

– ARTICLE –

Documentation of inter-island interaction in the Mariana Islands through geochemical characterization of volcanic stone artifacts

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Abstract

The Mariana Islands have at least a three-millennia human occupation and have been subject to decades of intensive archaeological research. However, unlike other regions of Oceania, intra- and inter-archipelago movement of volcanic stone/tools is poorly documented. We used non-destructive EDXRF to characterize the geochemistry of 36 geological samples from three islands (Sarigan, Rota, and Guam) and 287 artifacts and manuports from five islands (Alamagan, Saipan, Tinian, Rota, and Guam). We confirm that some reliable geochemical results can be obtained from heavily chemically weathered artifacts and define three primary and four secondary geochemical groups. Our results document ~1,500 years of interaction with notable north-south oriented clines in the prevalence of northern- and southern-sourced stone. For Guam, there is a significant association between two broad artifact categories and local and non-local stone. We propose complementary hypotheses for explaining the procurement and circulation of stone/tools—bet hedging, economic need, and prestige/costly signaling—that may explain different aspects of the current data and provide several avenues for future research.

Keywords: Mariana Islands; geochemistry; EDXRF; interaction; exchange

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1. Introduction

The Mariana archipelago in the western Pacific has one of the oldest settlement chronologies in Remote Oceania (Carson 2014) beginning sometime between 3230-3085 cal BP (Rieth and Athens 2019). While these islands have been the subject of hundreds of archaeological investigations, primarily through historic preservation compliance actions, the history of inter-island interaction is poorly understood. In contrast, over a century of sustained archaeological research focused on the production of stone adzes (Brigham 1902, Cleghorn 1992, Leach and Witter 1987, Leach and Witter 1990, Duff 1945, Duff 1970, Jennings *et al.* 2023, McCoy 1977, Mills and Lundblad 2014, Richards 2019, Skinner 1914, Weisler 1997, Weisler *et al.* 2026), pottery (Bickler 1997, Chiu *et al.* 2020, Dickinson and Shutler 1979, Fitzpatrick *et al.* 2003, Golitko and Terrell 2012), volcanic glass and obsidian tools (McCoy and Carpenter 2014, McCoy *et al.* 2011, Nagaoka *et al.* 2022, Reepmeyer *et al.* 2012, Ross-Sheppard *et al.* 2013, Torrence and Summerhayes 1997), and other items (e.g., Allen 2025) within Polynesia and Melanesia has documented inter- and intra-island and archipelago circulation (*sensu* Zedeño 1998). The spatially variable (“patchy”) distributions of tool-quality volcanic stone across the Mariana archipelago and its presence as tools and manuports in the archaeological record make it an ideal material to track movement, interaction, and transmission (first postulated by Spoehr 1957). Lithic provenance studies also enrich our present understanding of the economic relationships that pervaded daily life throughout the island arc.

While ceramics in the Marianas have been examined to determine sources of clays and tempers (Dickinson *et al.* 2003, Glascock *et al.* 2023, Graves *et al.* 1990, Kelly and Winter 2022), Mangold (1998) was the sole provenance study of volcanic stones prior to our research. Geochemical characterization of stone tools including adzes, lusong (mortars), other formal tools, debitage, fire-cracked rock, and manuports offer similar opportunities as ceramic studies for examining the movement of source materials within and between islands. This may also document long-distance voyaging, as has been recently inferred from an adze recovered from Pohnpei that likely originated from New Guinea (Nagaoka and Sheppard 2021). Many adzes in the Marianas were formed by pecking and grinding rod-shaped cobbles. These adzes resulted from a production technology that is different from most Polynesian adzes, but remarkably similar in production and form to adzes made on the Izu and Ogasawara Islands in Japan (Oda 1981, 1984). If geochemical databases can be developed that help tie stone artifacts to specific islands or quarry sites, it may be possible to better interpret the degree of social interaction and social organization between CHamoru¹ communities on an expanded scale from what has been achieved with other data sets.

Our analysis of 287 volcanic stone archaeological artifacts and 36 geological samples from six islands (Alamagan, Guam, Rota, Saipan, Sarigan, and Rota) using non-destructive energy-dispersive x-ray fluorescence (EDXRF) begins to address these issues (Figure 1). Our research is guided by four objectives that are methodological or substantive: [1] as a proof of concept, document the ability to obtain useful geochemical data from heavily chemically weathered artifacts; [2] develop a statistically robust geochemical dataset for artifacts and potential source locations for the

¹“CHamoru” is the preferred spelling for the indigenous people of the Marianas by the Government of Guam Kumisión I Fino’ CHamoru (CHamoru Language Commission), while “Chamorro” remains standard within the Commonwealth of the Northern Mariana Islands.

archipelago; [3] describe the spatial and temporal geochemical diversity of volcanic stone artifacts; and [4] develop hypotheses to explain interaction throughout the archipelago.

We assessed the extent of weathering over geological and archaeological time scales and demonstrate that accurate geochemical data can still be obtained from chemically weathered artifacts made from igneous rock. We define three major geochemical groups (A, B, and C) and four minor groups (A' high Sr, A' high Zr, AB trans, and B'), as well as outliers. Of the geological samples, only the Sarigan specimens are Group A confirming at least one northern source. In contrast Groups B, B', and C are found in the Guam geological samples with Group B also accounting for the Rota samples. The archaeological collections from each island reveal a diversity of geochemical groups with Group A-derived artifacts found on all islands. There is a notable trend for the prevalence of Group A, however, with proportions decreasing north to south, again supporting an interpretation of northern sources for this broad geochemical group. This contrasts with a south to north decrease in the proportions of Groups B and C. The larger Guam archaeological collection reveals a significant association between formal (e.g., adzes, pestles) and informal (e.g., debitage, scrapers) and local and non-local stone. We propose three hypotheses for the movement of stone/tools—bet hedging, economic need, and prestige/costly signaling—that may explain different aspects of circulation.

2. Archaeological and geological context

2.1. *Archaeological overview*

Ancestral CHamoru arrived in the Mariana Islands likely between 3230–3085 cal BP (Petchey and Clark 2021, Petchey *et al.* 2017, Rieth and Athens 2019, *contra* Carson 2011, Carson 2020, Carson and Kurashina 2012). This occurred during a period of dynamic population movement in the western Pacific and Island Southeast Asia (ISEA) (Cochrane 2018, Cochrane *et al.* 2021). Genetic studies identify various potential ISEA and/or a Taiwan source(s) for the CHamoru with Liu *et al.* (2022) terming the initial Marianas population First Remote Oceanian[FRO]_{Marianas} (Liu *et al.* 2022, Pugach *et al.* 2020, Vilar *et al.* 2013). Carson and colleagues (Carson *et al.* 2013; Hung *et al.* 2011) advocate for a homeland in the northern Philippines based on perceived similarities in ceramic attributes, but this has been challenged (Clark and Winter 2019, Montenegro *et al.* 2016, Winter *et al.* 2012). While the identification of an exact homeland is unresolved, the earliest settlers had sophisticated seafaring knowledge and technology and a suite of pottery, tools, and ornaments (Carson 2014:45-68).

Spoehr (1957) divided the Marianas sequence into the Pre-Latte and Latte Periods, with an intervening Transitional Period subsequently applied along with subperiod designations. The periods and subperiods are based on changes in ceramics and other aspects of material culture. There are significant limitations to this temporal parsing of the archaeological record (Tomonari-Tuggle *et al.* 2018:63-66), but it remains the standard framework. The periods are characterized by unique ceramics in terms of vessel forms, temper, decoration and surface treatments, and other physical attributes. With an initial emphasis on coastal residence (Carson 2014:15-20, Dixon *et al.* 2022), settlement expanded to interior regions and generally across the main islands over time. The Latte Period is named by the eponymous pillar and capstone foundations that had supported lashed timber and thatch structures. Of relevance to our study, volcanic stone artifacts (e.g., adzes, abraders, debitage) are present in limited amounts in the earliest deposits but become more prevalent in later deposits along with new tool forms (e.g., boulder or bedrock lusong).

