Geological Origin of the Volcanic Islands of the Caroline Group in the Federated States of Micronesia, Western Pacific

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Abstract

We present a geological review of the volcanic islands of the Caroline Islands group (Yap, Chuuk, Pohnpei and Kosrae) of the Federated States of Micronesia, to understand the origin and mechanism of formation of these volcanic islands. Previous geochronological data from the three volcanic islands (Chuuk: 14.8 to 4.3 Ma; Pohnpei: 8.7 to 0.92; and Kosrae: 2 to 1 Ma), indicate a progressive increase in age towards west, based on which a hot-spot origin was assigned. However, overlap in age of the volcanic islands and the absence of a hot spot east of Kosrae suggest involvement of other tectonic activity for their formation besides the simple hot-spot model. By observing geological features in the field (e.g., occurrence of structurally younger dikes which cross-cut the older volcanic sequences, presence of extensive dikes with columnar joints; indicative of extensional environment) and literature survey, we consider that the Caroline volcanic islands were not only remnants of a hot spot trace; as generally agreed by many authors, but were also produced in a fracture-induced subduction-related tectonic environment.

Key words: age, the Caroline Islands, hot-spot, plate motion volcanics

Introduction

The Federated States of Micronesia (FSM) is a group of 607 small islands, known as the Caroline Islands, in the western Pacific. It comprises four main states: (1) Yap, (2) Chuuk (Truk), (3) Pohnpei (Ponape), and (4) Kosrae (Kusaie), from west to east in the Pacific low latitudes in the northern equatorial region (Fig. 1).

The islands of Yap form an island arc system on the eastern convergent margin of the Philippine Sea Plate (PSP) and are connected to the Palau island arc in the south and the Izu-Mariana arc system in the north (Fig. 2). Tectonically the Yap island arc
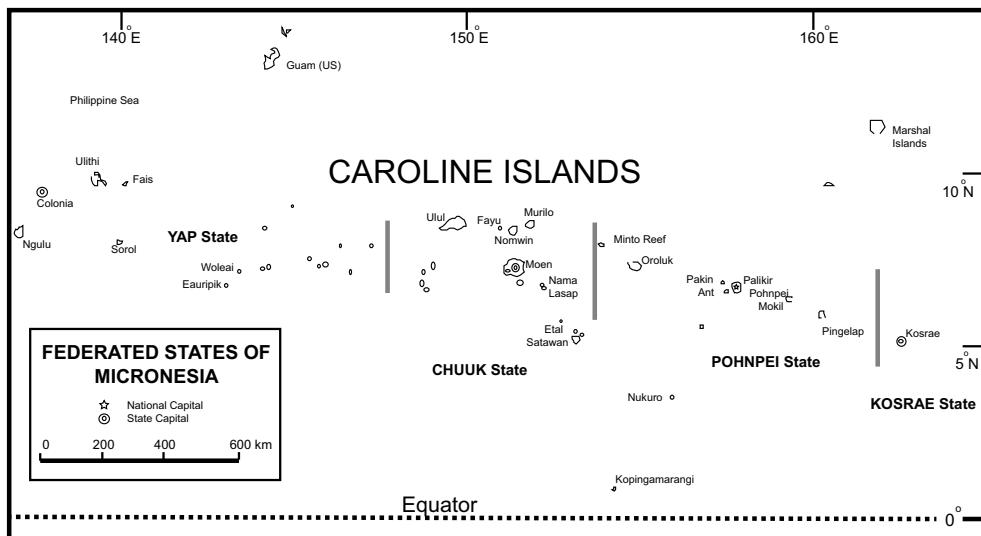
Fig. 1. Geographic location of the Caroline Islands in the Federated States of Micronesia, western Pacific (map modified from the FSM government official site: http://www.fsmgov.org/info/map.html).
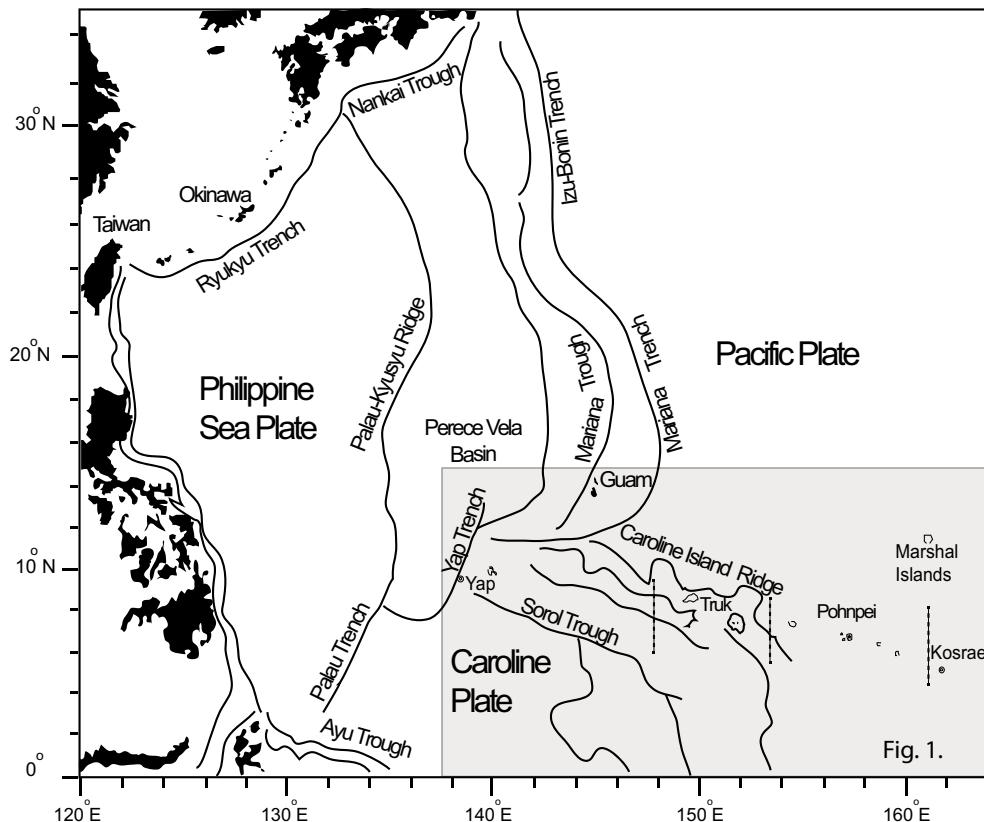

