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A MODEL FOR THE DEVELOPMENT OF TYPES OF ATOLLS AND VOLCANIC ISLANDS ON THE PACIFIC LITHOSPHERIC PLATE

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A MODEL FOR THE DEVELOPMENT OF TYPES OF ATOLLS AND VOLCANIC ISLANDS ON THE PACIFIC LITHOSPHERIC PLATE

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ABSTRACT

A literature review on atoll origins and volcanic island development on the Pacific lithospheric plate is combined with bathymetric data on the Hawaiian, Marshall, Caroline, Tuamotu and Society island chains to produce a model which helps explain the development of all major Pacific plate island types. This model incorporates the concept that as new lithosphere is formed along the East Pacific Rise older crust moves north-west towards Asia, cools and causes ocean deepening. Some distance from the East Pacific Rise relatively fixed melting anomalies produce volcanic island chains. In warmer waters these islands develop fringing reefs which continue to grow to wave level as the islands are carried on the cooling plate into deeper water. Raised volcanic island forms can develop on arches produced by the isostatic subsidence of new magmatic outpourings close by. As volcanic islands with fringing reefs move into deeper water almost-atolls and finally true atolls develop. Partly raised and raised forms result if atolls rise over minor upwarps on the crust produced by, 1) asthenospheric bumps, 2) arch flexuring resulting from isostatic subsidence of nearby magmatic outpourings, 3) compression within the lithosphere alongside Pacific plate subduction zones. The model also helps explain certain types of drowned atolls and guyots.

INTRODUCTION

This paper attempts to develop one model to explain the origins of all major types of island found on the Pacific lithospheric plate (Fig. 1). Literally tens of thousands of seamounts are scattered over

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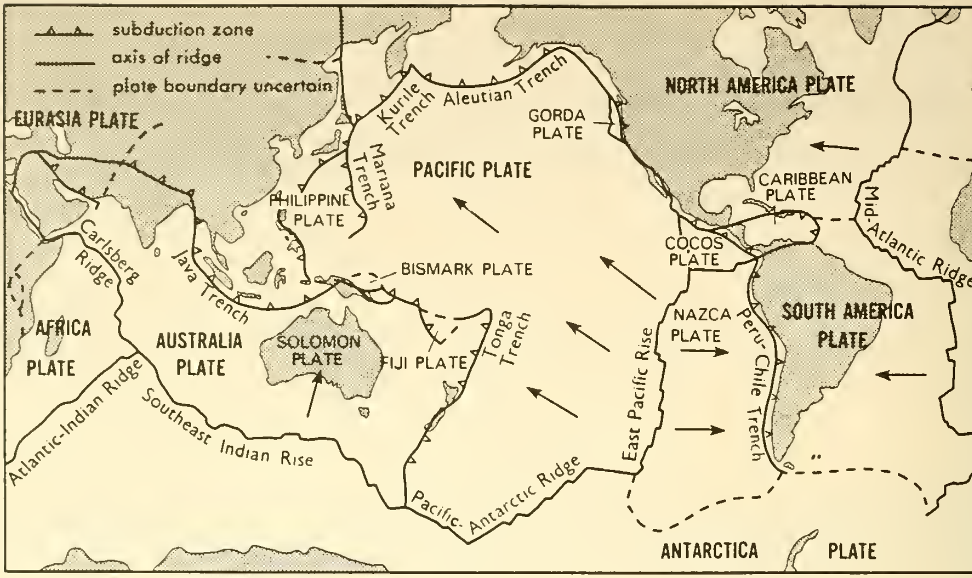

Figure 1. The Pacific lithospheric plate.

the surface of the Pacific plate but the majority of these igneous monoliths appear never to have reached the ocean surface and have therefore been preserved intact from alterations associated with subaerial weathering and erosion. Only occasionally do Pacific seamounts break the ocean surface forming islands. Some of these islands reflect characteristics of the submerged seamounts but take the form of tall volcanic peaks. More frequently they take the form of seamounts apparently truncated near sea level, capped by carbonate deposits, and variously described as atolls or reefs. Another striking feature of the Pacific plate is that islands of whatever type are normally only found in the somewhat shallower parts of the ocean near the East Pacific Rise, or where ocean temperatures normally remain above 22°C throughout the year.

Although fewer in number volcanic islands have received much more attention from geoscientists and geologists interested in origins and dynamics than their carbonate counterparts the atolls. It was only following WWII that the Pacific Science Board of the National Academy of Sciences organized a major program into atoll research and the text, *Atoll Environment and Ecology* by Harold Wiens (1962), represented a synthesis of this work. Perhaps partial blame for this lopsided research thrust was due to the seemingly explicable and visually more dynamic characteristics of volcanoes as compared to the confusion and disagreement surrounding the low, relatively featureless, atolls. Although back in 1842 Darwin proposed the simple yet elegant explanation that these atolls resulted from the slow submergence of volcanic islands his ideas were contested and went unproven until 1951 when drilling through the

Figure 2. Western Pacific Ocean showing the major island groups mentioned in the text. Profile transects along dashed lines are shown in Figures 7 and 10-13.

carbonate platform on Eniwetok in the Marshall Islands (Fig. 2) hit volcanic basement rock at depths exceeding 1,200 m (Ladd, 1973). Despite Darwin's early linkage of volcanoes to atolls it was not until the last few decades that researchers focused more critical attention on their interwoven histories. The last ten years in particular have seen a great increase in geoscientific research on Pacific plate atolls and their possible links to both the horizontal and vertical movements of seamounts. Because of the vast amount of information presently available on the Pacific plate it is now possible to produce an atoll development model much more complex than that inferred by Darwin's simple subsidence model. The following discussion of island types, literature review and island chain analyses is therefore an attempt to formalize major current ideas on Pacific plate island origins into one coherent dynamic working model.

PACIFIC PLATE ISLAND TYPES

In warm tropical waters capable of supporting reef environments no less than eleven distinct island types can be differentiated (Fig. 3). The classifications of Pacific island types by such researchers as Wiens (1962) and Leont'yev et al. (1975) are expanded here simply in preparation for the development of a model designed to explain why they differ. The precursor of all other island types on the Pacific plate is a volcanic island with no (or incomplete) fringing reef. All other types then depend on the development of a fringing reef and then some degree of subsidence or emergence or some combination of these two.

a) Volcanic island with no fringing reef. This island type usually takes the form of a young "high-island". During and particularly following the cessation of volcanic activity such cones are subjected to rapid subaerial weathering and erosion. Fringing reefs are absent or incomplete either because there has not yet been time for them to develop as is the case with Hawaii, or because they are located in poor reef growing waters such as with the Marquesas.

b) Volcanic island with fringing reef. Good reef growing conditions and time have permitted full or almost full development of a typical fringing reef such as that around Kusaie Island in the Carolines. If slow subsidence occurs the reef will remain at wave level due to upward growth, but will broaden. Volcanic activity may still occur intermittently and subaerial erosion and island dissection continue.

c) Raised volcanic island with fringing reef. Similar to type b above except that emergence has elevated the original reef above sea level and a new reef forms oceanward at wave level. Oahu in the Hawaiian Islands is such an example (McNutt and Menard, 1978). Subaerial erosion continues to lower maximum island elevation.

d) Almost-atoll. With this type the volcano is extinct and deeply eroded. Submergence has left one or more embayed basaltic islands and stacks in a lagoon surrounded by a barrier reef. Good examples of this type are Aitutaki in the Cook group and Truk in the Carolines.

e) Raised almost-atoll. If the almost-atoll undergoes uplift instead of subsidence then the central volcanic projections remain, the lagoon may drain and a new reef develops at wave level. An example of this is Atiu Island in the Cook group.

f) Atoll. If the almost-atoll continues to subside the fringing reef keeps growing to wave level while all traces of the original volcanic core disappear below sea level. Small low islets formed from coralline and algal rubble separate the reef from the shallow lagoon. Examples include Arutua in the Tuamotu group and Bikini in the Marshalls. As with Eniwetok, continued subsidence could lead to the development of a carbonate cap exceeding 1,200 m thick.