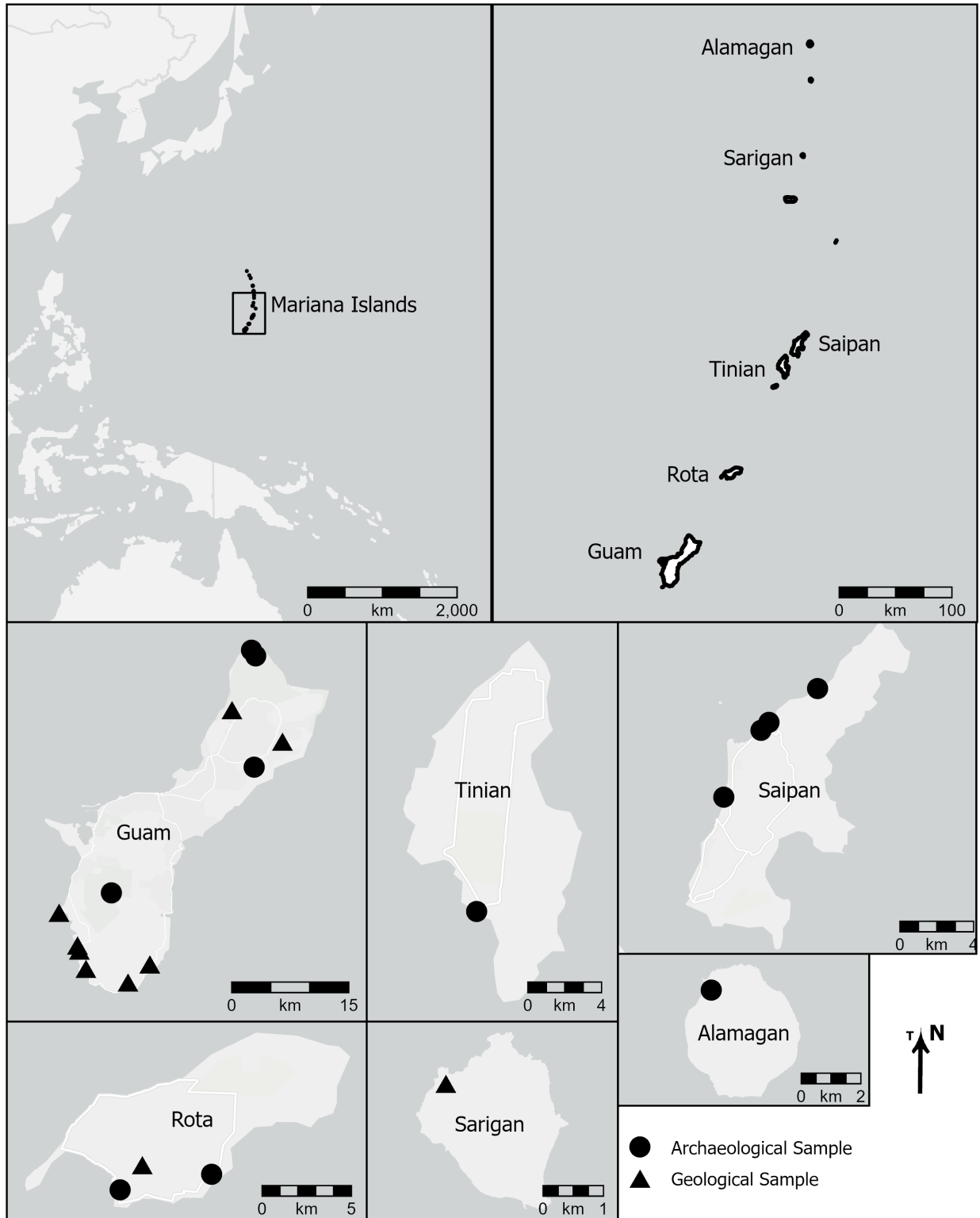


Figure 1: Map of the Mariana Islands with the geological and archaeological sampling locations.

2.2. Geological overview

The Marianas Islands began forming over 40 million years ago during the Eocene in the ‘proto arc’ stage of the Izu-Bonin-Mariana system (Reagan *et al.* 2008). Igneous deposits from the Sankakuyama Formation on Saipan, and the Facpi formation on Guam both date to this epoch. Major eruptive events on the main islands of Guam, Saipan, Rota, and Tinian proceeded through the Miocene (to 5.3 mya), and volcanism has continued into the historical era on smaller surrounding seamounts and islands, particularly heading northward. As coral reefs formed and lithospheric flexure lifted reefs above sea level, limestone deposits became interspersed with the igneous foundations (Gingerich 2003). For example, Guam is now dominated by limestone, which entirely covers the northern half of the island, and many portions of the southeastern island coast. Exposures of igneous rocks on Guam are limited to the interior and western shores of the southern half of the island, where basalts and andesites predominate, but a variety of other igneous rocks including dacites, boninites, and rhyolites add to a wide assortment of igneous source material across the island arc (Cloud *et al.* 1956; Reagan *et al.* 2008).

3. Materials and methods

The archaeological artifacts were collected by International Archaeology, LLC (IA) and International Archaeological Research Institute, Inc., (IARII) as part of historic preservation compliance/cultural resource management (CRM) projects (Athens and Leppard 2019, Dixon 2002, Cardno GS-AECOM Pacific Joint Venture 2024, Chambers and Mlyniec 2022, Filimoehala and Wiley 2021, Hlatky *et al.* 2023, Napolitano and Rieth 2026, Rieth and Meyer 2024, Rieth *et al.* 2026, Simonds 2021, Simonds *et al.* 2021, Simonds *et al.* 2024, Swift *et al.* 1991, Wickler 1990, Wickler and Rieth 2020) (Table 1). Two hematite artifacts were also analyzed (Supplementary Material) but are excluded from this study of igneous artifacts. Artifacts and manuports were collected from surface and subsurface contexts at coastal and interior locales. While most are undated, specimens with associated radiocarbon dates range from the fifth to sixth centuries AD to the late-fifteenth to early seventeenth centuries AD. The Supplementary Material Excel workbook provides provenience and dating information.

One of the authors (RO) collected the Guam (n=27) geological samples from outcrops, road cut exposures, and beach and river deposits, none of which had evidence of traditional CHamoru quarrying. Rota (n=7) and Sarigan (n=2) geological samples were collected by IARII staff as naturally occurring cobbles.

Table 1: Volcanic stone artifacts and manuports included in our study.

Specimen	Alamagan	Guam	Rota	Saipan	Tinian	Total
Abrader	0	0	0	1	0	1
Adze	2	104	1	7	0	114
Core	0	1	0	0	1	2
Fire-cracked rock	1	1	1	0	0	2
Flake	4	7	2	5	2	20
Grinding stone	0	13	0	0	3	16
Groundstone	0	4	0	0	0	4
Hammerstone	0	6	1	1	0	8
Lusong	0	5	1	0	0	6
Mano	0	3	0	0	0	3
Manuport	1	4	7	0	19	31
Metate	0	1	0	0	0	1
Modified stone	0	0	0	0	1 ¹	1
Pestle	0	5	0	2	0	7
Pestle or adze	0	24	0	2	7	33
Pounder	0	15	0	2	2	19
Scraper	0	1	0	0	0	1
Shatter	0	1	0	0	4	5
Slingstone	0	11	1	0	0	12
Total	8	206	14	20	39	287

¹ Four fragments of the same item were analyzed.

