of the drowned banks south of the Darwin Point in the Hawaiian Archipelago, must have been situated at depths where sea level was rising > 15 mm/y for more than 2000 years. This would have placed them below critical depth and explains why they drowned.

The Darwin Point as a measure of the threshold for atoll formation can therefore only be applied to foundations in tropical latitudes that lie within a critical depth of about 30 m of the surface during time periods when sea level rise is less than 15 mm/y. At rates of sea level rise greater than this for periods longer than 2000 years, coral reef growth is overwhelmed and reefs drown regardless of latitude. Coral reefs growing on high islands or continental shelves would not be so affected since settlement of larvae swimming or drifting upshelf (back stepping) would allow the reefs to keep pace with sea level rise regardless of the rate.

At moderate rates of sea level rise greater than zero but less than 15 mm/y, the Darwin Point would be displaced southeastward in the Hawaiian Archipelago. Conversely, a falling sea level would displace the Darwin Point to the northwest. Subsidence near the end of the chain would have a negligible effect since it is so slow (0.025 mm/y). A sea level fall greater than this would simply strand reefs above sea level. However, once sea level fall reversed, living reefs would once again be vulnerable to drowning. Hence, the Darwin Point has probably ranged across a latitude close to its present position southeastward down the chain to approximately where islands first reach sea level (about 24°N). This locale today is occupied by French Frigate Shoals (FFS) where modern reef accretion is estimated to be about 5.6 mm/y. Clearly, had FFS not been above sea level during periods of high sea level rise during the Holocene transgression, it too would have drowned. Islands southeast of FFS today are above sea level and therefore coral reefs (larvae) surrounding these islands can "back step" upshelf during periods of high sea level rise.

While the Darwin Point is not spatially fixed, and indeed can be overwhelmed, atolls in the Hawaiian chain appear to have been drowning between about latitudes 24 and 30°N for the last 34 Ma. The oldest dated coral (*Astreopora* sp.) in the H-E chain is 34 Ma and was recovered from Yuryaku Guyot (latitude 32.5°N). Yuryaku has a volcanic edifice dated at 43.4 + 1.6 Ma (Dalrymple and Clague 1976). This suggests that Yuryaku may have drowned at an age of about 10 Ma (43.4 minus 34 Ma) after formation over the hotspot. Interestingly, 10 Ma is similar to the age of FFS today (11.7 Ma, Dalrymple et al. 1974). Yuryaku may have drowned during a period of high sea level rise when the Darwin Point was near FFS (24 °N).

Colonization of corals and reefs in the H-E chain

A difference of about 35 Ma exists between the age of the oldest dated coral (34 Ma) and the oldest seamount or guyot in the chain (Meiji, 68–70 Ma) (Grigg 1988; Jackson et al. 1980). Eleven sites have been cored on six seamounts in the northern Emperor chain and while all are characterized by evidence of a shallow warm marine environment (coralline algae, bryozoa, large keeled benthic foraminifera, echinoid spines, bivalves and brachiopods), all except one (Koko guyot) are lacking evidence of reef building corals. Collectively, over 400 m of sediments have been recovered from the cores. It is therefore unlikely that corals were missed in cores had they been present. The absence of corals north of Koko guyot could be due to (a) cooler temperatures during the Early Tertiary, (b) a more northerly latitude (than present) of the Hawaiian hotspot during the early Tertiary, (c) a worldwide paucity of reef development in the Paleocene and Eocene, and (d) lack of colonization (Grigg 1988). The plausibility of these factors has been discussed in detail in Grigg (1988) and most of the evidence favors the fourth hypothesis. In brief, oxygen isotope data for planktonic foraminifera show that sea surface temperatures were relatively warm at high latitudes in the Eocene and Paleocene, ruling out the temperature hypothesis. Similarly, the paleolatitudes of most Emperor Seamounts back-calculate to the present position of the hotspot ruling out the more northerly hotspot hypothesis. The paucity of reef development in the Paleocene and Eocene may have contributed to the rarity of corals in the H-E chain during this period but it alone would not explain the complete absence of corals.