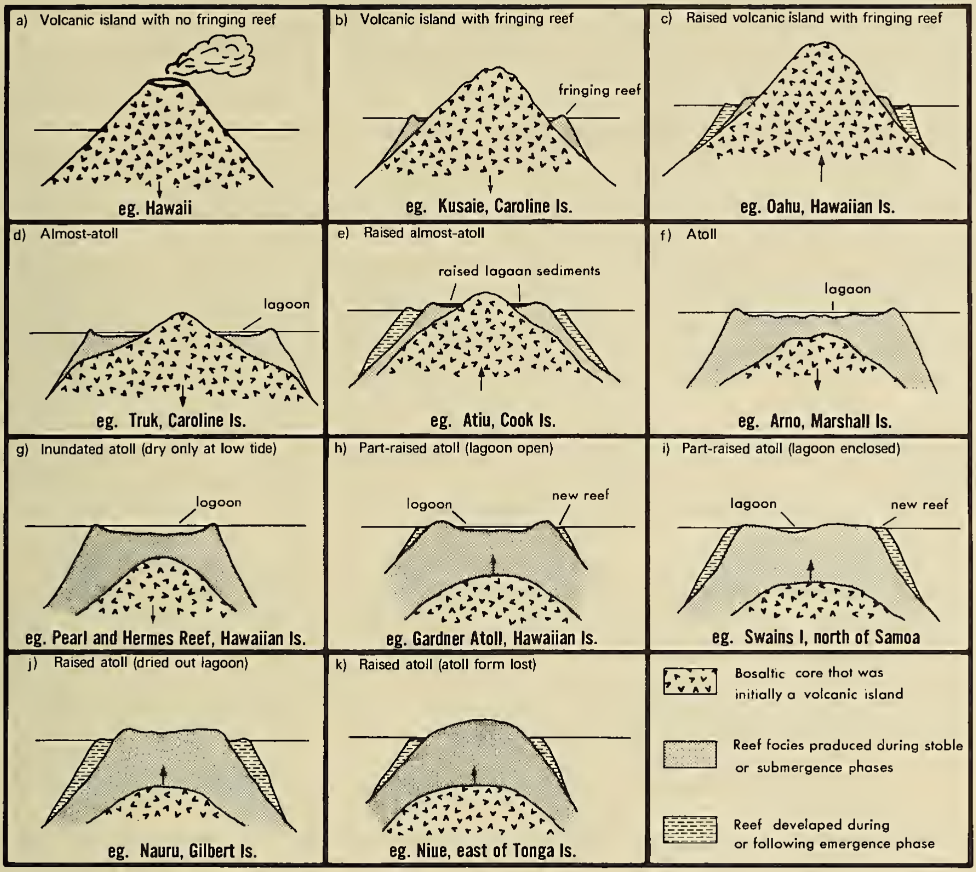

Figure 3. Island types on the Pacific lithospheric plate. Arrows indicate relative vertical motion. Modified from Wiens (1962) and Leont'yev et al. (1975).

g) Inundated atoll. In this type the annular reef sand bars only project above sea level at low tide. Examples of this include Pearl and Hermes reef in the Hawaiian Islands and Suvorov Atoll in the Cook group. Inundation of this typical atoll form may be due to, 1) deterioration of reef growing conditions followed by wave planation, 2) lack of time for the reef to regrow to wave level following subaerial erosion during Pleistocene low sea level stands and then rapid post glacial eustatic rise, or 3) a rate of subsidence too rapid for reef buildup to keep pace.

h) Part raised atoll with open lagoon. This type has the form of a regular atoll but has been raised only a few meters with the lagoon remaining tidal. An example of this is Gardner Atoll in the Hawaiian chain. Early reports that some of these raised reefs are due to 120,000 BP high sea level stands are not supported by more recent explanations (McNutt and Menard, 1979). Some atolls with higher than typical reef flats have also been attributed to this same high sea level stand, but recent reports again do not confirm this (Curray et al., 1970; Newell and Bloom, 1970).

i) Part raised atoll with enclosed lagoon. Here the atoll appears elevated sufficiently above sea level for the lagoon to be cut off and reduced in size. Elevation may exceed ten meters. Typical examples are Swain's Island north of Samoa and Vaitupu in the Ellice group.

j) Raised atoll with dried out lagoon. Here apparent uplift has been in the order of tens of meters. A karst type landscape described by the term "makatea" results, and small ponds may form in the lower depressions where the previous lagoon was located. Examples of this are Nauru Island in the Gilbert group and Makatea Island in the Tuamotus.

k) Raised-atoll with typical form lost. This atoll type has been sufficiently elevated long enough for all remnants of the typical atoll form to be lost. Irregular uplift may have left terraces. An example of this type is Niue Island east of Tonga.

It is recognized that many authors use other names or intermediate examples in their descriptions of island types and specific atolls. The eleven categories listed above serve only as indicators of important examples, and, as the model developed at the end of this paper shows, under ideal conditions they could be considered genetically related along a continuum. This continuum could also include foundered island types such as drowned atolls and guyots.

CLASSICAL VIEWS OF PACIFIC ISLAND ORIGINS

An explanation for the existence of volcanic islands on the Pacific lithospheric plate has never been considered a problem. It is clear they are the product of sub-oceanic and subaerial magmatic outpourings which have built igneous seamounts rising from the ocean floor at depths of 5,000 m or more to elevations above sea level sometimes exceeding 4,000 m. Why Pacific plate volcanoes develop at all has received considerable recent attention and some of the possibilities will be discussed in the next section. Origins for the many versions of atolls scattering the central and western Pacific have differed widely however, and they therefore constitute a more interesting topic for debate.

While Darwin was one of the first to propose a scientific explanation for the origins of atolls, he was certainly not the last. Since his 1842 edition of *"On the Structure and Distribution of Coral Reefs,"* Wharton (1897), Daly (1915), Davis (1928), Hoffmeister and Ladd (1944), Keunen (1947), MacNeil (1954), Menard (1969, 1973) and Purdy (1974) among others have all contributed ideas as to their origin and modification. Darwin's well known subsidence theory postulated that a subsiding volcanic island base was first surrounded by a fringing reef, then a barrier reef, and finally, as the volcanic rock disappeared below sea level, an atoll remained. Recent investigations into the structure and development of Bikini and Eniwetok Atolls basically support Darwin's premise that subsidence is the key factor. Drillings show that the coralline limestone caps on both these atolls exceeds 1,220 m (Ladd, 1973). It now seems clear that the life cycle of Bikini and Eniwetok was one of subsidence of volcanic mounds, reef building, emergence during the Miocene, and erosion and growth during the fluctuating sea level of the Pleistocene.

A major alternative to Darwin's ideas was Daly's "glacial-control theory". Rather than the island sinking, he envisaged that it was planated during a Pleistocene low sea-level stand and then, when the sea rose again, the reef grew to sea level giving rise to an atoll. While Davis (1928) considered Daly's theory as the only serious rival to Darwin's, he reasoned that if reefs were indeed killed during the glacial low sea level stands, then cliffed headlands ought to be commonplace along island shores inside present-day barrier reef lagoons. The headlands are in fact singularly absent in the warmer parts of the coral seas but become increasingly apparent towards the northern and southern limits of present-day coral growth. At best, Daly's theory was therefore only applicable to the marginal belt atolls (Purdy, 1974).

Hoffmeister and Ladd (1944) did not feel that barrier reefs and atolls were genetically related in the Darwinian sense. They considered that both simply developed through upward growth of corals at the edges of antecedent platforms. These platforms depended on a fortuitous combination of erosion, deposition, volcanic activity and tectonism. Keunen (1947), recognizing the possible relationships between the theories of Darwin and Daly, developed his own "glacially controlled subsidence theory". Unfortunately his theory is difficult to accept because he devised two mechanisms to account for the same thing. During the Tertiary he envisaged Darwinian subsidence, but during the Pleistocene a modified glacial control theory is required to give the same result through the upgrowth of reefs along the edges of truncated barrier reefs or atolls.

MacNeil (1954) did not agree with Keunen's idea that the Tertiary atoll was planed off during the Pleistocene and then regrew rapidly in the Holocene. He considered that subaerial limestone solution during the Pleistocene was the only logical explanation for the saucer shape of atolls, and that Holocene growth simply added a "veneer" of new carbonate to the karst landscape. This idea, fully developed by Purdy (1974) under the title "antecedent karst", ties together the essential premise of Darwinian subsidence and the significance of Pleistocene low sea level karst development. There is good evidence to support this antecedent karst theory (Bloom, 1974), and this theory accords most fully with our present knowledge of atoll morphology. Because of the significance of Pleistocene karst development on "emergent" island forms the topic is discussed more fully below.

Karst and Submerged Atolls

The "swinging sea level of the Pleistocene" has been a major factor in the morphology of modern reef complexes, although not in the sense that Daly intended by his glacial-control planation theory. Reefs in general were not in fact truncated at the glacial low sea level surface; rather rugged karst landscapes were produced on the emerged limestone terrains (Bloom, 1974). Evidence for this can be interpreted from drowned karst features that pass below sea level on the east Pacific continental shoreline, from the thickness of new post-glacial coral-algal deposits, from the present morphology of atolls, and by experimentation.

Emery et al. (1954) interpreted the closed depressions at 33 to 35 m below sea level in Bikini lagoon as sinks formed by groundwater circulation. Similar but more abundant depressions are developed to depths of 54 m in the eastern part of the lagoon of the almost-atoll, Truk. These were interpreted by Shepard (1970) as also being sinks on a glacial-age karst plain. Purdy (1974) presents a table summarizing the work of many other studies on antecedent solution unconformities on Holocene carbonate platforms, and there seems little doubt that present day atoll morphology closely reflects the karst landscape drowned by post-glacial eustatic rise.

Experimentation with acid on limestone blocks has also given impetus to the antecedent karst idea. Under a uniform acid shower the flat-top of an exposed limestone block develops into a rimmed basin that is such an excellent scale model of an atoll that MacNeil and Purdy regard the experiment as proof that glacial-age weathering is the primary control of present reef configuration (Purdy, 1974). The topography of the Mariana limestone on the northern plateau of Guam mirrors this experiment. Here the well-defined reef and lagoon facies of the limestone have been subaerially weathered to the point that the reef facies actually form a peripheral range of hills around a karst plateau that is underlain by lagoon facies. Likewise, Bourrouilh (1975, 1977) examined profiles through many atolls and comes to the same conclusion.