3.1. Energy dispersive x-ray fluorescence (EDXRF) analysis

Sourcing artifacts made from sedimentary rocks, such as limestones, is fraught with difficulties due to heterogenetic compositions within the same formations. Igneous rocks, however, usually exhibit relatively homogeneous geochemistry. The composition of lavas from different eruptive events can potentially be used to discriminate between different eruptions, volcanoes, and islands. When working with artifacts made from igneous rocks, EDXRF offers the opportunity to non-destructively study the elemental composition of artifacts and compare them with potential geological sources. There are limits, however, to what can be presently achieved. Mapping the full range of geochemistry in the Marianas is still far from complete, and many eruptive events from the same island arc are often quite similar to each other. Our research represents an initial attempt to build a more robust database of lithic artifacts made from igneous sources in the Marianas, and to add to the comparative database for Marianas geochemistry.

The 287 archaeological artifacts and 36 geological samples from igneous sources were analyzed with EDXRF at the University of Hawai‘i at Hilo Geoarchaeology Lab (Supplementary Material). The lab processed all samples using a Thermo Scientific ARL Quant’X EDXRF spectrometer with an extended sample chamber and a silicon drift (SDD) detector. The specific analytical conditions for analyzing Oceanic Island Basalts (OIB) with EDXRF have been refined over nearly two decades, beginning with the method published by Lundblad *et al.* (2008). The specific method and calibration used in this study is referred to as “2-21” meaning that it was developed and calibrated by the lab in February of 2021. The method generates quantitative or partially quantitative data for 26 elements:

Na, Mg, Al, Si, P, S, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Rb, Sr, Y, Zr, Nb, Ba, Mo, La, Ce, and Pb, and is calibrated with 22 geological standards that are similar to OIB. A full description of the method is posted on the lab's university web page (<https://hilo.hawaii.edu/depts/geoarchaeology/TheUHHiloEDXRFMethod.php>).

4. Results

4.1. Addressing chemical weathering on geological and archaeological samples

Post-depositional chemical weathering of stone is a variable that complicates the sourcing of stone artifacts, especially when non-destructive methods are attempted (Lundblad *et al.* 2008; Ogburn *et al.* 2013). We differentiate “geological weathering,” meaning chemical weathering that has affected an igneous rock since the time the rock was formed, from “archaeological weathering,” meaning weathering that has occurred on the surface of an artifact since the time people created the item. In the Marianas, geological weathering could span millions of years, where archaeological weathering would be limited to approximately three millennia. Microenvironmental conditions, such as varying hydrology, exposure to limestones, and varying soil pH could all affect what may have once been the relatively uniform geochemical signature of a homogenous igneous magma. The long-term effects of weathering could significantly affect the surface patination and interiors of the erupted lavas. While understanding the original geochemistry of a particular eruption might be of primary importance to petrologists, it is more important to the archaeological community to map the geochemical range in the weathered igneous rocks that CHamoru people quarried or collected for stone tool production.

4.1.1. Estimating geological weathering

Developing a complete understanding of the range of igneous geochemistry and post-depositional chemical changes in Marianas' lavas is beyond the capacity of this single study, but our research adds to the data already accumulated (Cloud *et al.* 1956; Reagan *et al.* 2008) and begins to address general trends in geochemistry from weathering. Thirty-six geological samples of igneous rock from several localities on Guam (Hågat-Humåtak [Facpi dike], Humåtak [road cut exposure and beach cobbles], Inalåhan [Ija Research Station and Malojloj], Malessu' [Priest's Pools]), and Yigu [Mt. Santa Rosa] (n=27), one location on Rota (southern slopes of Mt. Sabana) (n=7), and one location along the coast of Sarigan (n=2) were sampled and analyzed on freshly exposed surfaces (see Supplementary Materials). Thirteen of these samples were also analyzed on geologically weathered cortical surfaces and then compared with analyses of freshly exposed surfaces to observe the relative effects of chemical weathering between the cortex and the core.

The comparison between weathered cortical surfaces and freshly exposed interiors demonstrates consistent long-term surface weathering trajectories that resulted in often profound changes to rock geochemistry (see Supplementary Materials). There was a greater than 5% weight percent change for most elements. Accumulation on weathered surfaces occurred for Al₂O₃, P₂O₅, S, TiO₂, V, MnO, Fe, Ni, Cu, Zn, Y, Zr, Mo, La, Ce, and Pb compared with interior values. In contrast, Na₂O, MgO, SiO₂, K₂O, CaO, Cr, and Sr were depleted on weathered surfaces. Without considering the

geological weathering on the primary geological cortex, the depletion of SiO₂ is enough to make lavas that erupted as andesites appear to be basalts. Mid-z trace elements Rb, Sr, Y, Zr, and Nb have been reliably used on archaeological basalts to determine sources in other parts of the Pacific and appear less affected by geological weathering than most of the major oxides (Lundblad *et al.* 2008). But in the cases of half of the geological specimens analyzed here, there was more than a 25% loss of Sr on the weathered surfaces compared with interior values. Furthermore, in the case of one pyroclastic geological sample from Mt. Santa Rosa, Guam, the measured concentration of Y significantly increased from 29 ppm on a fresh surface to 691 ppm on the weathered surface. Lastly, Nb is almost entirely depleted in all geological samples from the Marianas. While this trait will be useful in discriminating between Mariana artifacts and those of Pohnpei, for example (Spengler *et al.* 1994), Nb cannot be used to discriminate between groups within the Marianas.

Despite the consistent effects of chemical weathering over geological time, only two of the thirteen geological samples analyzed on cortical and freshly exposed surfaces resulted in group reclassifications when comparing weathered and interior surfaces in our broadly defined geochemical groups (A, B, C, discussed below).

4.1.2. *Estimating archaeological weathering*

Comparing archaeologically weathered surfaces on artifacts with freshly exposed surfaces on the same artifacts requires some alteration to the artifact itself but can address the effects of geochemical weathering over the time scale of human occupation. Four fragmentary adzes and one fragmentary lusong had fresh surfaces exposed on their formerly broken edges as a part of the thin-sectioning process (described below). Despite Sr demonstrating significant mobility over geological time scales, it was the least-changed element from the interior to exterior surfaces of archaeologically weathered samples. The trace elements Rb, Y, Zr, and Ba also retained over 95% agreement between fresh and archaeologically weathered surfaces.

4.2. *Defining broad geochemical groups*

We followed a protocol of identifying broadly defined geochemical groups based on a multivariate cluster analysis of Rb, Sr, Y, Zr, and Ba concentrations. As discussed above, these elements consistently demonstrated the smallest effects of archaeological weathering. While archaeological weathering shows some effects on the concentrations of these elements, the variation is much less than the distance between central values of these three broad geochemical groups. Following the completion of the cluster analysis, we divided the assemblage into three major clusters, A, B, and C that each likely contain multiple geological sources that share similar geochemistry. We also used discriminant function analysis to examine the degree of separation of the major clusters, and what smaller clusters might exist within the major ones (Glascock *et al.* 1998:29-30). In the cases of A and B we have subdivided them into A/A'-high Sr/A'-high Zr/ AB trans and B/B' to better define variation in the major groupings (Figure 2).