Fig. 2. Simplified sketch map of the Pacific Plate, the Philippine Sea Plate and the Caroline Plate (modified after KOBAYASHI 2004). The map shows approximate position of the Yap Trench, the Caroline Island ridge, and trenches and troughs in the surrounding areas.

is situated on margin of the Caroline Plate which has almost been subducted beneath the PSP. Other three states of the FSM (Chuuk, Pohnpei, and Kosrae) lie on the Pacific Plate, east of the Mariana-Yap-Palau trench system along the Caroline ridge (Fig. 2).

A number of publications describe the volcanic activity in the Caroline Islands and their petrological characteristics (e.g., Iwasaki 1915, Kinoshita 1926, Tayama 1936, 1952, Yosii 1936, Iwao 1941, Yagi 1960, Stark and Hay 1963, Ishikawa and Yagi 1969). However, the origin of these islands and the source of magma remained controversial. In the late twentieth century several publications focused on the volcanic islands in which geochemical and age-data were reported (e.g., Mattey 1982, Dixon *et al.* 1984, Keating *et al.* 1984a, 1984b, Spengler 1990, Lee *et al.* 2001). Most of the above authors suggested a hot-spot origin for the Caroline Islands, however, differences in geochemical nature of the volcanic rocks and presence of silica undersaturated and oversaturated lavas on same islands pose a number of questions on the hot-spot only origin for these islands. For example (1) if the Caroline Islands were formed only from a hot spot, where did the hot spot go after the last event of volcanism in Kosrae Island ca. 1 Ma? (2) The Caroline Islands do not lie along a line, unlike the Hawaiian chain which lies along a narrow line and the volcanic islands increase in age away from the current hot spot location; rather they mark a broad zone within the Pacific Plate along the Caroline ridge. (3) The overlap in age of the volcanic islands suggests that volcanic activity occurred simultaneously on these different islands, which is not likely if they were formed from a hot spot. (4) Moreover, the geochemical and isotope composition of volcanic rocks on the Caroline Islands are somehow different from the rocks of Hawai`i suggesting a different magma source than the Hawaiian lavas.

This paper aims at presenting a review of the geological set up of the Caroline Islands and discusses the possible source of magma which formed these islands. Our observations in the field and literature study reveal that assigning only a hot-spot origin for the Caroline Islands is not likely. There might have been some other tectonic activities along the western margin of the Pacific Plate besides an unknown hot spot (which does not exist anymore), which possibly produced volcanic islands along the Caroline ridge.

Previous Studies

First geological report on the Caroline Islands was presented by Iwasaki (1915). Based on his preliminary investigation, he used the terms "*Takashima*: high islands and *Hikushima*: low islands". The Chuuk, Pohnpei, and Kosrae islands were parts of *Takashima* which are formed by volcanic activity. The Yap Islands were part of *Hikushima*, which are composed mainly of amphibolite facies metamorphic rocks with minor volcanics. Based on petrographic and geochemical study on the rock samples collected by Iwasaki (1915), Kinoshita (1926) suggested that nepheline basalts on Chuuk are similar to the rocks of Pohnpei and concluded that their magma source was

same. Several other Japanese researchers described geology of the Caroline Islands (e.g., TAYAMA 1936, 1952, YOSII 1936, IWAO 1941, YAGI 1960 etc.). STARK and HAY (1963) conducted detailed field survey in the Chuuk Islands for military geology and presented detailed petrography of volcanic rocks in Chuuk Atoll. BRACEY and ANDREWS (1974) suggested that the Caroline Islands could have been part of a relict island arc because of the complex bathymetry of the islands. JARRARD and CLAGUE (1977) proposed a hot-spot origin to the Caroline Islands. Their results were based on a comparative study of the bathymetry of the Caroline Islands with other hot-spot origin islands. They suggested that the Caroline and Kodiak-Bowie chains, presently being subducted into the Pacific trenches, were once as long as the Hawaiian chain (the longest of the WNW trending chain in Pacific). First geochronological work on the volcanics of Pohnpei was done by DIXON *et al.* (1984). They reported major and trace elements compositions and K-Ar ages from five volcanic rocks samples from Pohnpei and proposed a multi-stage (polybaric) fractional crystallization which formed these islands. KEATING *et al.* (1984a, 1984b) reported K-Ar age, paleomagnetic and geochemical data for the Chuuk, Pohnpei and Kosrae Islands and suggested a hot-spot origin. Several other publications also supported the idea of a hot spot (e.g., SPENGLER 1990, LEE *et al.* 2001).

Geologic Setting

Geology of Yap

Yap State is located in the western Pacific from 7° and 10° N latitude and 137° and 148° E longitude (Fig. 1). It is comprised of four large islands, seven small islands, and 134 atolls (Fig. 3A; modified from Yap Visitor's Bureau homepage: http://www. fsminvest.fm/yap/index.html). The large islands, namely Yap, Map (Maap), Tomil, and Rumong; are volcanically raised islands and are mainly composed of metamorphosed ultramafic and volcanic rocks with some coral sand and mangrove mud (NEDACHI *et al.* 2001).