The significance of antecedent karst in the discussion of Pacific island types is two-fold. First, it is clear that the present atoll morphology is fundamentally karst induced, rather than growth induced. Second, it illustrates the point that certain atolls may have been subject to more rapid solution during Pleistocene low sea level periods and that the slow rate of growth following post-glacial eustatic rise has not yet allowed these drowned atolls to re-emerge as islands.

Drowned or submerged atolls are quite common. Tayama (1935) considered that of the 20 shoals or banks in the Western Carolines at least eleven are atolls drowned by tectonic subsidence. It is quite unlikely that tectonic subsidence is sufficiently rapid to cause their drowning, particularly as they are found under good coral growing conditions. Rather, regrowth following the production of antecedent karst has simply not been sufficiently rapid to raise these shoals to sea level again. However, this mechanism could trigger the demise of atolls in areas which, even with today's conditions, would be considered marginal reef growing areas. A probable example of this is the shoal located at 35°N, 172°E some 1,250 km northwest of Kure Atoll in the Hawaiian Chain at a depth of 60 m. It is also quite possible that truncation during some Pleistocene low sea stands did occur to the extent that with subsequent eustatic rise corals simply found themselves in water too deep in the euphotic zone to survive, and the shoal stopped growing. While this supposition tends to agree with the planation aspect of Daly's theory, the most unlikely form that would result would be an atoll.

THE TECTONIC POSSIBILITIES

An acceptance of Darwin's atoll origin model requires the acceptance of island subsidence. But is subsidence merely isostatic or are other more complex factors needed to account for the great vertical displacements required to alter volcanic island peaks into atolls with carbonate caps as thick as 1,200 m? With all island types in mind the question of emergence must also be addressed. Tectonic information needed to help answer these questions include; lithospheric plate movements, lithospheric cooling and compressions; melting anomalies (hot-spots) and volcanic activity; asthenospheric bumps, lithospheric loading and isostatic changes.

Lithospheric plate movements, lithospheric cooling and compressions

The earth's lithosphere is made up of seven major, and a number of minor, rigid lithospheric plates (Fig. 1). These plates are usually in motion relative to each other. Where plate margins separate asthenospheric magma upwells to form new lithosphere, and where plates collide the denser is normally subducted below the lighter (Fig. 4). Because of the inherent potential for fracturing along plate boundaries their distribution tends to coincide with seismic and volcanic activity. Volcanic activity, however, can also be associated with melting anomalies in the thin (75-100 km) oceanic crust. For a detailed explanation as to how mid-ocean ridges form please see Dillon (1974).

Evidence substantiating the fact that the Pacific Plate ages with distance from the spreading centre along the East Pacific Rise comes from a number of sources. McDougall (1971) has dated the volcanic (basaltic) islands of the Hawaiian Chain using the potassium-argon method and found that they increase in age towards the north-west. Each island in the Hawaiian-Emperor Chain is presumed to have been created over a stationary melting anomaly presently capped by the island of Hawaii (Wilson, 1963 a,b; Shaw and Jackson, 1973).

Very convincing evidence as to the older nature of the north-western portion of the Pacific Plate comes from the study of ocean sediments (Heezen et al., 1973). Sediments close to the East Pacific Rise are thin or non-existent, while with distance from the rise the sediment lens thickens. Sediments in contact with the Pacific Plate close to the Kurile subduction zone were actually deposited in equatorial waters during the Mesozoic (Upper Jurassic) at least 120 million year ago (Heezen & McGregor, 1973). Rates of platal movement have also been established. Le Pichon et al. (1973) estimate that the Pacific Plate is underthrusting the Aleutian Trench at 6.5 cm per year, while Heezen et al. (1973) indicate that the plate presently has a westward component of 8 cm per year and a northward component of 2 cm per year.

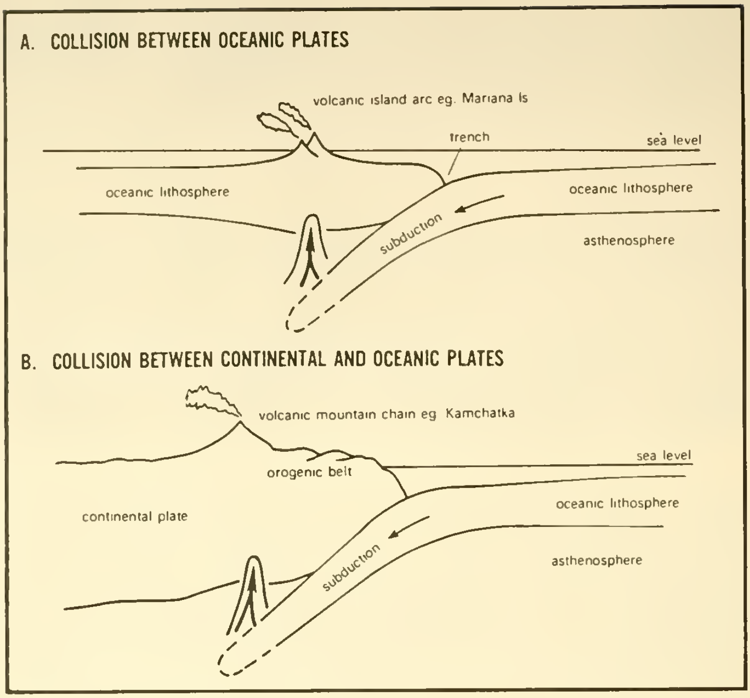

Figure 4. Typical subduction patterns in the western Pacific.

In the discussion of the relationship between plate tectonics and island type differences another important characteristic of ocean plates must be stressed. The upper surfaces of ocean plates are not in fact horizontal relative to sea level. As the hot newly-created lithospheric plate moves away from the accreting plate boundary along the East Pacific Rise it progressively cools and "contracts". Because this occurs at the same time as upper asthenosphere cools and "accretes" to the lower lithosphere surface, lithospheric thickening is the actual result. The overall effect of this cooling, however, is to cause the ocean to deepen with increasing distance from the East Pacific Rise and creates a sloping of the crustal plate. Le Pichon et al. (1973) calculate that at the East Pacific Rise average depth is 2780 m, while at 30 million years the Pacific Plate is at a depth of 4350 m, and at 75 million years at a depth of 5610 m. Clearly any volcanic islands or seamounts produced on the slopes of the East Pacific Rise or over a melting anomaly will be carried tangentially into deeper water. So regular is the rate of ocean deepening due to lithospheric cooling with distance from the East Pacific Rise that Sclater et al. (1971) indicate an impirical relationship between ridge elevation and age of the crust that can be used to date crust up to 40 my old to within 2 my.

There is no unanimity as to the time required for crustal cooling-ocean deepening to approach zero. Sclater and Francheteau (1970) infer that the effects of lithospheric cooling cease by the time the plate has moved 6,000 km (approximately 75 my), while Watts and Cochran (1974) indicate negligible cooling at 80 my. Le Pichon et al. (1973) suggest that cooling continues beyond 75 my but is greatly reduced in rate. That the ocean progressively deepens towards subduction zones is clear, however, and crustal cooling may well be the principal cause. Crustal cooling need not necessarily be regular or linear in all parts of the Pacific plate at the same time. This is because crustal reheating at asthenospheric bumps and fixed melting anomalies (Menard, 1973; Crough, 1978; Rotondo, 1980) can cause expansion and thinning of the plate above with a renewed cooling-ocean deepening pattern to the north-west (Fig. 5).

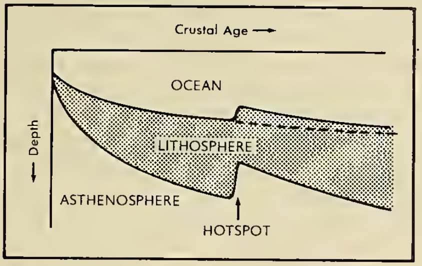

Figure 5. Inferred interaction of the lithosphere with a mid-plate hot-spot. From the ridge to the hot-spot the lithosphere thickens and subsides by cooling. At the hot-spot, extra heat drives the isotherms upwards, thins the lithosphere and causes uplift. Beyond the hot-spot, the lithosphere cools rapidly because it is thin and thus subsides as younger lithosphere at the same depth, rather than as normal lithosphere of the same age (dashed line). After Detrick and Crough (1978, Fig. 4).

It is obvious that if the Pacific plate is being forced north-west to be subducted below the edge of Asia there must be considerable compressional forces acting close to the subduction zone. Hanks (1971) reports strong horizontal compressional stresses seaward of the Kurile trench. Watts and Talwani (1974) call the positive gravity anomalies seaward of many trenches "outer gravity highs" and indicate that they correlate well with regional rises of up to a few hundred meters. Pacific plate margins showing slight upwarps before final subduction include areas along the Kurile, Bonin, Japan and Philippine trenches. The outer gravity highs seaward of the southern Bonin and Mariana trenches also correlate with regional topographic rises but they can be explained without inferring horizontal compressional stresses (Watts and Talwani, 1974). Topographic rises are not present along all subduction zones. In the discussion of island forms close to subduction zones the presence or absence of these topographic rises must be considered.