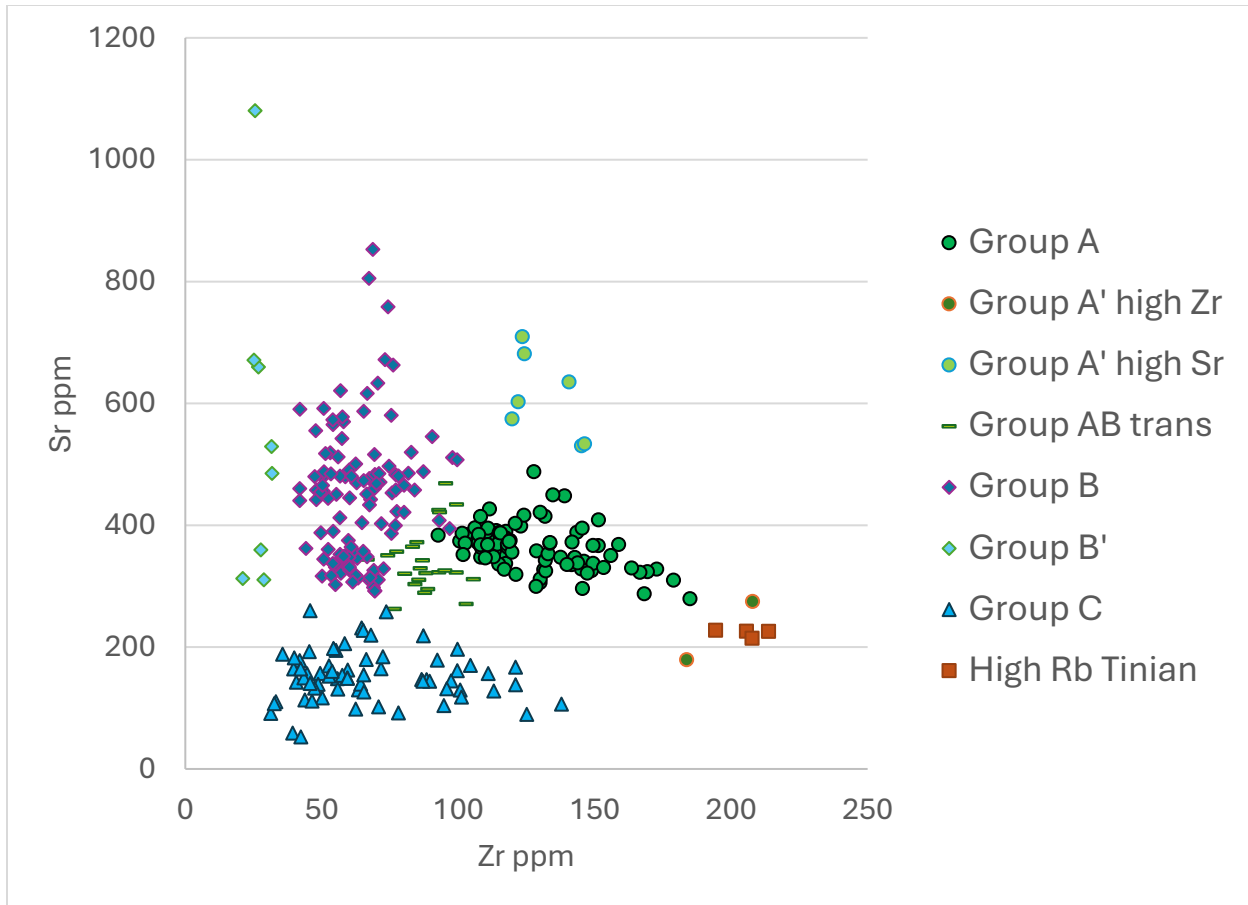


Figure 2: Sr to Zr biplot showing the degree of group separation and confirmed with discriminant function analysis trace elements. Archaeological weathering on exterior surfaces did not change group assignments when compared with freshly exposed interior surfaces.

Elevated SiO₂ is the major indicator of andesite vs basalt, and andesite is known to dominate the igneous rock on Saipan in particular. Unfortunately, SiO₂ on weathered surfaces is highly susceptible to depletion, so it was not used in our multivariate analyses. After group assignments from the cluster analysis, discerning relative trends in SiO₂ between the three major groups is still possible.

The main cluster of Group A is present in the two Sarigan geological samples and absent from the 34 geological samples analyzed from Guam and Rota. One cobble analyzed from Humatak Beach, however, falls in the range of the fringe sub-group A' high Sr. Artifacts or manuports derived from stones in Group A are common if not abundant in all archaeological collections (Table 2), and Group A exhibits a steady relative decrease in the lithic assemblages as one heads southward from Alamagan to Guam. From the geological sampling and artifact distribution patterns of the group, Group A is local to Sarigan and possibly other northern islands; however, it may still be identified on Tinian and Saipan with additional sampling. Group A generally contains silica rich andesites (average of 52.9% for SiO₂ on weathered artifact surfaces, which should represent depleted silica concentrations), and tends to have the highest concentrations of Na₂O, Al₂O₃, K₂O, Y, Zr, Ba, La Ce,

and the lowest MgO, V, Cr, Ni. This fits well with the calc-alkaline andesites in the Northern Marianas (Meijer and Reagan 1981).

Some of the samples on the fringes of Group A have been labeled A' because they do not fit neatly in the main clusters. In the Supplementary Materials Excel workbook, A' is further subdivided into A' High Sr, A' High Zr, and AB trans to designate the various regions that the samples occupy around the main cluster on a discriminant analysis and Sr-Zr biplot. Twenty-four of these samples are transitional between groups A and B, and are strongly represented by formal tools (pestles and adzes) on Guam, in contrast with manuports, pestles, and adzes on Tinian. A group of four additional samples from Tinian that refit to the same artifact display higher Rb than any other samples and are considered an outlier. They also exhibit Pb concentrations above 40ppm which is either a contaminant, or a radically different kind of eruptive event.

Group B is more mafic than Group A, but the transition between the two groups appears somewhat gradual. It tends to have the lowest SiO₂ and highest CaO and Fe of any of the geochemical groups and appears to be dominated by basalts, while Groups A and C are more andesitic. Group B matches the majority of cobbles from a beach in Humåtak and an inland area of Inalåhan on Guam and the geological samples for Rota. It is the dominant group among the Guam archaeological collections. Based on the geological sampling and artifact distribution patterns, Group B is local to southern Guam and Rota.

Group B' is comprised of outlier geological samples from Priest's Pools along the Yledigao River in Malessó' and pillow basalts exposed in a road cut and a beach cobble from Humåtak on Guam. A single artifact, an adze, recovered from the southern interior of Guam is assigned to Group B'. This group is considered local to southern Guam.

Group C includes geological samples from Facpi dike at Hågat-Humåtak and Mt. Santa Rosa in Yigu, Guam. These sources are approximately 37 km apart (straight line), spanning the majority of Guam's length, and are along opposing coastlines. Its archaeological distribution is limited to the three southern islands (Tinian, Rota, and Guam). Group C is considered local to Guam and potentially Rota based on the presence of multiple unmodified manuports recovered from the latter. Group C, like Group A, contains numerous samples with SiO₂ in the range of andesites (high 50s to 60s) and has the lowest TiO₂, MnO, and Zn, Ba, and highest Cr, Ni of any geochemical group.

Thin-sections were made from four broken adzes to better characterize the mineralogy of the geochemical groups (A, AB trans, B and C) (Figure 3-Figure 6). Groups B and C have larger plagioclase laths in the groundmass than Group A, but all three samples are fairly similar and typical of what we would expect for Marianas andesites.

Table 2: Summary of main geochemical group distributions by island and percentages of sample assemblage for each group by island for volcanic artifacts, organized from Guam in the south to Alamagan in the north.