NEDACHI *et al.* (2001) described geological environment of the Yap Island which was previously subdivided into the following geological units as Yap formation, Map formation, and the Tomil volcanics. The Yap formation (mainly composed of greenschist and amphibolites) constitutes the basement rock whose metamorphic grade increases eastward from greenschist facies to amphibolite facies (NEDACHI *et al.* 2001). It is derived from a melange trapped in the Yap Trench. Sporadic unmetamorphosed ultramafic units (clinopyroxinite to olivine websterite) intrude into amphibolites. The Map formation is composed mainly of tectonic breccia, sandstone and siltstone. The breccia contains metamorphosed fragments of the Yap formation and some other igneous rocks; therefore it is younger than the Yap formation. Based on foraminifera from the sandstones and siltstones of the Map formation, a Miocene age was assigned to it (COLE *et al.* 1960). SHIRAKI *et al.* (1978) suggested mid-ocean-ridge basalt origin to the mafic and ultramafic rocks on Yap. The Tomil volcanics (andesitic; exposed
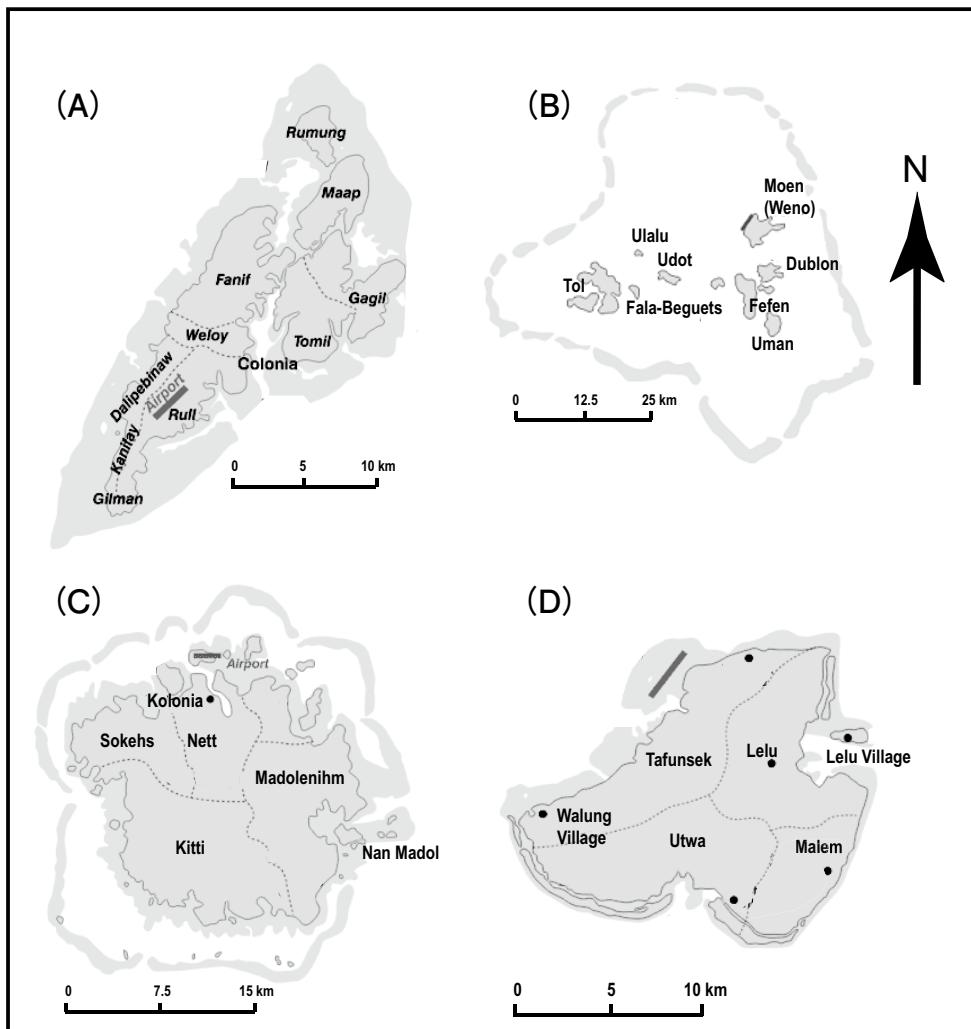
Fig. 3. Four states of the FSM; (A) Yap, (B) Chuuk (Truk), (C) Pohnpei (Ponape), and (D) Kosrae (Kusaie).
Maps are modified from the FSM visitors' center.

over a wide area of the Tomil and Map Islands) are composed mainly of agglomerate, breccia, tuff and lava. SHIRAKI *et al.* (1978) considered that the Tomil volcanics are geochemically and mineralogically similar to andesite on the Mariana and Palau arcs.

Geology of Chuuk

Chuuk State lies at about 7° 08' and 7° 41' N latitude and 151° 26' and 152° 2' E longitude in the western Pacific (Fig. 1). It includes 12 volcanic high islands and 24 low coral-reef islands in a lagoon enclosed by a barrier reef forming a near-atoll (Fig. 3B). Forty one low coral islands exist along the atoll. STARK and HAY (1963) subdivided the volcanic islands of Chuuk into three groups as (1) eastern group (Moen

(Weno), Uman, Dublon, and Fefen), (2) central group (Udot, Eot, Eiol), and (3) western group (Tol, Fala-Beguets, and Ulalu). Based on their field observation, STARK and HAY (1963) interpreted that the volcanic islands are remnants of a large shield volcano in which lava flows predominate with minor pyroclastic deposits. They also reported that most of the lava flows were ejected from fissure vents as dikes and dike swarms. Petrographically, lava flows and dikes on the Chuuk Islands represent the alkali-olivine-basalt-trachyte association, similar to other volcanic islands of the Pacific. The undersaturated lavas (nepheline basalts) on the Chuuk Islands are similar to that of Hawai`i, therefore, they suggested same magma source for the rocks on the Caroline Islands to that of Hawai`i.