Melting anomalies and volcanic activity

All Pacific plate island types require an original volcanic base. It is easy to envisage magmatic outpouring forming volcanic islands close to spreading centres that then drift away from these ridges as the plate cools and moves into deeper water. But how do we account for volcanic islands such as Hawaii which are both young and distant from the East Pacific Rise? A number of explanations have been proposed to explain this phenomenon of mid-oceanic plate volcanic activity which is not directly attributible to spreading centres along mid-oceanic ridges. They include the 1) hot-spot theory, 2) gravitational anchors, 3) asthenospheric bumps, and 4) slip-strike motion theory. The term "hot-spot" is frequently used to describe the phenomenon of magma discharge that forms line island-seamount chains on oceanic plates. Because the term hot-spot is also often used in the more specific sense as a theory to explain the origin of these island-seamounts, the term "melting anomaly" (Shaw and Jackson, 1973) will frequently be used to encompass all theories on their origin. The "hot-spot" theory depends upon the principle of a thermal plume originating at a fixed spot beneath the surface of the oceanic plate in the asthenosphere (Wilson, 1963; Morgan, 1965, 1972a,b). Essentially a convection cell mechanism is operative. This in turn causes weakness in the 100 km thick lithesphere and outpourings of magma occur over the plume. Magma discharges from a series of closely spaced point source vents that coalesce into a single vent as eruptions progress in time (Jackson & Shaw, 1975). As the ocean plate moves across this fixed hot-spot a series of volcanic seamounts results. It is most likely, however, that volcanism is not as precise as this ideal description infers, nor is it necessary that magmatic outpourings be aligned perpendicular to the East Pacific Rise spreading centre (Moberly and Larson, 1975).

Shaw and Jackson (1973) proposed that volcanic activity at the south-eastern end of the Austral, Tuamotu and Hawaiian Chains is not the result of fortuitous location of thermal plumes but rather is a consequence of shear melting caused by plate motion. Once such melting begins a dense residuum is formed and sinks. This downwelling ultimately forms "gravitational anchors" that stabilize the anomalies and cause inflow of fresh parent materials into the source area for the basalts. Such gravitational anchors, they feel, provide a much more sensitive inertial guidance system for positioning of melting anomalies.

Menard (1973) noted the close relationship between asthenospheric bumps and the actively growing end of volcanic chains on the Pacific Plate. He concluded that melting anomalies are located on the "updraft" sides of positive gravity or depth anomalies and are being overridden by moving plates. It is quite possible that this "warping" of the lithospheric plate determines the location of the melting anomaly, which, according to Menard (1973) would be the result of a thermal plume. Because of the importance of asthenospheric bumps in epeirogenic uplift resulting in raised island forms they will be discussed more fully in the next section.

Handschumaker (1973) suggested that the Emperor Seamounts may have been formed as a result of extrusion induced by strike-slip motion. Jackson and Shaw (1975), however, found that there is no evidence that any significant intraplate finite strain has been imposed on the lithosphere in the region of linear chains, so this theory is considered unlikely to explain the linear seamount chain phenomenon.

Melting anomalies may therefore result from a number of possible mechanisms. The very fact that they do occur, however, produces the seamount-island chains on which atoll development depends. They also help account for the renewed crustal cooling-subsidence phase needed for atoll development (Fig. 5). It should be stressed that not all melting anomalies give rise to atolls, however. No atolls are found in waters where either cold or the simple absence of certain reef species prevent reef development as in the Marquesas, or where certain seamounts never reach the ocean surface. Kidd et al. (1973) indicated that there are as many as 150 terrestrial plumes giving rise to melting anomalies so oceanic seamounts are not the exception. While evidence indicates that melting anomalies are relatively stationary as in the Hawaiian Emperor Chain (Jackson et al., 1980), it is also possible that some are less fixed, particularly where they abut other continental plates and are subject to forces not directly attributable to their own lithospheric plate motion.

Asthenospheric bumps

Menard (1973) was perhaps the first to fully appreciate the relationship between the emergence of Pacific islands and broad low "bumps" on the ocean floor. Because he attributed these bumps to an asthenospheric surface which is not exactly level, he called them "asthenospheric bumps". In actuality they appear as low bumps up to several hundred metres in vertical elevation and 1,000-3,000 km in width on the surface of the ocean plate and are detected as positive gravity anomalies. As the plate moves over these asthenospheric bumps the general tendency for the lithosphere to deepen due to cooling (Le Pichon et al., 1973) is temporarily counteracted. Any islands or atolls on the upslope side begin to rise out of the water instead of subsiding in the expected way (Fig. 6). Ocean, Nauru and Marcus islands are good examples of the effects of asthenospheric bump uplift on islands (McNutt and Menard, 1978).

Asthenospheric bumps are located in many parts of the Pacific. Care must be taken in evaluating their overall significance however. While it is tempting to associate all seamounts and islands riding over one asthenospheric bump with one melting anomaly, it may be that peaks produced by another melting anomaly nearer the East Pacific Rise have simply advanced to this new bump-melting anomaly area (Rotondo et al., 1981). In this way the idealized sequence of atoll formation may appear confused as high islands from the nearby melting anomaly may be associated with atolls from another but distant melting anomaly.

Isostatic subsidence and lithospheric loading

Darwin's original atoll development model infers isostatic subsidence

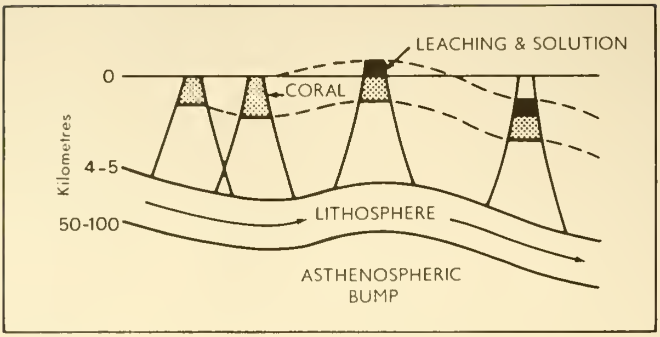

Figure 6. Idealized history of an atoll emerging-subsiding as it passes over an asthenospheric bump. After Menard (1973).

due to the islands own mass. Although some atolls have been subsiding for more than 50 ml years and have undergone subsidence exceeding 1,000 m it is very unlikely that isostasy alone could occur over such long periods of time. McNutt and Menard (1978) suggest that lithospheric loading by a new volcanic island produces a response over geologic time scales of 100,000 years or more, while Watts and Cochrane (1974) state that after only a few million years of loading isostatic adjustments approach zero and that the ocean plate then seems capable of supporting seamount chains for periods of tens of millions of years. Isostatic subsidence, for newly formed volcanic islands and submerged seamounts is very real, however, and immediately gives rise to a "moat-arch" development (McNutt and Menard, 1978, 1979; Jarrard and Turner, 1979).

Depression of the lithosphere by a new volcanic mass is variously described as crustal loading or lithospheric loading, and a crustal moat develops peripheral to the seamount. This moat may fill rapidly with sediments and not appear on bathymetric maps. Beyond the outer edge of the moat, flexuring develops an arch which experiences uplift in the order of tens of metres. If there are islands at various distances from this new loading mass those within the developing moat will experience gradual subsidence, while those on the developing arch will be slowly elevated. McNutt and Menard (1978) argue that the uplift of Atui, Mitiara, Mauke and Mangaia atolls in the Cook Islands result from lithospheric loading by three nearby volcanoes. Jarrard and Turner (1979), while agreeing with this conclusion, disagree as to the exact amount of resultant elevational change.

When magmatic outpourings cease above a melting anomaly and the volcanic island "drifts" away isostatic subsidence will soon cease. Likewise any island over which it had an influence would continue to move into deeper waters due to non-isostatic crustal cooling-ocean deepening. This picture can be confused in practice, however, if a new seamount again develops before other islands have had the opportunity to move beyond any new moat-arch development. Likewise, atolls drifting past a hot-spot seamount system not associated with its own igneous pedestal development could undergo subsidence or uplift depending on their proximity to the new crustal loading. McNutt and Menard (1978) consider this latter mechanism explains the emergence of some Tuamotu atolls following recent moat-arch development in the Tahiti area.

In our consideration of island types on the Pacific plate isostasy by itself seems of minor short term influence in causing volcanic islands to subside. Unless a volcanic island ceased growth at, or just above, sea level an atoll could hardly result from isostatic causes alone. Isostasy can clearly have a major influence on other island types, however, causing increased but modest subsidence rates for existing atolls within the new moat and emergence of atolls or volcanic islands on the arch. Beyond the arch little or no isostatic influences will be felt and Watts and Cochrane (1974) consider that the 400 m thick carbonate cap on Midway could not be due to this influence.

CASE STUDIES ON SPECIFIC ISLAND CHAINS

A number of island groups are examined to show how the various island types within them correspond to the tectonic, volcanic and reef growing conditions known to be operating on the Pacific plate. Three island groups in the North Pacific were examined using information from the literature and extracting bathymetric data from maps produced by the Scripps Institution of Oceanography (Chase et al., 1970). These island groups are the Hawaiian, Marshall-Gilbert and Caroline. The Tuamotu and Society Island groups in the southern hemisphere were also examined with bathymetric data coming from a bathymetric map of the Pacific produced by the Academy of Sciences (1964).