Island	A		A' high Sr		A' high Zr		AB trans		B		B'		C		Outlier	
	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%
Alamagan	6	75	-	-	-	-	1	12.5	1	12.5	-	-	-	-	-	-
Saipan	16	80	-	-	-	-	1	5	3	15	-	-	-	-	-	-
Tinian	15	38.4	1	2.6	1	2.6	9	23	7	18	-	-	5	12.8	1	2.6
Rota	3	21.4	-	-	-	-	-	-	1	7.1	-	-	9	64.3	1	7.1
Guam	49	23.8	4	1.9	2	1	13	6.3	87	42.2	1	0.5	41	19.9	9	4.4

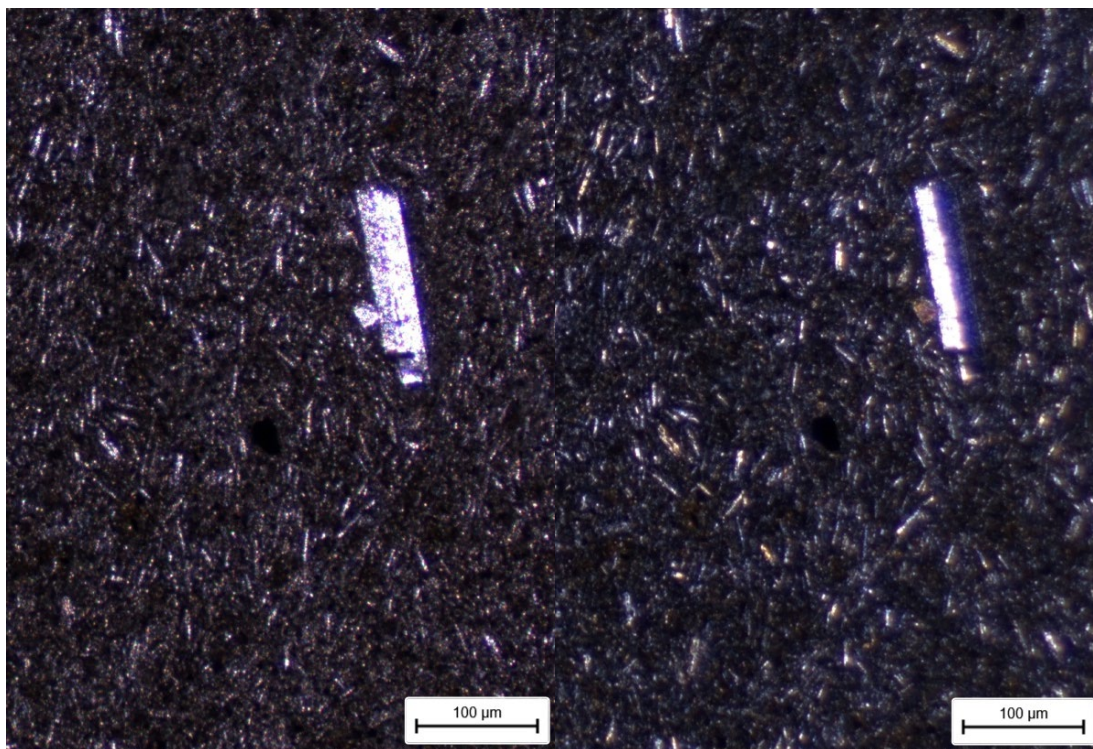


Figure 3: Group A. Photos of artifact 201926-2020.176 (a) plane polarized light (PPL) and (b) cross polarized light (XPL) showing a rare phenocryst of plagioclase in groundmass of aligned plagioclase laths. Plagioclase phenocrysts are all less than 1 mm long and have a composition of ~An45 based on 2V extinction angles that range from 30°-35°.

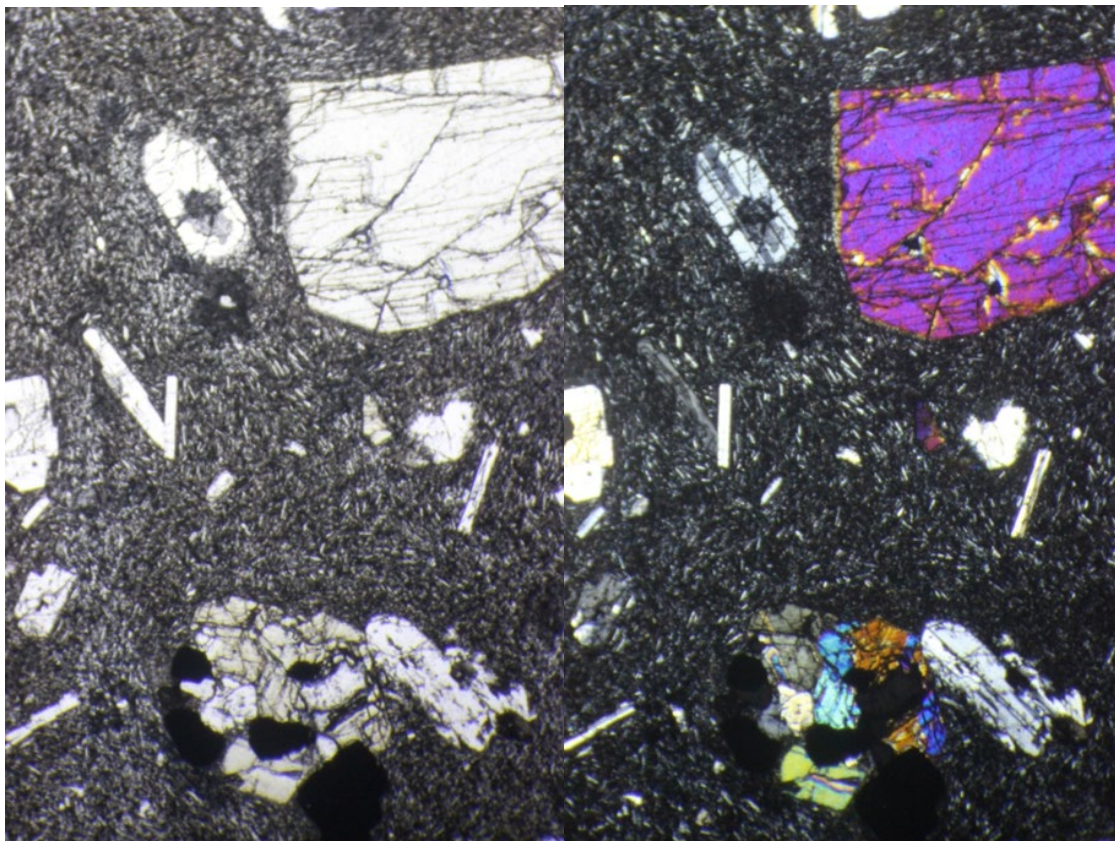


Figure 4: Group AB trans. (a) Photos of artifact 201908-085 (a) PPL and (b) XPL show a larger orthopyroxene (~2mm across) and smaller plagioclase feldspars in matrix of very fine plagioclase laths, many of which appear to be aligned. Groundmass has fine laths of plagioclase feldspar. Phenocrysts are plagioclase feldspar (~An45 based on 2V angles of 30-35°) and orthopyroxene (1-2mm). Field of view is ~5 mm top to bottom.