Islands of the eastern group were made of olivine-basalt with minor andesite. The lava flows on central islands are mainly andesite and basalt which intermingle with breccias. Islands of the western group show different rock types than those of the central and eastern groups. Tol, the biggest island in the western group, is entirely composed of olivine-basalts and andesite flows that are cut by dikes. Based on presence of olivine-basalt, nepheline-basalt and mililite-nepheline-basalt, STARK and HAY (1963) suggested that these rocks originated from a different magma source. Most of the Chuuk lavas were formed by fractional crystallization of undersaturated olivine-basalt parent magma; however the source of such lava is unclear.

Based on chemical composition, MATTEY (1982) recognized three magma types in Chuuk i.e. (1) the Chuuk Main Lava Series (CMLS), (2) the Chuuk Transitional Lava Series (CTLS), and (3) the Chuuk Nephelinite Series (CNS). Rocks of the CMLS are aphyric to highly porphyritic basalts, hawaiites, mugearites and trachytes. Their major and trace element composition are similar to those of Hawaiian alkali basalts. Rocks of the CTLS, exposed in Tol, are mainly basalts which were characterized by slightly lower ratios of more incompatible to less-incompatible trace elements (such as Nb/Zr, Ba/Zr, Ce/Zr etc.). These volcanics are less alkalic than the CMLS and were interpreted by MATTEY (1982) as a different magma source. Rocks of the CNS are nepheline basalts which are exposed on Tol and unconformably overlie the older CTLS and CMLS lavas. These rocks are highly enriched in Rb, Th, Ba, Sr, La and Zr relative to the CMLS.

Geology of Pohnpei

The island of Pohnpei is situated at 6°54' N longitude and 158°14' E latitude in the western Pacific (Fig. 1). Pohnpei has a land area of 338 km^2 and is surrounded by a barrier reef (Fig. 3C). The island is roughly circular in shape and is characterized by steep mountains in the deeply dissected interior.

Rocks exposed on Pohnpei are alkali olivine basalts, trachytes, hawaiites, ankramites, and nephlinites to basanites. Numerous dykes of several cm to several ten cm intrude the volcanics. MATTEY (1982) recognized three magma types from Pohnpei and termed them as (1) the Pohnpei Main Lava Series (PMLS), (2) the Pohnpei Transitional Lava Series (PTLS), and (3) the Pohnpei basanite Series (PBS). SPENGLER

(1990) reclassified the volcanic rocks on Pohnpei into two major units i.e. the shield building lavas and the overlying post-shield deposits.

Rocks of the PMLS are comagmatic and consist of basalts, hawaiite, mugearite and a trachyte. Unlike the Chuuk volcanics, the PMLS are characterized by phenocrysts of olivine and relative Ti- and Na-rich clinopyroxene. Hawaiites are the most abundant in this series and consists of phenocrysts of olivine, clinopyroxene and rare magnetite. Major element compositions are similar to those of the Hawaiian alkali basalts. Minor and trace elements show some differences from the CMLS. Rocks of the PTLS contain slightly lower incompatible ratios as compared with the PMLS. In them olivine, clinopyroxene and plagioclase phenocrysts are common. The magma type for these rocks was considered as different from the PMLS i.e. less alkalic. Rocks of the PBS are distinguished from the PMLS by a small range of higher more-incompatible to less-incompatible element ratios. Silica is undersaturated. These lavas gave K-Ar age of less than 1 million years and are significantly younger than the PMLS which has an average age of 6 Ma (KEATING *et al.* 1984a). This seems to be post-erosional magma similar to the CNS on Chuuk.

SPENGLER (1990) subdivided the volcanic rocks on Pohnpei into two major units as (1) the shield-building lavas and (2) the overlying post-shield deposits. K-Ar age data suggest that the shield building stage initiated at around 8.5 Ma, and the volcanic activity remained until 1 Ma (DIXON *et al.* 1984, KEATING *et al.* 1984a). The post-shield deposits were further subdivided into two groups, the Awak Volcanics and the Kupwuriso Volcanics, based on differences in age, general flow morphology, and chemical composition, although, the contact between them was not distinguished on geological map (SPENGLER 1990). SPENGLER (1990) reported that the Awak stage lasted in between 7 to 3 Ma, the Kupwuriso stage extended from 2.1 to less than 1.0 Ma, and both stages have similar origin like the rocks of Hawai`i. On the basis of geochemical and isotope data, SPENGLER (1990) interpreted that the data for Pohnpei fall within the modern-day oceanic island or hot spot field. However, based on their Pb isotope data (SPENGLER 1990), the three volcanic series do not show isotopically homogeneous source. SPENGLER (1990) also compared isotopic data for basalt of the Pohnpei with basalt from the Ontong Java Plateau (OJP) but observed very little or no mixing between magmas of Pohnpei and the OJP. He reported that Pohnpei lavas are more radiogenic in 208Pb/204Pb than the overall Hawaiian lavas. The general trend toward less radiogenic 87Sr/86Sr values going from shield-building to alkalic capping the post-erosional stages observed in many individual Hawaiian volcanoes was not seen in the Pohnpei data set.