Conversely, a number of paleoceanographic events during the Tertiary provide strong support for the fourth hypothesis. These events include (1) closure of the Tethys Sea, (2) isolation of Antarctica, (3) global cooling, and (4) increased latitudinal temperature gradients. Collectively, all of these changes may have served to strengthen gyral circulation and western boundary currents (sources of coral larvae to Hawaii) in the north Pacific (Kennett 1982).

All corals that exist in the Hawaiian Archipelago today are Indo-West-Pacific in origin (Grigg 1988). Hence the western boundary current system (Kuroshio and Subtropical Counter-Current) is the primary source for transport of coral larvae across the western Pacific to Hawaii. The Hawaiian Islands appear to have been completely isolated from the IWP until the middle Oligocene about 34 Ma ago when gyral circulation strengthened in the north Pacific. Even today with vigorous western boundary currents in the north Pacific, only $\sim 10\%$ (47 out of over 500 IWP coral species) have colonized the Hawaiian Archipelago, leaving it a highly attenuated fauna. Colonization continues today but is sporadic, punctuated by periods of extinction and recolonization. Three species of *Acropora* appear to be in the process of re-colonizing the archipelago today (Grigg 1981). This source of larval input may have reduced speciation within the Hawaiian Archipelago by diluting genetic drift. As such, it may explain the low incidence of endemism in the coral biota of the Hawaiian Islands today.

Conclusion

In summary, while coral reef research in the H-E chain has greatly advanced our knowledge of Hawaiian zoogeography and the history of individual islands, paleoecological studies of coral biota and reefs in the chain are still in their infancy. Much work remains to be done, particularly with regard to changes in species composition due to extinction, recolonization and speciation events. This can be accomplished by more biostratigraphic study of both elevated and submerged fossil coral deposits. More drilling or dredging also is needed in the northern Emperor Seamounts to confirm the absence of corals there in the Early Tertiary. The paleoceanography of this fascinating group of islands, seamounts and guyots will undoubtedly have to be revisited many more times in the future before it is completely understood.

References

Adey WH (1973) Coral reef morphogenesis: a multi-dimensional model. Science 202:831–837

Betz F, Hess HH (1942) The floor of the North Pacific Ocean. Geogr Rev 32:99–116

Branchon P, Shaw J (1995) Reef drowning during the last deglaciation: evidence for catastrophic sea-level rise and ice sheet collapse. Geology 23:4–8

Brousse R (1985) L'age des iles du Pacific: volcanisme et installation corallienne. Proc Fifth Int Coral Reef Symp 6:389–400

Bryan WA (1915) Natural history of Hawaii. Hawaiian Gazette. Honolulu, Hi, 569 pp

Buddemeier RW, Smith SV (1988) Coral reef growth in an era of rapidly rising sea-level. Coral Reefs 7:51–56

Christofferson E (1968) The relationship of sea-floor spreading in the Pacific to the origin of the Emperor Seamounts and the Hawaiian chain. EOS, AGU Trans 49:214

Clague DA, Dalrymple GB (1987) Geological evolution of the Hawaiian Emperor volcanic chain. In: Decker et al. Eds. Volcanism in Hawaii. US Geol Surv Prof Pap 1350, 1:5–54

Crough ST (1979) Hotspot epeirogeny. Tectonophysics 61:321–333

Dalrymple GB, Clague DA (1976) Age of the Hawaiian-Emperor bend. Earth Planet Sci Lett 31:313–329

Dalrymple GB, Lanphere MB, Jackson ED (1974) Contributions to the petrology and geochronology of volcanic rocks from the leeward Hawaiian Islands. Geol Soc Am Bull 85:727–738

Dalrymple GB, Clague DA, Lanphere MA (1977) Revised age for Midway volcano, Hawaiian volcanic chain. Earth Planet Sci Lett 37:107–116

Dana, JD (1849) United States exploring expedition during the years 1838,1839, 1840, 1841, 1842. Putnam, New York 756 pp

Dietz RS (1961) Continent and ocean basin evolution by spreading of the sea floor. Nature 190:854–857

Dietz RS, Menard HW (1953) Hawaiian swell, deep and arch, and subsidence of the Hawaiian Islands. J Geol 61:99–113

Eaton JP, Murata KJ (1960) How volcanoes grow. Science 132:924–938

Fletcher CH, Sherman CE (1995) Submerged shorelines on Oahu, Hawaii: archive of episodic transgression during the deglaciation. J Coastal Res Special Issue 17: Holocene cycles: climate, sea levels and sedimentation, pp 141–152