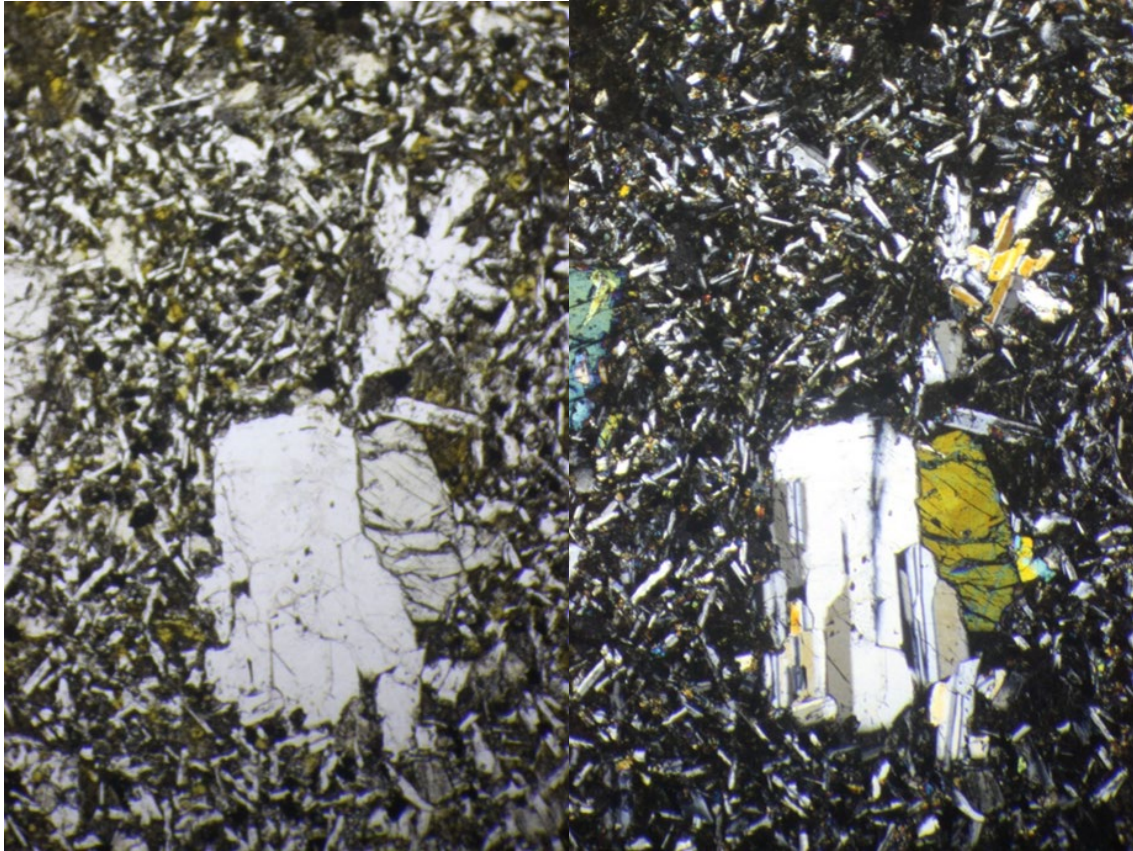


Figure 5: Group B. Photos of artifact 201908-102.01 (a) PPL and (b) XPL show cluster of larger plagioclase feldspar crystals (An55-60 based on 2V angles of 35-45°) with adjacent orthopyroxene phenocryst amongst randomly oriented plagioclase lath-rich groundmass. These laths are larger than those of either Group A or C samples. Field of view is ~5 mm top to bottom.

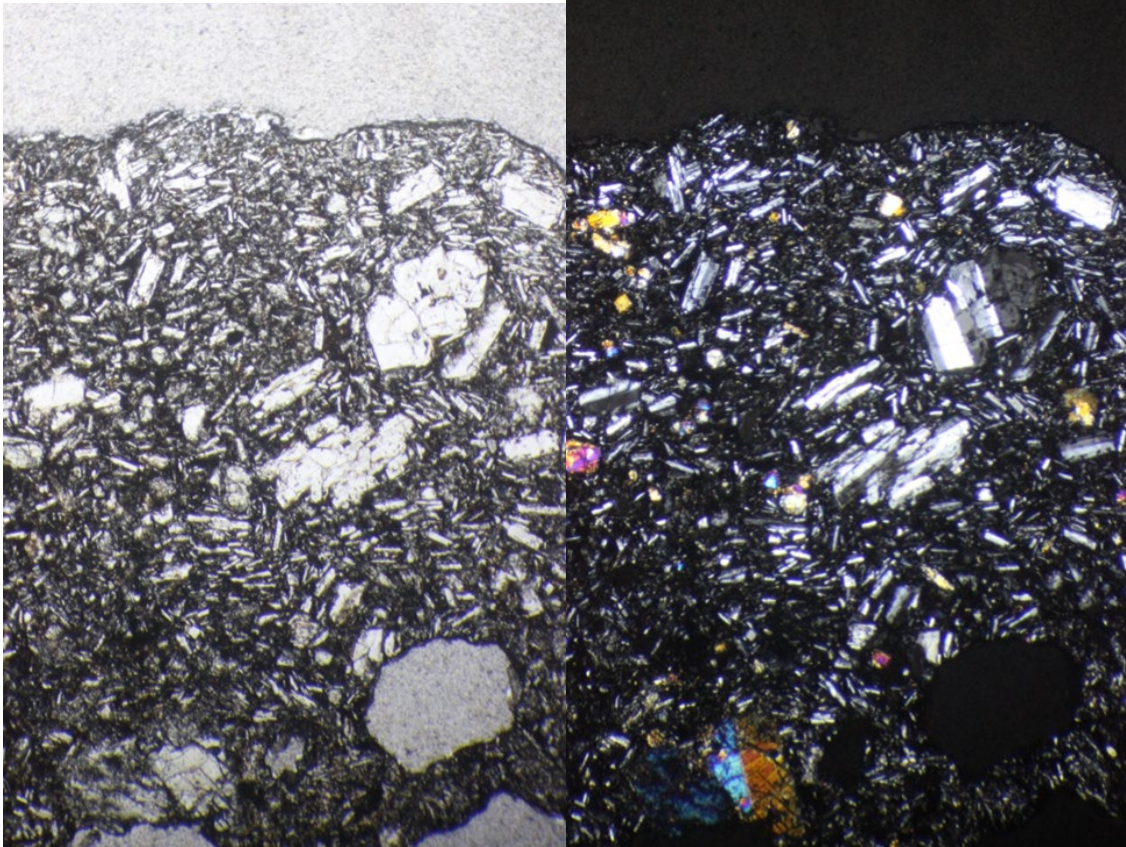


Figure 6: Group C. Photos of artifact 201908-72 (a) PPL and (b) XPL show phenocrysts of plagioclase (~An45 based on 2V angles of 30-35°) and microphenocrysts of (likely) pyroxene, in a groundmass of plagioclase laths. Plagioclase crystals are more equant than those from other groups. Field of view is ~5 mm top to bottom.

5. Discussion

5.1. Spatial and temporal geochemical diversity of volcanic stone artifacts and manuports

Geographically, Groups A and B are present in varying proportions in the archaeological collections from all islands included in our analysis (see Table 2). This documents the movement of stone along an approximately 250 km axis within the archipelago (straight line distance between Guam and Alamagan). The AB trans group is present on all islands except Rota, while the other groups (A' high Sr, A' high Zr, B', and C) and outliers are so far limited to the three southernmost islands (Tinian, Rota, and Guam). Table 3 presents the geochemical results by island and specimen type. Sample sizes vary between the islands, which may affect the artifact diversity of each collection, but certain artifact-geochemical patterns are apparent. At the archipelago scale (all collections aggregated), Group A is represented by 15 of 18 artifact forms, fire-cracked rock, and manuports with Groups B and C slightly less diverse but comparable to each other (11 and 12 types, respectively). Only scrapers, lusong, and slingstones lack Group A specimens with the latter two the only artifact forms that are solely represented by Groups B and C. Adzes have the greatest geochemical diversity with specimens in all but the A' high Zr group, as well as the outlier group. The “pestle or adze” class

and manuports are slightly less diverse than adzes with specimens in five geochemical groups. Most artifacts and fire-cracked rock are assigned to four or less geochemical groups.

At an island scale, sample size is affecting artifact and geochemical diversity as evidenced by more than a doubling of geochemical representation and more than quadrupling of artifact forms with a nearly 26x increase in collection counts between Alamagan (n=8) and Guam (n=206). Alamagan, Saipan, and Rota have more limited diversity, with Groups A and B accounting for most artifacts. For all islands, the greatest diversity of artifacts and manuports are composed of Group A or Group B. The broad geochemical diversity of Guam adzes (six geochemical groups) is unique for the archipelago, with Tinian manuports (five geochemical groups) and Guam grinding stones (four geochemical groups) presenting the next greatest diversities for any island-specific collections.