Geology of Kosrae

Kosrae is located at approximately 5° N latitude and 163° E longitude and covers an area of 110 km^2 (Fig. 1). It is the second largest island and the most easterly state of the FSM. Kosrae is also a volcanic island and is surrounded by mangrove swamp (Fig. 3D). MATTEY (1982) reported only two magma types from Kosrae i.e. (1) the

Kosrae Main Lava Series (KMLS) and (2) the Kosrae Nepehlinite Series (KNS). Rocks of the KMLS are mainly basalts, ankaramites, and hawaiites containing phenocrysts of olivine, Ti-clinopyroxene, kaersutite and phlogopite. These rocks are similar to the PMLS basalts. Rocks of the KNS are a group of highly to moderately undersaturated lavas and dikes and are distinguished from the KMLS.

Formation of the Caroline Volcanic Islands

The volcanic activity on Yap was associated with the convergence of the Caroline and Pacific Plates. The volcanic activity in the remaining three volcanic islands (Chuuk, Pohnpei and Kosrae) of the Caroline Islands started at 14 Ma and remained until 0.9 Ma. Age of these islands increases progressively towards west. These three islands lie in a broad zone between 4° and 8° latitudes (Fig. 1), forming a sub-linear chain. In contrast, the hot-spot originated islands such as the Hawaiian chain form along a narrow line and the age of the sea mounts increases away from the hot spot due to traveling of the lithosphere over a mantle plume. In case of the Caroline Islands, it is true that the age of the volcanic islands decreases towards east; however, there is a broad range in the age of volcanism even within the same island (e.g., in Pohnpei the rocks range in age from 8.7 to 0.92 Ma; DIXON *et al.* 1984).

Age of rocks on the Yap Island

WEISSEL and ANDERSON (1978) reported that the island arc volcanism on Yap probably terminated in Late Oligocene or Miocene. Based on sedimentation rates from the rocks dredged from the rift axis in Ayu Trough, they proposed that margins of the basin were formed in mid-Miocene (ca. 10 to 12 Ma). BECCALUVA *et al.* (1980) reported K-Ar age (ca. 11 to 7 Ma) for the Yap Trench volcanics. There is no evidence of volcanism after that time in the Yap arc.

Plate convergence at the Yap Trench ranges from 0.6 to 0.3 cm yr^{-1} whereas, the Yap island is moving together with the rigid PSP at 9.2 cm yr^{-1} (N73°W) with neither backarc opening nor intra-plate deformation (KOBAYASHI 2004 and references therein). Along the Chuuk Islands, the motion of the Pacific Plate is 8.3 cm yr^{-1} (N60°W) and the western end of the Caroline ridge is moving together with the Pacific Plate (KOBAYASHI 2004). The movement of the PSP with respect to its present pole of rotation at 3 to 4 Ma caused to reduce the convergence rate significantly at Yap and Palau due to which the old volcanic islands of Yap and Palau uplifted by the upward pressures (KOBAYASHI 2004). Deep seated rocks beneath the remnant rift have been thrust up to form metamorphosed ophiolites in the Yap Island.

Age of rocks in the Chuuk Islands

STARK and HAY (1963) proposed that age of the Chuuk volcanoes could be no later than Miocene because the limestone xenoliths in Udot and Eot contained Cycloclypeus

and Miogypsina fossils (TAYAMA 1952). On the basis of geochemical, K-Ar age, and paleomagnetic data, KEATING *et al.* (1984b) interpreted that the volcanics in the Chuuk lagoon were formed from a fractional crystallization of heterogeneous magma source. K-Ar dates for the shield-building lavas range in age from 14.8 to 8.4 Ma for the CMLS, 10.6 to 7.2 Ma for the CTLS and 5.4 to 4.3 Ma for the post-erosional CNS lavas. Paleomagnetic results suggest that the Chuuk Islands was formed by a hot spot during 1 to 14 million years at 4.4° north of the equator. They considered these volcanics as the equivalent of the Hawaiian lavas but the abundance of alkali lavas in Chuuk and their rare occurrence in the Hawaiian lavas raise questions on their origin. In the Hawaiian Islands, most of the early and shield-building lavas are tholeiitic but in Chuuk the early shield-building lavas are alkali and the post-erosional volcanics grade into silica-undersaturated nephelinites. LEE *et al.* (2001) also reported K-Ar age data for lava samples collected from Weno which ranged from 11.3 to 6.7 Ma.

Age of rocks on the Pohnpei Island

DIXON *et al.* (1984) subdivided the volcanic rocks on Pohnpei into two major units i.e. the shield-building lavas and the overlying post-shield deposits and reported their K-Ar age data. They reported 8.7 Ma for the early shield-building stage and < 1 Ma for the post-erosional event. They argued that the age span for the Pohnpei volcanics is significantly large relative to other Pacific islands which span mostly < 3 Ma. Another issue was that the volcanics rocks which yielded 8.7 Ma and < 1 Ma were petrographically or by appearance same.

Age of rocks on the Kosrae Island

The shield-building stage of rocks on the Kosrae Island (i.e., the KMLS and the KNS) was reported to be between 2 to 1 Ma (KEATING *et al.* 1984a). There is no evidence of volcanic activity east of Kosrae. Based on this feature, most of the authors concluded that hot spot died after forming the seamounts of Kosrae. However, why the hot spot died was explained by none.

Constraints on the Magma Source and Age of the Volcanic Islands

Two different models can be proposed for the origin of volcanic islands of the Caroline Islands: (1) formation of the volcanic chain (Chuuk, Pohnpei and Kosrae) by a hot spot and (2) formation of seamounts (Caroline ridge) along a fractures zone in the western Pacific due to subduction-related tectonic setting. STARK and HAY (1963) correlated the undersaturated lavas of Chuuk to that of Hawai`i and based on their similarity they suggested similar magma source. They pointed out that the presence of nepheline-basalt and melilite-nepheline basalt on Tol Island suggests that the rocks originated from a different source. Below we explain the mechanism of formation of the Caroline Islands by presenting geophysical and geochemical evidence both from field and through the literature survey.