Hawaiian-Emperor Chain

This chain was selected because not only is it the most intensively researched group but because it is also the best example of a continuous line island group that runs from warm reef-promoting waters to cooler reef-inhibiting waters. The Hawaiian-Emperor chain lies entirely within the North Pacific and constitutes the Hawaiian Islands, the atolls and shoals of the Midway group, and the seamounts and guyots of the Milwaukee-Emperor chains (Fig. 7). This volcanic (basaltic) ridge runs from the Island of Hawaii, a total of 6,340 km to the Kamchatka Trench. Figure 7 depicts the peaks and corresponding ocean floor depths from a point south-east of Hawaii to the Kamchatka Peninsula. Data was taken from bathymetric maps prepared by Chase et al. (1970) which use 200 fathom depth intervals. In order to determine ocean floor depths and the heights of peaks with respect to sea level and the ocean floor, a line was plotted from a point south-east of Hawaii through the major peaks to the Kamchatka Trench (see Fig. 2 for profile route). Sampling points were placed at regular intervals along this line and data on the elevations and depths between the closest volcanic islands, atolls or submerged seamounts were recorded for each point. In all there were 132 points along the 6,700 km transect and using this data a profile of the more prominent peaks was produced (Fig. 7).

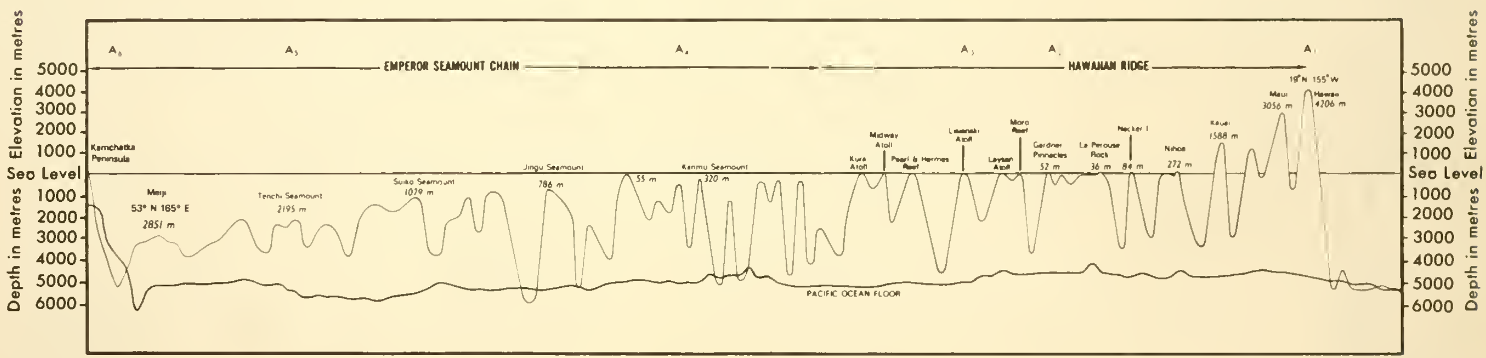

Figure 7. Profile of the Hawaiian-Emperor Chain (modified from Rotondo, 1975 Fig. 1.9). For profile route see Figure 2.

To obtain data on sea floor depths four lines were drawn parallel to the central ridge line at three and six centimetres to either side. Ocean depths were recorded exactly on these parallel lines at right angles to the 132 points on the central ridge line. The ocean floor profile in Figure 7 is the average of these four depths for each of the 132 profile positions. It should be noted, however, that this ocean floor curve is not coincident with the surface of the lithospheric plate. Since the Pacific plate was formed at the East Pacific Rise, thin layers of sediment as well as outpourings of magma associated with the Hawaiian melting anomaly have been superimposed on it to varying degrees. Despite the visible bumps that result from these magmatic ourpourings, the bumps are actually locked onto the plate as it moves into deeper water due to lithospheric cooling with age (Le Pichon et al., 1973). Minor asthenospheric bumps would be independent of these outpourings and could well cause the "bobbing" motion described by Menard (1973), but they could not be detected simply by examining bathymetric maps.

An examination of these profiles shows a number of interesting characteristics. Following the peak-curve from the Island of Hawaii north-west, it can be seen that the average high island elevation drops off rapidly due to the longer exposure to subaerial erosion (Fig. 7). There is no reason why these islands should appear to be reduced in elevation in a linear way because the original islands were never all at the same elevation to begin with (MacDonald and Abbott, 1970). The majority of these high islands, however, did exceed 1,000 m before cessation of volcanic activity, and heavy orographic precipitation combined with high temperatures and easily weathered besalts gives rise to rapid chemical weathering (Scott and Street, 1976). This subaerial erosion, together with coastal erosion, combine to rapidly reduce the elevation of islands, and this trend does appear in the profile.

The findings of Moore (1970) concerning isostatic readjustment of the Pacific Plate to the additional load of a new volcanic island must also be considered here because they indicate that isostatic subsidence is not as significant as originally suggested by the Darwinian subsidence model. According to Moore (1970) the absolute subsidence of the still-active Island of Hawaii is 4.4 mm per year. This agrees well with Apple and MacDonald (1966) who estimated that the west coast of Hawaii is subsiding at 3 mm per year. Moore also indicated that Maui (0.8-1.3 my, McDougall, 1964) is subsiding only 1.7 mm per year, Oahu (2.2-3.4 my) is stable, and Kauai (3.8-5.6 my) is actually rising. There is of course the real possibility that the Hawaiian chain in general will experience subsidence as it moves north-west because it will be descending the now cooling flank of a rise created over the Hawaiian hot-spot (Fig. 5). This cooling is similar to that near the mid-oceanic ridge and for the Hawaiian Islands would appear as in Figure 8. The true picture is somewhat confused near the hot-spot because of the current moat-arch development around Hawaii and the residual effects of Maui which must combine to give rise to the isostatic subsidence-emergence noted by Moore (1970) above. Oahu clearly does have a raised reef probably resulting from the arch produced by the combined masses of Maui and the earlier development of Hawaii. Now that Hawaii has become so massive

Oahu has stopped rising possibly because the Hawaii moat has now radiated outwards to bring Oahu into its flanks. The emergent island of Kauai continues to rise, however, as it may now have been fully overtaken by the Hawaii arch.

The most northerly islands in the Hawaiian chain with visible basaltic rock, Necker, La Perouse Rock and Gardner Pinnacles, are all reduced to less than 90 m above sea level. It is unlikely that all of this reduction results from subaerial and marine erosion alone. Each of these islands is surrounded by extensive flat reef-shoals and all indications are that they have undergone gradual submergence (Menard, 1973). Between Gardner Pinnacles and Kure Atoll, island and ocean floor subsidence is clearly indicated (Fig. 7). North of Kure only one seamount, between Jingu and Kaumu seamounts at 35°N, 172°E, is within 60 m of sea level. Apart from this peak, which must have been a Pleistocene island, there are no peaks north of Kure that could have been above sea level in recent times. This peak is no doubt a submerged atoll which experienced difficulties in producing reef growth sufficient to keep it at wave level as it continued to move into cooler waters. Karst formation on this eustatic low-sea level island during the Pleistocene would have encouraged this submergence relative to present sea level.

North of 35°N, 172°E, peaks deepen in a relatively linear fashion, and parallel deepening of the ocean bottom occurs. Close to the Kamchatka Trench, seamount elevations are variable, the ocean floor receives greater thicknesses of continental sediments and there appears to be minor buckling associated with bending of the Pacific Plate as subduction begins. This buckling effect is confirmed by Watts and Talwani (1974) but it will only have the effect of modestly raising deeply submerged seamounts close to the trench. Irregularities are to be expected, however, as most seamounts never reached sea level even when they were first formed, and at their present great depths it is difficult to differentiate between a seamount that never reached the ocean surface, and a guyot which may have been truncated at sea level and subsequently subsided. The term guyot must be treated with caution here because not all flat topped seamounts (i.e. guyots) are considered

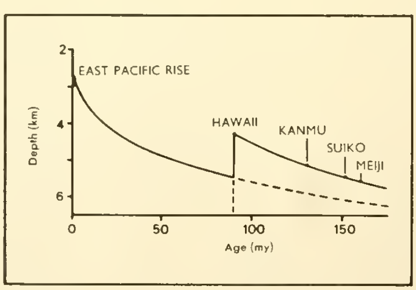

Figure 8. Subsidence after reheating at Hawaiian hot-spot. Hawaii depicted at the depth of normal 25 my lithosphere. Dashed line is expected subsidence without reheating. Modified from Crough (1978, Fig. 16).

to have been planated at sea level. Recent corings on Ojin, Nintoku, Yomei and Suiko seamounts in the Emperor Seamount Chain (Jackson et al., 1980) confirm that these guyots were in fact volcanic islands before subsidence allowed them to pick up carbonate caps. Borings on Suiko (Fig. 7) hit a "Paleocene shallow-water reef or bank assemblage of carbonate sand and sandy mud with algal nodules, from 52.5 to 163.5 meters. Basalt directly underlies the shallow-water limestone" (Jackson et al., 1980:11). Paleomagnetic measurements indicate that Suiko was formed at approximately 25°N latitude at a time when carbonate deposition (and possibly discontinuous reef formation) was occurring in water somewhat cooler than around the present-day Hawaii. The paucity of coral material on seamounts in the northern Emperor Chain is in marked contrast to seamounts at the bend of the Hawaiian-Emperor Chain (see A4 on Fig. 2) where corals are more abundant (Jackson et al., 1980). It appears then that a southward movement of the Hawaiian hot-spot into warmer waters accounts for the earlier development of bryozoan-algal caps (without coral) to the present day coral-algal caps. Figure 8 suggests that given time present day Hawaiian atolls will indeed become truly submerged atolls just as this appears to have already happened to Darwin Guyot in the Mid-Pacific Seamounts to the West (Ladd et al., 1974). This guyot has subsided to a depth of 690 fathoms but has preserved intact the atoll annular ring and ten-fathom deep lagoon.