Guam is the only island with a sample size sufficient for a more detailed analysis. Two chi-square tests were conducted to examine the relationship between two generalized artifact groups—formal and informal tools—and geochemical groups. The formal tool category consists of adzes, grinding stones, groundstone fragments, lusong, mano, metate, pestles, pestles or adzes, and slingstones. These are tools created through some combination of flaking, pecking, and grinding to produce relatively complex finished geometries. Expedient tools, in contrast, consist of debitage (cores, flakes, shatter), hammerstones, pounders, and scrapers. These are simple tools that require minimal, if any, modification for fabrication. The initial chi-square test examined whether there is an association between the artifact categories and the primary geochemical groups (A, B, and C). The association between these variables was not significant, $\chi^2(2, N=146) = 5.18, p=.075$. A second chi-square test was based on Groups B and C collapsed into a “local” category with Group A categorized as “non-local.” While the null hypothesis is that there are no associations, the alternative hypothesis—that there are non-random associations between the two artifact categories and geochemical groups—is predicated on procurement, tool manufacturing, and tool use-life costs. Simplified, we expect more costly non-local stone or finished tools to be more commonly used for formal tools with less costly local stone used for expedient tools. The relationship is significant, $\chi^2(1, N=146) = 4.18, p=.041$. Standardized residuals do not identify particular cells as driving the significance (values are <2).

Temporal resolution is less clear. The first ~1,500 years of the CHamoru occupation sequence is missing with the earliest archaeological samples in our dataset dating sometime between the fifth and sixth centuries AD. It is likely that most of the artifacts, particularly those collected as surface finds, date to the Latte Period (ca. tenth century AD to the seventeenth or eighteenth centuries). However, only 41 specimens can be assigned an absolute date range or a bracketed absolute date range (based on terminus post quem and/or terminus ante quem determinations), and of these 38 can be placed in chronological bins for analysis. Chronological bins are based on conventional radiocarbon ages (CRA) and are devised for heuristic purposes. As presented in Table 4, Group A was present on Tinian by CRA 1550-1599 (calibrated between the fifth and sixth centuries AD), which barring a source on that island, indicates movement of stone from the northern islands by this time. Movement of this group to Guam and the other southern islands post-dates CRA 550. Group B, which derives at least from Guam and Rota, and Group C, which is also found on Guam, were present on Tinian by CRA 800-849 (calibrated between the twelfth and thirteenth centuries AD). While limited, the temporal information documents intra-archipelago movement of stone or finished tools beginning by the late Pre-Latte Period.

Table 3: Artifacts and manuports by geochemical group and island.

Sample	A	A'high Sr	A'high Zr	AB trans	B	B'	C	Outlier
<u>Alamagan</u>								
Adze	1	-	-	-	1	-	-	-
FCR	1	-	-	-	-	-	-	-
Flake	4	-	-	-	-	-	-	-
Manuport	-	-	-	1	-	-	-	-
Subtotal	6	-	-	1	1	-	-	-
<u>Saipan</u>								
Abrader	1	-	-	-	-	-	-	-
Adze	5	-	-	-	2	-	-	-
Flake	5	-	-	-	-	-	-	-
Hammerstone	1	-	-	-	-	-	-	-
Pestle	2	-	-	-	-	-	-	-
Pestle or adze	1	-	-	-	1	-	-	-
Pounder	1	-	-	1	-	-	-	-
Subtotal	16	-	-	1	3	-	-	-
<u>Tinian</u>								
Core	1	-	-	-	-	-	-	-
Flake	1	-	1	-	-	-	-	-
Grinding stone	2	-	-	-	-	-	1	-
Manuport	8	1	-	3	3	-	4	1
Pestle or adze	-	-	-	5	2	-	-	-
Pounder	-	-	-	1	1	-	-	-
Shatter	3	-	-	-	1	-	-	-
Subtotal	15	1	1	9	7	-	5	1
<u>Rota</u>								
Adze	1	-	-	-	-	-	-	-
FCR	-	-	-	-	-	-	1	-
Flake	2	-	-	-	-	-	-	-
Hammerstone	-	-	-	-	-	-	1	-
Lusong	-	-	-	-	-	-	-	1
Manuport	-	-	-	-	-	-	7	-
Slingstone	-	-	-	-	1	-	-	-
Subtotal	3	-	-	-	1	-	9	1
<u>Guam</u>								
Adze	22	1	-	8	58	1	12	2
Core	1	-	-	-	-	-	-	-
FCR	1	-	-	-	-	-	-	-
Flake	5	-	-	1	-	-	1	-
Grinding stone	4	-	2	-	1	-	6	-
Groundstone	1	1	-	-	1	-	1	-
Hammerstone	1	1	-	-	1	-	3	-
Lusong	-	-	-	-	1	-	4	-
Mano	2	-	-	-	-	-	1	-
Manuport	1	-	-	1	-	-	-	2
Metate	1	-	-	-	-	-	-	-
Pestle	-	-	-	1	3	-	-	1
Pestle or adze	7	1	-	1	9	-	5	1
Pounder	2	-	-	-	8	-	3	2
Scraper	-	-	-	1	-	-	-	-
Shatter	1	-	-	-	-	-	-	-
Slingstone	-	-	-	-	5	-	5	1
Subtotal	49	4	2	13	87	1	41	9
Total	89	5	3	24	99	1	55	11

Table 4: Dated archaeological samples by chronological bins and geochemical groups; note the gaps between some chronological bins.

	1550-1599	950-999	800-849	750-799	600-649	550-599	<550
A	2	0	2	0	1	2	11
A'high Sr	0	0	0	0	0	0	0
A'high Zr	1	0	0	0	0	0	0
AB trans	0	1	0	0	0	0	4
B	0	0	2	1	0	1	2
B'	0	0	0	0	0	0	0
C	0	0	1	0	0	0	6
Outlier	0	0	0	1	0	0	0
Islands	Tinian	Guam	Tinian	Rota	Alamagan	Alamagan	Alamagan, Guam, Rota, Saipan, Tinian

5.2. Explaining interaction within the Mariana archipelago

Explaining intra-archipelago interaction is a somewhat premature goal since we are at the stage of describing the physical record of interaction. Our descriptive results allow us to begin posing hypotheses. The Marianas archipelago is comprised of high islands with diverse and broadly distributed marine and terrestrial resources. However, seasonal and periodic typhoons and droughts may have fostered socio-cultural behaviours that buffered against subsistence shortfalls and concomitant negative effects on population (Hunter-Anderson 2010:149). One such behaviour, a form of bet hedging (Allen 2004), could have been the establishment of social relationships within and between islands (e.g., Alkire 1978:118-131, Petersen 2009)—facilitated by the exchange of stone/stone tools, pottery, and other goods—to ameliorate localized adverse environmental effects. The costs of establishing and maintaining these relationships (e.g., loss of goods, risk of injury or death during seafaring, lower reproductive rates) would have been offset by long-term success via these extended partnerships. Testing this hypothesis requires modelling the environmental variables and selection criteria favouring this or alternative behaviours. It also requires evidence from the archaeological record demonstrating that populations were interacting. A complementary economic hypothesis assumes that the archipelago’s patchy distribution of volcanic stone suitable for formal tool production, particularly higher quality stone for adzes, necessitated sailing for procurement and exchange. Additionally, directly obtaining stone from the northern islands may have been a source of prestige and a form of costly signaling (Allen 2025) for populations on the southern islands.