Hot-spot model

　　Generally, hot spots are considered stationary or fixed with respect to mantle and plates move over them. When plates move the upwelling mantle materials from these hot spots form linear chains of seamounts (MORGAN 1971). The distribution of seamounts, thus, marks the history of the motion if their age has been determined. Based on the progressive change in the age of the Caroline seamounts (Chuuk, Pohnpei and Kosrae) which increases towards NNW, JARRARD and CLAGUE (1977) proposed a hot-spot model hypothesis. They suggested that Caroline and Kodiak-Bowie chains, presently being subducted into the Pacific trenches, may once have been as long as the Hawaiian chain (the Hawaiian chain is the longest of the WNW trending chain in Pacific). KEATING et al. (1984a) interpreted that Chuuk, Pohnpei and Kosrae were formed at the same paleolatitudes based on their paleomagnetic data. Moreover, the progressive increase in age towards west led the authors to consider the three islands as a trace of a young melting anomaly or hot spot across part of the oldest portion of the Pacific Ocean crust. If their idea of a fixed hot spot is correct, the hot spot would have been located somewhere in the east of Kosrae (note that the age of Kosrae is < 1 Ma). The absence of volcanoes east of Kosrae indicates either the hot spot has died out or there was a drastic change in the Pacific Plate's motion which misplaced the hot spot somewhere in the Pacific. However, why such a young hot spot dies requires geophysical evidence.

　　Hot-spot origin for the Caroline volcanic islands was also supported by several other authors (e.g., KEATING et al. 1984a, 1984b, POLLITZ 1986, SPENGLER 1990, LEE et al. 2001) on the basis of pieces of evidence such as (1) the islands of Chuuk, Pohnpei and Kosrae form a sub-linear chain in the western Pacific and show a progressive younging direction towards east, (2) similarities in the field occurrence, textural and mineralogical features, and chemical compositions with the Hawaiian volcanics, and (3) the convex-northward configuration of the island trend from Pohnpei to Kosrae, and (4) minor change in the absolute motion of the Pacific Plate between 5.0 and 3.2 Ma. The above features support the formation of these islands by a hot spot which was once located in the low northern equatorial region, however where did it go is unclear. In addition, SPENGLER (1990), on the basis of Pb isotope data, interpreted that generation of Pohnpei lavas require at least three different source components with discrete Pb contents. If they had same source as those of the Hawaiian volcanoes, their isotopic compositions should have been similar which are not. This infers that the volcanism on Caroline seamounts was not produced by a simple hot spot process with should have more or less homogenous magma source.

　　Moreover, based on geochemical data and K-Ar dating, DIXON et al. (1984) argued that simply a hot-spot model hypothesis for the Caroline ridge is not likely because the volcanics on Pohnpei have younger age (ca. < 1 Ma) which overlap with the age data of the Kosrae volcanics (ca. 1 to 2 Ma). Besides, the volcanics on Chuuk (14.8 to 4.3 Ma) and on Pohnpei (8.7 to 0.9 Ma) show an age overlap (Fig. 4). These age values are too long for a hot spot activity on a single island based on the motion
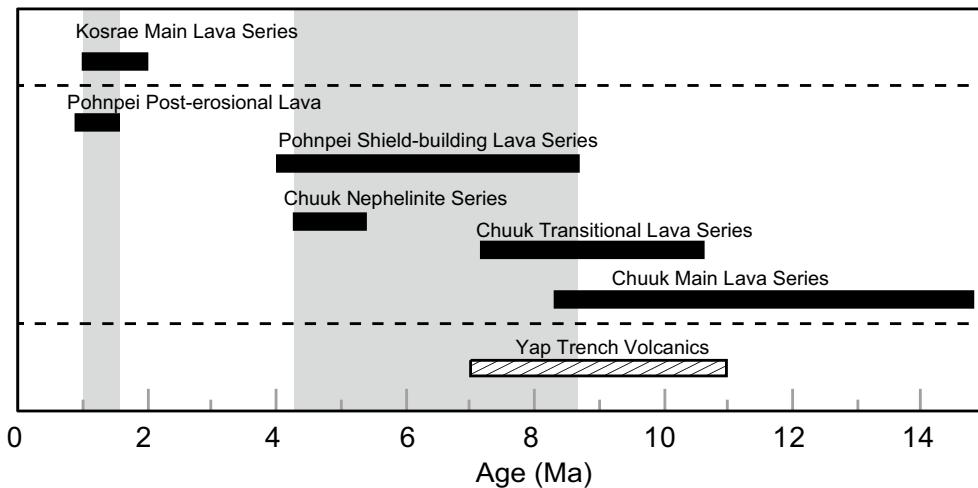
Fig. 4. Diagram indicating age of the volcanism in the Caroline Islands. The volcanic series with their age values for Yap, Chuuk, Pohnpei and Kosrae are shown from bottom to top and are separated by broken lines. Shaded portion shows age overlap in the volcanism.

of Pacific Plate which was to be > 8 cm yr^{-1} (Kobayashi 2004). The shield-building event for most of the volcanoes is usually < 1 Ma and in well-documented linear chains of the hot-spot type in the Pacific, the maximum age range is < 3 Ma. This means volcanism on Pohnpei does not seem to be related only to the hot spot. Moreover, the Caroline Islands and the Caroline Ridge itself are not a liner structure but form a broad feature. Therefore, a simple hot-spot model (volcanism on a plate due to passage over a fixed mantle) cannot fit here.

Weissel and Anderson (1978) suggested that relative motion of the Caroline Plate (south of the Caroline Ridge) may have undergone some modification beginning in the Late Miocene (12 to13 Ma). This is the time when volcanism on the Caroline Ridge initiated (Chuuk lavas of 12 Ma). This volcanism can be due to interaction of the Caroline Plate with the Pacific Plate beginning in the Early Miocene and continuing to the present. The occurrence of shallow seismicity in the eastern Caroline Ridge (Weissel and Anderson 1978) supports this hypothesis.