On the basis of the above analysis a schematic representation of what may well have happened to the Hawaiin-Emperor seamount chain over the last 70 my is presented (Fig. 9). While this figure clearly generalizes the actual profile given in Figure 7 it does exhibit a remarkable approximation to the known facts and tectonic possibilities. It should be noted that not only does Figure 9 account for many of the island types illustrated in Figure 3, but it indicates four distinct island-seamount zones or "phases". It should also be noted that but for the fact that many of the Emperor Seamounts were formed in poor reef-growing waters, submerged atolls would extend all the way to Kamchatka.

Marshall-Gilbert Chain

These islands differ quite markedly from the Hawaiian-Emperor chain. They are in fact much more scattered and do not represent a characteristic line island group. The chain also lacks almost-atolls and high volcanic islands at its south-eastern end. Likewise there is no clear indication that the chain continues north-west, as does the Emperor Chain, to be subducted into a trench.

Figure 10 is based on a composite profile of the scattered atolls, shoals and seamounts of the Marshalls, and therefore differs from the single profile-transect method used in Figure 7, for the Hawaiian chain (bathymetric data from Chase et al., 1970). Because of the difficulty in interpretation of seamounts north of the Marshalls it was difficult to decide exactly the path taken or to be taken, by the most northerly seamounts in the chain. As a result two profiles are drawn. Both begin on the equator (B1 on Fig. 10) and move north-northwest to Wake (B2 and B3). Then one continues in the same direction to B4 in the deep ocean north of the Mapmaker Seamounts. It is possible that the numerous

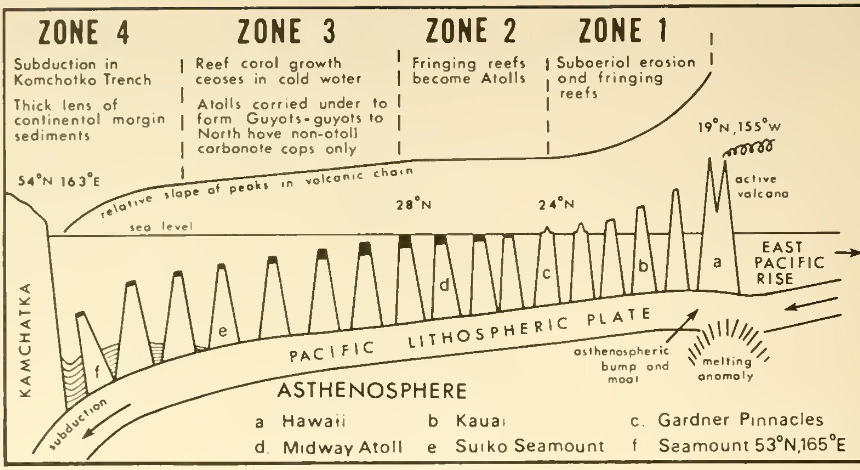

Figure 9. Schematic representation of the major physical factors influencing the Hawaiian-Emperor Seamount Chain (modified from Scott et al., 1976).

seamounts to the west and northwest may be part of the Marshall chain so another profile continues from B3 through Marcus Island to B5 at the Bonin Trench.

For both profiles the generalized ocean floor depth increases towards the northwest. The members of the Gilbert group shown on the profile are of a line island type, but appear to be separated from the Marshalls both visibly and bathymetrically. The numerous atolls of the Marshalls are scattered in two general lines running SSE to NNW and are associated with numerous seamounts (not shown in Fig. 10). North of Taongi Atoll none of the Marshall Seamounts appear to have reached sea level. From the bathymetric map Wake Atoll would appear to result from a different melting anomaly than that which produced the main Marshall cluster. Marcus Island and the shoal just beside the Bonin trench represent isolated peaks, but it is more likely they were previously shallow drowned atolls. Marcus is now rising over an asthenospheric bump and is now a raised atoll (McNutt and Menard, 1978). The shoal close to the Bonin trench may have been elevated close to sea level by the outer gravity high produced just before subduction.

In the case of the Marshalls, which must represent a senile volcanic chain produced by a long-inoperative hot-spot, the gradual movement into deep water combines with subaerial erosion to leave only atolls. Drillings on Bikini and Eniwetok (Ladd, 1973) at the northern end of the Marshall Chain hit basalt at depths exceeding 1,220 m, and shallow water fossils taken just above the basalt basement are about 55 my old. It is therefore quite probable that the parent volcanoes on which these atolls developed were formed just south of the equator in shallower water. They then collected these vast thicknesses of carbonate deposits on their slow

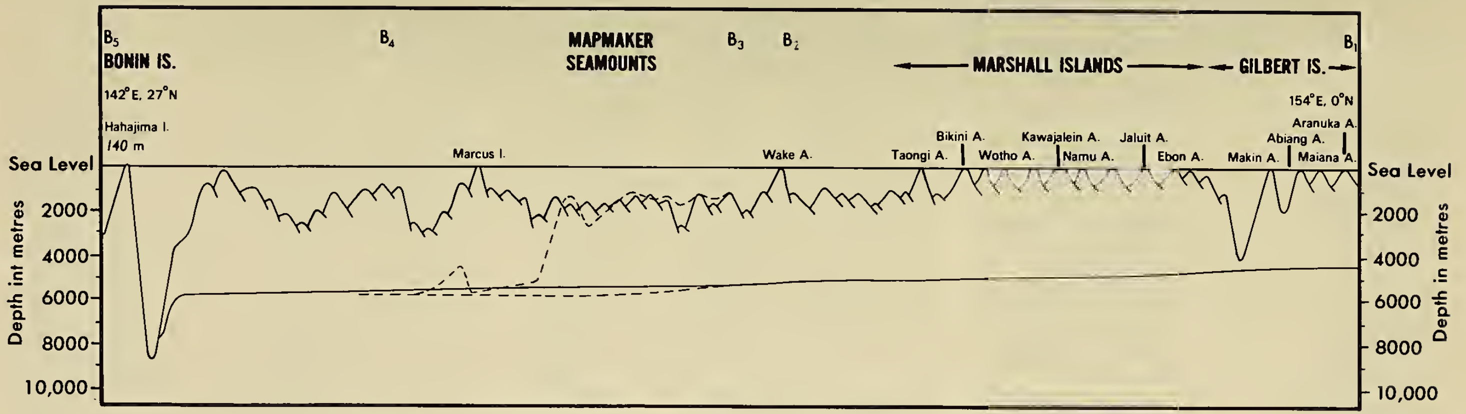

Figure 10. Profiles along the Marshall-Gilbert island chains.

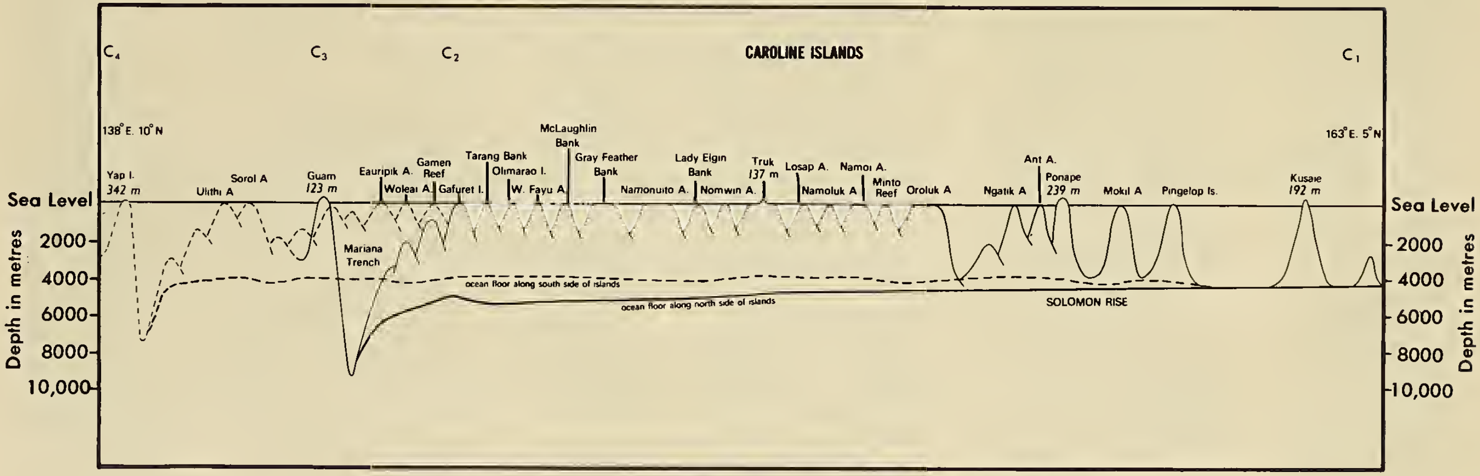

Figure 11. Profiles along the Caroline Island Chain.

journey northward. Such thicknesses are greatly in excess of those in the northern end of the Hawaiian Chain and reflect the truly equatorial location of their parent melting anomaly. In the Hawaiian Islands great thicknesses of carbonate are inhibited by a much shorter passage through reef-promoting waters between the time their basalt cores are reduced to sea level and the time atolls suffer demise north of 30°N in cooler waters.