Our study confirms the movement of volcanic stone within the archipelago and identifies three geographic patterns. One, Group A, sourced to Sarigan and possibly other northern islands, exhibits a decreasing frequency in archaeological collections north to south (Figure 7). Two, Group B, confirmed from Guam and Rota, and Group C, also confirmed from Guam and potentially assignable to other southern islands, present an opposite trend to Group A by decreasing from south to north. While these patterns are paired because of the effects of a closed array (i.e., an increase in the

proportion of one group dictates a decrease in the proportion of another group), the zero or near-zero values at the geographical ends reflect attenuated access to these stone sources or tools with distance. Three, on Guam, there is a significant association between formal and expedient tools and local and non-local stone. Accessing and procuring Group A stone may reflect an economic need and generation of prestige/costly signaling. The younger and more abundant stone from the northern islands that are volcanically active may have produced better quality tools (e.g., because of less geological weathering), which outweighed the costs associated with directly procuring it by southern populations. These costs—e.g., production and maintenance of sailing canoes, specialized navigation skills, ability to allocate resources away from subsistence activities—may have advertised the wealth and fitness of these individuals or groups. Conversely, the northward movement of potentially lower quality Guam/southern island stone may document the fostering of broadly distributed social networks and, secondarily, economic needs. Either hypothesis and alternatives should be evaluated in terms of equifinality and underdetermination (e.g., Perrault 2019).

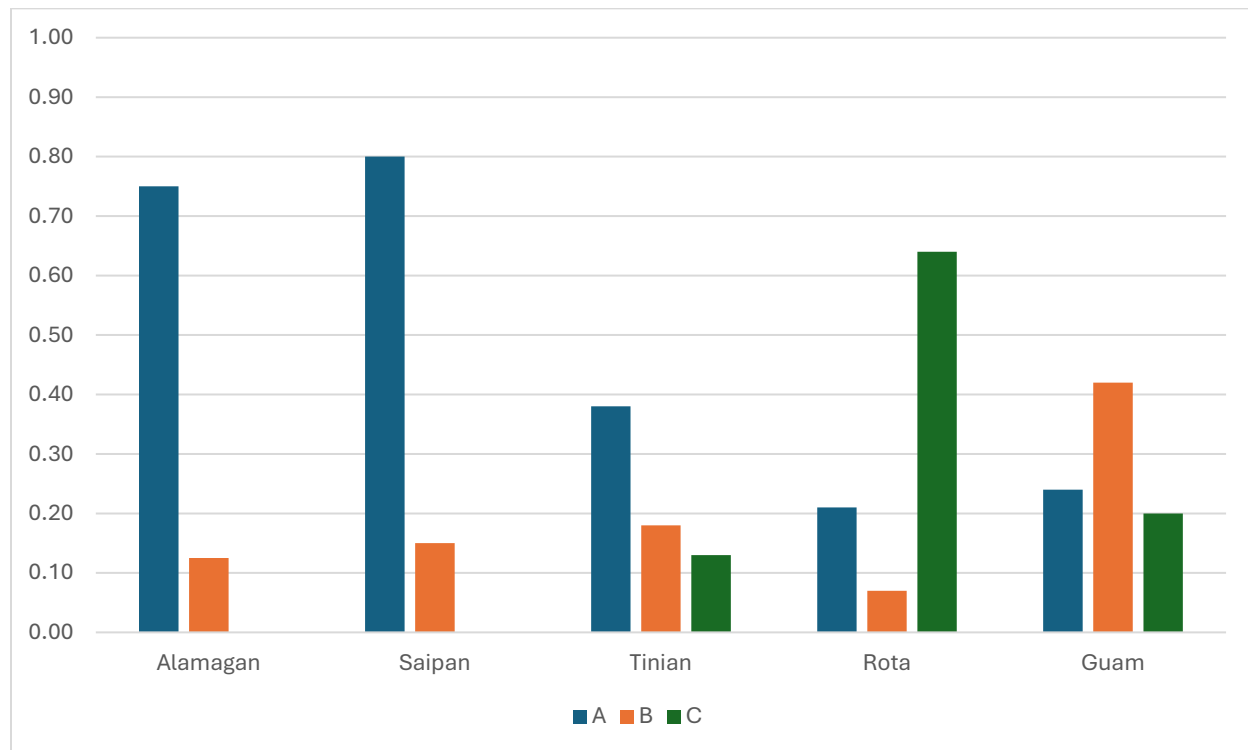


Figure 7: Stacked bar chart of the proportions of the major geochemical groups for Alamagan, Saipan, Tinian, Rota, and Guam.

6. Conclusion

Compared with many other archipelagos in Oceania, the Mariana Islands are an enigma. Linguistically and genetically distantly related to other populations and with idiosyncratic aspects of material culture (e.g., latte), the archipelago appears to have had a long history of relative isolation. Contact with Palau based on genetics (Liu *et al.* 2022) and the late pre-contact introduction of *Rattus*

exulans from an unknown source(s) (Pregill and Steadman 2009) are exceptions that highlight the general pattern of isolation. Our analysis of geological samples from Sarigan, Rota, and Guam and nearly 300 volcanic stone artifacts from archaeological deposits on Alamagan, Saipan, Tinian, Rota, and Guam document at least ~1,500 years of intra-archipelago interaction, which reconfirms an extensive and consistent pattern of open-ocean voyaging by CHamoru people. Movement or circulation of stone or finished tools appears to have been common with a maximum extent of ~250 nautical miles between Guam and Alamagan (straight line distance). The data are spatially patterned with the prevalence of northern-sourced stone decreasing to the south and the inverse for southern-sourced stone. For Guam, there is a significant association between formal and expedient tools and the use of local or non-local stone. Further documenting the movement of stone within the archipelago requires additional research, and this in turn is needed to test models and hypotheses to explain this past behaviour. We have proposed three non-mutually exclusive hypotheses (bet hedging, economic need, and prestige/costly signaling). To advance this research we offer the following suggestions:

- Additional geological samples are required to refine the sourcing of our geochemical groups and to more fully record geochemical diversity across the archipelago.
- There are several spatial lacunae that must be addressed by future sampling: southern Guam, Aguijan, and the northern islands. Additional sampling of Saipan, Rota, and Tinian is needed.
- Artifacts dating to the first half of the CHamoru occupation must be sampled along with well-dated artifacts from the entire sequence. This should include post-Spanish contact items to document how this European intrusion affected existing circulation and access to stone resources.
- Conventional pedestrian survey, and potentially unmanned aerial vehicle (UAV, drone) survey, is needed to identify CHamoru quarries. Presently, no pre-Spanish contact quarries have been documented.
- CRM and other researchers should incorporate geochemical analysis into project planning and budgets. The cost is negligible and the incremental sampling by firms and individual researchers will have a significant amplifying effect.
- With sufficient data, models of exchange should be developed and tested.

Supplementary Materials

The supporting information can be downloaded at <https://doi.org/10.70460/jpa.v16i1.411> S1: MS Excel workbook with geochemical, discriminant analysis, weathering, and other statistical results.

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Data Availability Statement.

Data are presented in the appendices and are openly available for further use at the University of Hawai'i at Hilo Geoarchaeology Lab website (<https://hilo.hawaii.edu/depts/geoarchaeology/>).

Partnerships

This research did not use any primary data from Indigenous contexts.

Conflicts of Interest

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Author Contributions

Conceptualization, T.M.R. and P.R.M.; methodology, P.R.M., S.P.L., and T.M.R.; software, T.M.R., P.R.M., C.B.; validation, P.R.M., S.P.L., Y.Y. and Z.Z.; formal analysis, P.R.M., S.P.L., C.B.; data curation, P.R.M., S.P.L.; writing—original draft preparation, T.M.R., P.R.M., and L.S.; writing—review and editing, T.M.R., P.R.M., S.P.L., L.S., D.F., M.N., R.O., and C.B.; visualization, P.R.M., S.P.L., T.M.R., and L.S.; funding acquisition, T.M.R. All authors have read and agreed to the published version of the manuscript.

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