Based on sedimentation rates from the rocks dredged from the rift axis in Ayu Trough, Weissel and Anderson (1978) proposed that margins of the basin near Yap and Ayu trenches were formed in mid-Miocene (ca. 10 to 12 Ma). The spreading activity along the Ayu Trough ceased 5 to 6 million years ago. Based on seismic data and geophysical and physiographic features, Weissel and Anderson (1978) proposed presence of extensional environment along the Pacific-Caroline boundary. The presence of numerous normal faults with throws of up to 3 km along the plate boundary supports their idea.

Fig. 5. Photographs of the dike complex (A) which shows vertical to subvertical columnar joints and (B) a view from the top of dikes in which hexagonal shape of dikes is seen clearly (hammer in the middle is for scale). Photographs were taken in a stone quarry north of the Weno (Moen) in the Chuuk Islands (looking west in A, and from top towards south in B).
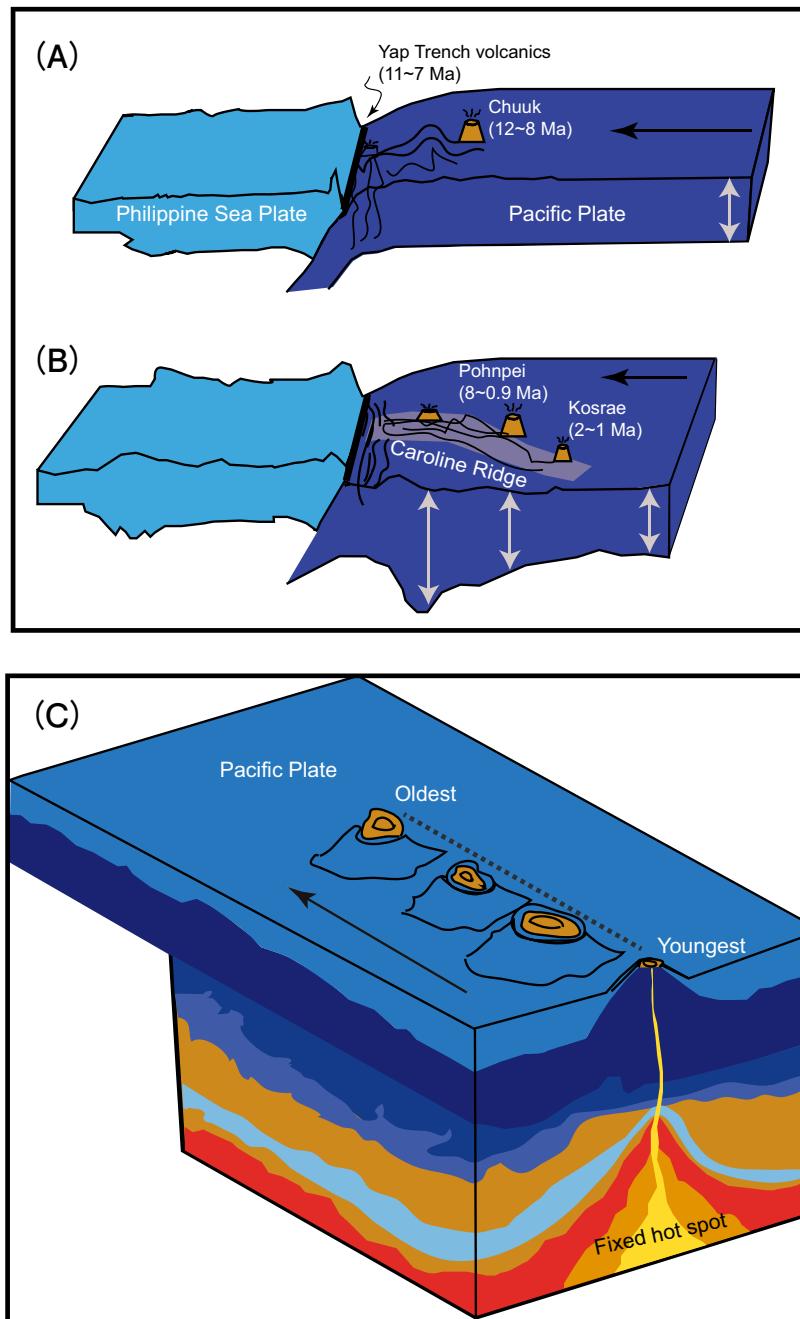
Fig. 6. Schematic diagram comparing (A and B) the formation of the Caroline Islands in a subduction-related tectonic setting versus (C) the formation of volcanic island chain by a simple hot-spot model (example of the Hawaiian chain; figure modified and redrawn from the URL: http://pubs.usgs.gov/gip/dynamic/hotspots.html#anchor19596916). Curved black lines on the figures "A and B" are the fractures forming the Caroline Islands (highlighted band), whereas the dashed-line in figure "C" shows the linear trend of a hot spot-produced volcanic islands. Black arrows indicate the plate motion. Grey arrows (double-sided) indicate thickness of the crust (figures not to scale).