Caroline Islands

The Carolines run west-northwest from Kusaie to the Mariana Trench (Fig. 11). Like the Hawaiian-Emperor Chain there are volcanic islands to the south-east and atolls to the west. Unlike the Hawaiian Chain, however, the almost-atoll form is also present, and the complete chain lies within warm tropical waters conducive to reef growth. The presence of almost-atolls as well as young volcanic islands and atolls make the Caroline Chain one of the more typical line island chains insofar as island form is concerned.

A composite profile based on data taken from bathymetric maps compiled by Chase et al. (1970) is shown in Figure 11. As is the case with the Marshall profile in Figure 10 the western end of the chain appears as a confused pattern on the bathymetric maps, thus this portion of the profile follows two separate paths (see Fig. 2 for profile routes). Figure 11 also shows two profiles for the ocean floor, one along the southern side of the chain and one along the northern. They are separated because it is considered that to average these depths would be misleading. This discrepancy may arise because the southern side of the atoll portion of the chain on the Pacific plate appears to be under considerable stress from the north-eastern advance of the Bismark portion of the Australia plate and the Eauripik-New Guinea Rise. Long east-west trenches just south of Woleai Atoll tend to support this conclusion. Thus, depths to the south of the chain are not considered to be reliable indicators of Pacific plate deepening as it approaches the Mariana Trench.

It is also possible that the melting anomaly which gave rise to these islands has been forced to migrate east as the Australia plate slowly moves north-east. This hypothesis might help explain the more east-west orientation of the Carolines that supposedly lies on a rigid lithospheric plate with a northwest movement and on which most line islands trend northwest. While deformation of the Pacific plate similar to that found by Rea (1970) north of the Hawaiian Ridge may account for some of this east-west trend it is unlikely to account for such a marked departure from the normal line-island trend.

Despite these problems the Caroline Islands reflect the classical Darwinian atoll formation sequence when superimposed on a plate moving into deeper waters. It differs from the Hawaiian-Emperor chain sequence, however, in that atolls do not appear to die off except where subduction causes rapid subsidence into the Mariana Trench. Some circumstantial evidence also suggests that as the Carolines move towards the west they enter deeper water. While there is no reason to assume that newly-formed islands have always been of the same size, the hypothesis presented here would require gradual reduction in area at sea level if they were moving into deeper water. Wiens (1962) indicated that the average dimensions of the 15 westernmost sea-level atolls is 12.2 x 5.6 km, while the average for those 17 to the east (in relatively shallower water) is 16.8 x 9.6 km.

Tuamotu and Society Islands

There is a total of 72 atolls in the Tuamotu Islands (Fig. 12). At the southeastern end of the chain is a near-atoll, Mangareva, an old volcano in a similar stage to Truk in the Carolines. Mangareva consists of a dozen small embayed islands and stacks in a lagoon surrounded by a well-developed barrier reef some 41 km in diameter. Pitcairn, a relatively young volcanic island, lies 450 km to the southeast of Mangareva. If Pitcairn was actually produced by the same melting anomaly responsible for the Tuamotu Archipelago proper, then the Tuamotu Chain cannot yet be considered a totally senile volcanic chain.

In the area of the Tuamotu Islands there is no doubt as to the actual deepening of the ocean floor as it moves northwest towards the equator. These islands are relatively close to the East Pacific Rise where lithospheric cooling causes most rapid increases in depth (Heezen et al., 1973), and as they move into successively more suitable reef growing conditions atoll development conditions are optimal. The large number and close spacing of the Tuamotu atolls is also indicative of their origin in shallower waters close to the East Pacific Rise. On average more of the newly formed seamounts would have reached sea level here simply because of the shallower water.

Because of their ideal position south of the equator it is probable that many of the larger atolls in the Tuamotu group will survive for many millions of years during their slow passage through warm equatorial waters. It is possible, however, that some of the smaller atolls will suffer demise even in equatorial waters because as island bases move into deeper water the top of their carbonate peaks will become so narrow that they will no longer support any island form whatsoever. Data for the Tuamoto Archipelago profile given in Figure 12, as well as for the Society Islands (Fig. 13), were extracted from Russian bathymetric maps of the Pacific (1:40,000,000) giving depths in 500 m intervals (Academy of Sciences, 1964). Although it does not show up well on a profile of this scale (Fig. 12) some of the atolls at the north-western end of the Tuamotus are raised. While there is some disagreement as to the absolute uplift involved there is general consensus that the uplift of Matahira, Tikehau, Makatea, Niau and Anoa is due to arch flexuring following recent crustal loading by Tahiti and Mahetia to the west-south-west in the Society Islands (McNutt and Menard, 1978, 1979; Jarrard and Turner, 1979).

The Society Islands (Fig. 13) appear more like the Hawaiian than the Tuamotu except that they do not continue as seamounts to the north-west as do the Hawaiian. The Society group are probably much younger than the major portion of the Tuamotus because of their short length and lack of subaerial erosion. They exhibit all the characteristics of a

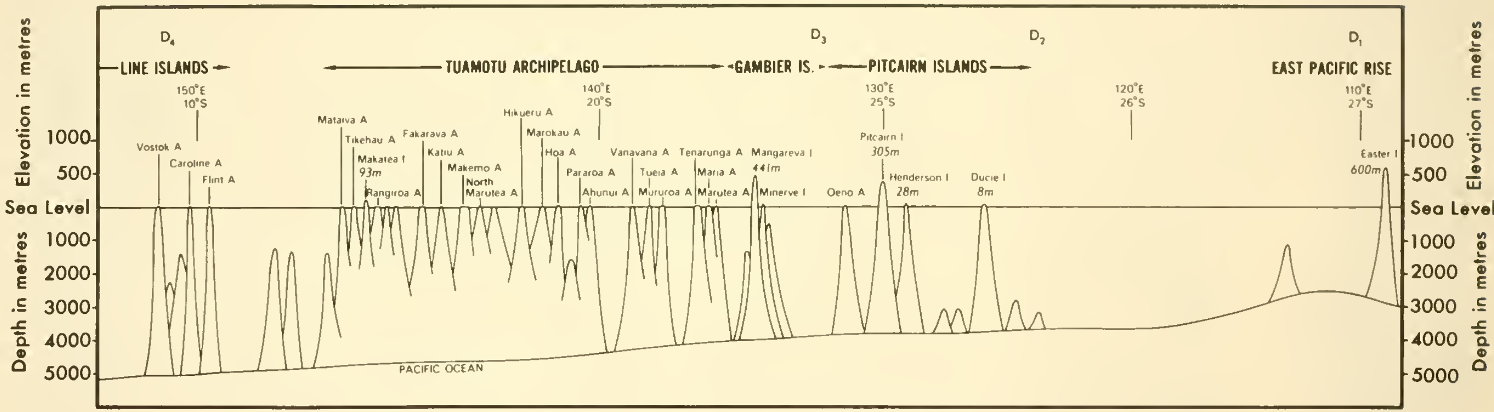

Figure 12. Profile from the East Pacific Rise through the Tuamotu Archipelago.

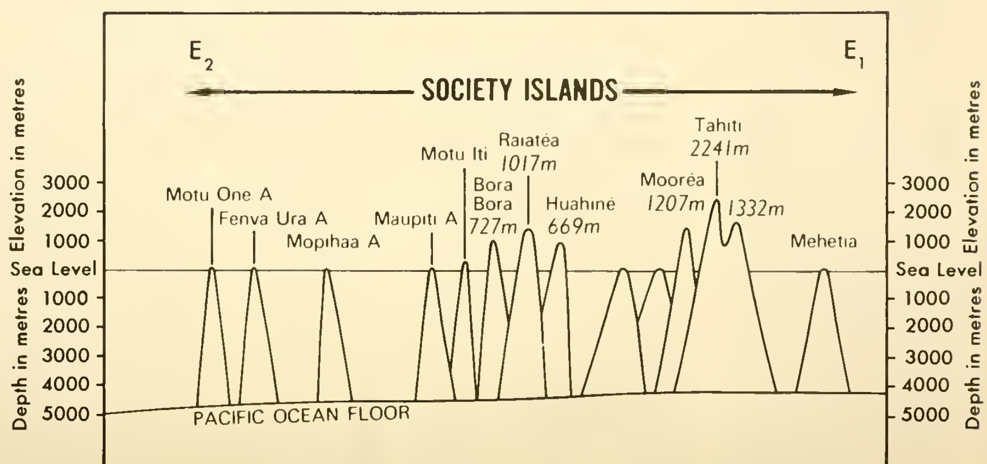

Figure 13. Profile through the Society Islands.

young island chain being subaerially eroded to sea level and being carried progressively into deepening water where their fringing reefs ultimately form atolls.