Grigg RW (1981) *Acropora* in Hawaii. Part II. Zoogeography. Pac Sci 15:15–24

Grigg RW (1982) The Darwin Point: a threshold for atoll formation. Coral Reefs 1:29–34

Grigg RW (1983) Community structure, succession and development of coral reefs in Hawaii. Mar Ecol Prog Ser 11:1–14

Grigg RW (1988) Paleoceanography of coral reefs in the Hawaiian-Emperor chain. Science 240:1737–1743

Grigg RW, Maragos J (1974) Recolonization of hermatypic corals on submerged lava flows in Hawaii. Ecology 55:387–395

Grigg RW, Epp D (1989) Critical depth for the survival of coral islands: effects on the Hawaiian Archipelago. Science 243:638–640

Grigg RW, Jones AT (1997) Uplift, not giant waves: the origin of high elevated coral reef deposits in Hawaii. Marine Geology (in press)

Hess HH (1962) History of the ocean basins. In: Engel EAJ et al. (ed) Petrologic studies, a volume in honor of AF Buddington, pp 599–620, Boulder, Colo, GSA

Kennett JP (1982) Marine geology. Prentice Hall, Englewood Cliffs, New Jersey, pp 813

Jackson ED, Koisumi I, Dalrymple GB, Clague DA, Kirkpatrick RJ, Greene HG (1980) Introduction and summary of the results from DSDP Leg 55, the Hawaiian- Emperor hotspot experiment. In: Jackson et al. (eds) Initial reports of the deep sea drilling project. Wash DC, US Gov. Printing Office 55:5–31

Ladd HS, Tracey JI, Gross MG (1967) Drilling on Midway Atoll. Science 156:1088–1094

Ludwig KR, Szabo BJ, Moore JG, Simmons KR (1991) Crustal subsidence rate off Hawaii determined from $^{234}U/^{238}U$ ages of drowned coral reefs. Geology 19:171–174

McDougall I (1971) Volcanic island chains and sea-floor spreading. Nature 231:141–144

Menard HW (1984) Origin of guyots: the Beagle to Seabeam. J Geophy Res 89:11117–11123

Moore JG (1987) Subsidence of the Hawaiian ridge. In: Decker et al. (eds) Volcanism in Hawaii. US Geol Prof Pap 1350 (1):85–100

Morgan J (1972) Deep mantle convection plumes and plate motions. Am Assoc Pet Geol Bull 56:203–213

Morhange C (1992) Essai de quantification de l'evolution geomorphologique d'un archipel volcanique tropical ne d'un point chaud: le cas des iles de la Societe en Polynesie Francaise. Z Geomorph N F 36:307–324

Nunn P (1994) Oceanic islands. Blackwell, Oxford, UK, pp 413

Parsons B, Sclater JG (1977) An analysis of the variation of ocean floor bathymetry and heat flow with age. J Geophy Res 82:803–827

Rotondo G (1980) A reconstruction of linear island chain positions in the Pacific: a case study using the Hawaiian Emperor chain. MS Thesis, University of Hawaii, pp 58

Schlanger SO, Gillett GW (1976) A geological perspective of the upland biota of Laysan Atoll (Hawaiian Islands). Biol Linnean Soc 8:205–216

Schlanger SO, Jenkyns HC, Premoli-Silva I (1981) Volcanism and vertical tectonics in the Pacific Basin related to global Cretaceous transgressions. Earth Planet Sci Lett 52:435–449

Stehli F, Wells J (1971) Diversity and age patterns in hermatypic corals. Syst Zool 20:115–126

Stearns HT (1946) Geology of the Hawaiian Islands. Hawaii Div Hydrogr Bull 8:1–106

Stoddart DR (1992) Biogeography of the tropical Pacific. Pac Sci 46:276–293

Turcotte DL, Oxburg ER (1973) Mid-plate tectonics. Nature 244:337–339

Watts AB, ten Brink US (1989) Crustal structure, flexure and subsidence history of the Hawaiian Islands. J Geophy Res 94:10473–10500

Wilson JT (1963) A possible origin of the Hawaiian Islands. Can J Phys 41:863–870