Fracture-induced volcanism

Formation of the seamounts on the converging plate by the subduction-related deformation is likely. If two oceanic plates are colliding, the older plate will possibly subduct because of its high density and coldness (as is the case with the PSP and the Pacific Plate; the Pacific Plate is subducting beneath the PSP). WESSEL and KROENKE (1997, 1998) reported that some seamounts appear to form in the proximity of divergent plate boundaries and adjacent fracture zone systems and are not related to hot spot activity. Because seamounts produced by hot spot volcanism, must be traced back to their known hot spot location. WESSEL and KROENKE (1997) discovered a geometric relationship between hot-spot-produced seamounts and the hot spot locations which allowed them to determine hot spot locations from seamount locations without requiring seamount age information. They applied the hot-spotting method to all seamounts in the Pacific Plate and obtained the cumulative volcano amplitude image in which the location of well developed hot spots were marked with "X" sign. In their figure 5 (WESSEL and KROENKE 1997: 368) they got a very prominent "X" mark for the location of the Hawaiian and the Louisville hot spots. However, no specific sign was obtained for hot spots in the south and western Pacific which have been remained controversial including that of the Caroline hot spot.

One strong piece of evidence which poses question on the hot-spot origin for the Caroline Islands is the presence of basal dike system with columnar joints (indicating extensional environment) in Chuuk (Fig. 5) and Pohnpei. These features cannot be simply explained by a hot-spot model.

Alternate to the hot-spot model is the fracture-induced volcanism. If the volcanic chain is on a broad zone instead of a narrow and straight line, the seamounts might have formed from a volcanism along fractures which were produced by forces acting along the plate edges. In such cases ridges would be parallel as can be seen in the Pacific Plate near the Caroline Ridge. However, in such case the volcanism will likely occur all along the fracture system and there is no need to have a progressive increase in age in a certain direction. The progressive increase in age towards west in the Caroline volcanic islands, therefore, led the authors (JARRARD and CLAGUE 1977, KEATING et al. 1984a, 1984b, SPENGLER 1990) to propose a hot-spot model.

It is already known that on the western side of the subducting Pacific Plate half graben (LEE 2004) exists which extend in east-west and northwest-southeast trend. These fractures might have provided space for the volcanism along the broad Caroline Ridge. Due to westward motion of the Pacific Plate and slow subduction along the Yap Trench, the crustal portion of the Pacific above the unknown hot spot (if ever existed) increased the crustal thickness and caused the young and weak hot spot to die in a short period of time i.e. less than 14 Ma.

Based on our observations in the field and literature study, we believe that fracture model is much realistic (Fig. 6A&B). The reason why the volcanic activity ceased earlier in the west and remained active until < 1 Ma in the east could be explained by the thickening of the Pacific Plate's crust progressively as shown in Fig. 6. As

discussed above, there is almost negligible convergence along the Yap Trench and the Pacific Plate motion towards northwest is > 8 cm yr^{-1}. This would imply to increase the thickness of the Pacific Plate's crust near the convergent boundary. When the crust is thickened enough, it would have been difficult for the magma to escape which will ultimately cease the volcanism in the west. As the Pacific Plate moves progressively westward, the fractures formed in the forthcoming eastern portion caused next event of volcanism, therefore the rocks on Pohnpei and Kosrae are younger than those on Chuuk. The presence of numerous dikes (cross-cutting the breccias and older volcanic units), and columnar joints in Chuuk and Pohnpei also indicate extensional environment, which could be only possible if there is a fracture system propagating eastward from the subduction front.

The formation of the Caroline Islands by a hot spot might be correct but the age overlap of about two million years in volcanism on Chuuk (ca. 14 to 4.3 Ma) and Pohnpei (8.7 to 0.9 Ma), and the presence of younger (ca. 0.9 Ma) volcanic rocks on Pohnpei than the rocks on Kosrae (ca. 2 Ma) suggest that volcanism was active between 6.7 and 8.7 Ma on Chuuk and Pohnpei, and the post-erosional event on Pohnpei (ca. 0.9 Ma) coincides with the shield-building event in Kosrae (< 2 Ma). If we propose a simple hot-spot model for the Caroline Islands similar to the Hawaiian chain (Fig. 6C), this cannot be possible to have rocks of the same age on these different islands which are several hundred km away from each other. If that part of the plate moved upon a stationary hot spot (once occurred there), there could not be age overlap on these islands. The large time span from 8 to 0.9 Ma for the volcanism on Pohnpei would imply that the motion of Pacific Plate during this time was almost negligible, which is not realistic. Moreover, the presence of volcanic rocks <1 Ma on Pohnpei and 2 Ma on Kosrae would also imply that the hot spot was almost active below both of the above islands in a same time. This also seems questionable. Therefore, our notion that the Caroline seamounts were formed by fracture-induced volcanism due to subduction-related tectonic activity is plausible. The presence of numerous dikes which cross-cut the older sequences and the pyroclastic flow deposits and breccias indicate that volcanism persisted on these islands for long time which contradicts the hot-spot model hypothesis. If the hot-spot model was the only cause of producing the Caroline Islands, then the geochronological results might be erroneous. Systematic geochemical and geochronological work on each representative unit of the volcanics and the young dikes intruding these sequences is required to clarify the origin further.

Conclusions and Future Target

The Caroline volcanic islands are geologically important for understanding the hot-spot versus fracture-induced subduction-related tectonic model. Geochronological data from the volcanic islands (Chuuk: 14.8 to 4.3 Ma; Pohnpei: 8.7 to 0.92; and Kosrae: 2 to 1 Ma), indicate a progressive increase in age towards west which led a

number of authors to propose a hot-spot origin for their formation. However, overlap in age of the volcanic islands (Fig. 4), absence of a hot spot east of Kosrae, and the occurrence of these islands along a broader zone in the Pacific (Fig. 6B), instead of a volcanic chain along a line (Fig. 6C), contradict the hot-spot only origin. Based on geological field and literature survey we propose that the volcanism on the Caroline Islands was not only due to the hot spot activity but the volcanic islands were most probably formed in a fracture-induced subduction-related tectonic environment. Further, geochemical and geochronological work on individual lithological units is required to elucidate the origin of these islands.

Acknowledgements

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