A MODEL FOR ISLAND-TYPE DEVELOPMENT

The following model is based on an acceptance of the idea that successive volcanic islands are formed over relatively stationary hot-spots on an oceanic lithospheric plate which is moving tangentially into deeper water. Important additional considerations include, the possible effects of asthenospheric bumps, moat-arch development due to lithospheric loading, uplift due to outer gravity highs close to subduction zones, an acceptance of the antecedent-karst influence on atoll form, and the realization that upward reef growth will slow, and ultimately stop, if it enters cool waters. Bearing these points in mind the eleven island types given in Figure 3 can now be illustrated in one dynamic working model (Fig. 14).

In Figure 14 new lithosphere is seen to accrete to the oceanic plate margin along the East Pacific Rise as the plates are forced apart by strong upwelling in the viscous asthenosphere below. With distance from this ridge the plate cools and ocean deepening is quite rapid. The seventeen volcanic island-atoll-submerged seamount positions north-west of the oceanic ridge shown in Figure 14 are described below. It should be stressed that probably no island chain actually possesses all of the eleven island-type possibilities at one time. It is very likely, however, that most types are found in major island chains during some stage of their history. This model is extended to show submerged seamounts which were former islands.

Position 1. The rigid oceanic plate overrides a hot-spot which injects magma through the lithosphere to form a young, active volcanic island. Isostatic subsidence creates a moat-arch flexuring of the crust. Fringing reefs have not yet had time to develop.

Position 2. Relatively inactive volcanic island undergoing some residual isostatic subsidence but sinking more rapidly due to the moat development caused by lithospheric loading at position one. By now a fringing reef has developed and elevation of volcanic peaks is being rapidly reduced by subaerial erosion. Any subsidence due to tangential movement caused by crustal cooling is minor.

Position 3. Volcanic island with complete fringing reef undergoing no vertical change. Isostatic changes due to its own mass no longer operate and any tangential movement-subsidence caused by crustal cooling or any residual moat effects from position two are counteracted by arch flexuring due to lithospheric loading at position one.

Position 4. Volcanic island undergoing uplift due to the arch flexuring created by crustal loading at position one. The fringing reef will be raised out of the water and a new reef develops seaward to wave level. Subaerial erosion continues and will affect both raised reef and basalt.

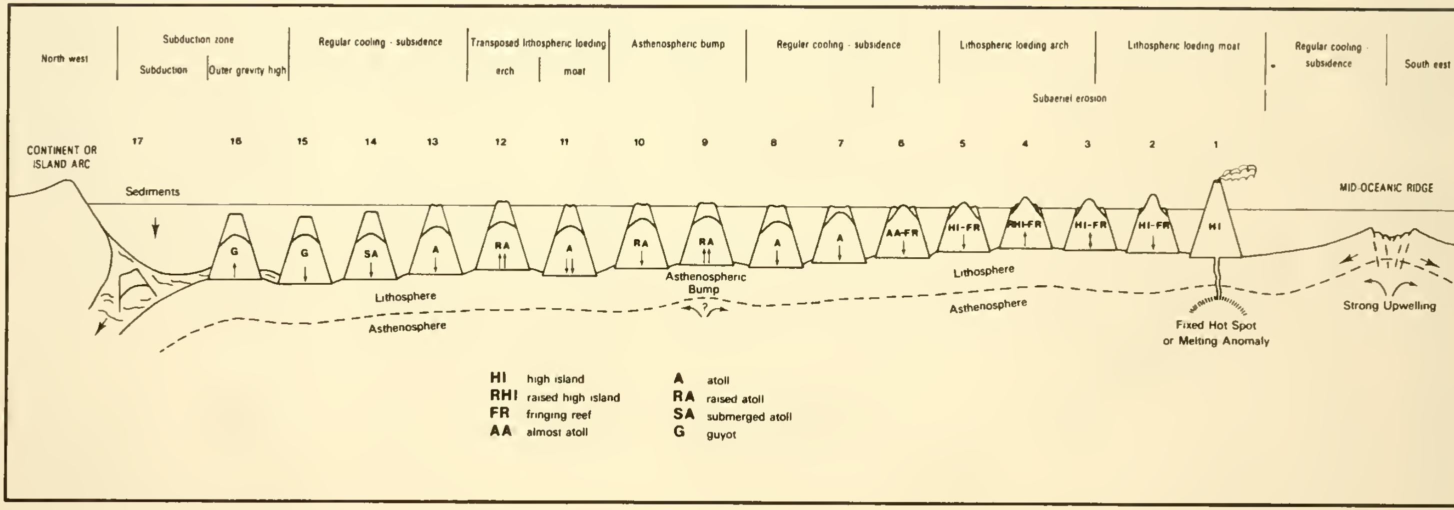

Figure 14. A model for island-type development on the Pacific lithosphere plate. For explanations of the seventeen positions indicated see text. Vertical arrows indicate relative rates of subsidence-emergence.

Position 5. Volcanic island undergoing subsidence due to crustal cooling-deepening and "lee-of-arch" deepening. Fringing reef grows upwards and begins to form a barrier reef as the volcanic island is reduced in both elevation and areal size.

Position 6. Almost-atoll stage. A few remnant volcanic pinnacles or islets remain in the centre of a large lagoon partly rimmed by low reef-rubble islands. Subsidence due to crustal cooling only. If an asthenospheric bump (see position 9) or a lithospheric loading arch (see position 12) develops here, we would get a raised almost-atoll.

Position 7. Crustal cooling-subsidence continues until no volcanic remnants can be seen. Reef keeps growing to wave level and a true atoll develops.

Position 8. Typical atoll developing a thick carbonate cap as crustal cooling-subsidence continues. If causes for vertical movement other than cooling-subsidence are not considered this form can be maintained and the carbonate cap continues to thicken until it reaches either a subduction zone or waters too cool for proper reef growth.

Position 9. Part-raised or raised atoll develops as an atoll rises up the south-east flanks of an asthenospheric bump. No magmatic outpourings occur. Degree of uplift determines which type of part-raised or raised atoll will develop.

Position 10. Raised atoll or part-raised atoll descending the north-west side of the asthenospheric bump undergoes rapid subsidence due to crustal cooling to form a regular atoll again. (No influence of the lithospheric-loading influencing position eleven is indicated here although arch flexuring might in fact occur.)

Position 11. Rapid subsidence due to the moat effect of new lithospheric loading offset from the line island chain by a short distance. Atoll form remains intact and carbonate cap thickens quickly. Submergence processes are essentially similar to those at position two. This could occur at any position along the chain where a new hot-spot breaks through or where the atoll in question moves alongside the hot-spot of another island chain e.g. the Tuamotu atolls passing Tahiti's hot-spot.

Position 12. Part-raised or raised atoll rising rapidly due to the arch effect generated by lithospheric loading near position eleven. Degree of uplift again influences raised atoll form.

Position 13. Typical atoll form returns as the island passes beyond the moat-arch effects of positions eleven and twelve. Here subsidence is attributable to tangential movement as the crust cools.

Position 14. An inundated or drowned atoll develops if the structure moves into water too cool to support algal-coral populations needed to maintain a sinking carbonate platform at sea level. Drowned forms could also result if rapid subsidence occurs as an atoll enters a subduction zone.

Position 15. Guyot stage results when the atoll is deeply submerged. Here submergence will be quite slow if only crustal cooling is operating. Guyots (or atolls) near a continental or island arc margin will receive thick sediment layers around their bases.

Position 16. Temporary uplift of guyot as it crosses the outer gravity high just before subduction. If this had occurred while the drowned-to-typical-atoll stages were present then a raised atoll form should develop.

Position 17. Guyot (or atoll if still in warm waters) will be subducted into the trench where it undergoes accretion-destruction.

CONCLUSION

It is concluded that island-types on the Pacific plate result primarily from the subsidence of volcanic islands due to the tangential motion of the lithospheric plate. An analysis of melting anomaly island groups such as the Hawaiian, Caroline, Marshall, Tuamotu and Society chains tends to confirm this conclusion, and such peculiarities as raised or drowned atolls can be explained if asthenospheric bumps, lithospheric loading, outer gravity highs and subaerial erosion during Pleistocene low sea level stands are considered. The almost complete absence of islands north of 28^{o}N in the Pacific, other than those attributable to plate collisions, is considered to be due to the combined action of rapid subaerial erosion of basalts and this tangential component. These geomorphic and tectonic processes clearly encourage rapid subsidence of volcanic islands produced over melting anomalies, but if their reduction to sea level occurs during passage through warm tropical waters upward reef growth normally prevents their demise. Rapid subduction or movement into cooler waters eventually cuases upward reef growth to diminish and the atoll becomes submerged. Drowned atolls and guyots may result before final subduction.

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