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Sourcing sandstone cobble grinding tools in southern California using petrography, U–Pb geochronology, and Hf isotope geochemistry

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ABSTRACT

Procurement strategies for grinding tool lithic material among mobile societies are thought to rely on opportunistic selection of resources locally available at habitation sites and along migratory routes. In San Diego County, California, non-local appearing quartzarenite cobble handstones were identified in the ground stone assemblages of some hunter-gatherer archaeological sites dating from ca. 7000 years ago. Due to the nature of the cobble material, both natural and cultural processes may have played a role in the spatial distribution of the artifacts recovered by archaeologists. In this study we employ three techniques to investigate the geological origins and source location(s) of the quartzarenite cobbles: thin section petrography, U–Pb geochronology, and Hf isotope geochemistry. Results confirm the Neoproterozoic-lower Paleozoic age of the cobbles, while metamorphism of southern California basement rocks of similar age indicates that the cobbles must have been transported into the area, probably during Eocene times. People collected the cobbles from source locations and carried them at least 4–10 km and possibly farther. We consider the diagnostic value of the three techniques for characterizing resource distributions of sedimentary cobble material and related procurement strategies, and more broadly, their global applicability for sourcing other archaeological materials made of sedimentary and metasedimentary rock.

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1. Introduction

Ethnoarchaeological studies yield evidence of strong cultural preferences for certain lithic types associated with concepts of processing efficiency and energy investment in grinding tool procurement among contemporary sedentary and semi-sedentary agriculturalists (e.g., Hayden, 1987; Horsfall, 1987; Schneider, 2002a,b). Petrographic and chemical characterization techniques have proven important for demonstrating long-distance transport of some highly-valued ground stone items, such as ancient basalt milling tools, in sedentary agricultural and emerging agricultural societies (Weinstein-Evron et al., 1995, 1999, 2001; Williams-Thorpe, 1988; Williams-Thorpe and Thorpe, 1993; Williams-Thorpe et al., 1991; Peacock, 1980). Provenance of ground stone tools in mobile hunter-gatherer societies, on the other hand, is rarely investigated. This is in large part due to the assumption that people who move regularly to exploit seasonal food resources would not choose to carry bulky food-processing tools or tool raw materials for long distances (e.g., Basgall, 2008). Research by Schneider (1993) has helped to develop and apply a behavioral theoretical framework based on the socioeconomics of mobile versus sedentary groups to milling implements and milling implement quarries in eastern California and western Arizona. In the case of residentially mobile societies, Schneider (1993) posited an embedded procurement strategy for grinding tool lithic material. An embedded procurement strategy is defined as one in which raw material is obtained incidentally during the conduct of other primary activities (Binford, 1979). Among people who move seasonally to obtain subsistence items, such a strategy is characterized by opportunistic selection of naturally-shaped materials widely scattered along migratory routes. For example, selected tool

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materials would include stream cobbles for handstones and flat bedrock or boulder surfaces for netherstones. Cobble material appropriate for handstones, such as food-processing manos, polishers, or abraders, is typically distributed across the landscape as a "ribbon source", along the course of a stream or river bed (Miksa and Tompkins, 1998). Where alluvial fans or large river terraces cover broad areas, cobble resource distributions may be described as effectively "continuous". Both continuous and ribbon-shaped resource distributions are readily exploited according to an embedded procurement strategy because the resource can be accessed from a number of locations (Miksa and Tompkins, 1998). Energy expended in tool procurement would be minimized by selecting any serviceable cobble from the nearest access location along seasonal migratory routes.

Exceptions to this idealized behavioral framework have been recognized in mobile hunter-gatherer contexts, but the evidence has been indirect. Schneider (1993) notes the possibility that a cobble or quarried material of a preferred size or shape might be retained for future use or transported to other areas during migratory movement. She points to the dike quarries of the Eastern Mojave and Colorado deserts as examples of convenient sources of naturally flat rock slabs that could be carried into regions where suitable material may not have been available. Basgall (2008) cites wear attributes of handstones used by Gypsum period Mojave desert mobile foragers as evidence that the handstones were transported as personal gear, perhaps when foragers were traveling to less familiar places or when resources were unpredictable. His interpretation is based on the assumption that handstones that are transported and retained for long periods of time will show greater formalization and use-related modification. The Gypsum period handstones in his sample were of especially durable lithic material. Preferred rock sizes, shapes, or types like those described by Schneider (1993) and Basgall (2008) often have limited resource distributions in restricted locations ("point sources", Miksa and Tompkins, 1998) and may be subject to a more targeted procurement strategy.

A recent study of lithic types in San Diego County Archaic (ca. 7500–2000 BP) and Late Prehistoric (ca. 2000–200 BP) hunter-gatherer ground stone assemblages ($n = 30$) by these authors revealed spatial patterns in grinding tool lithic choice that in most cases reflect the sites' known local geology. These results are consistent with Schneider's (1993) model: archaeological assemblages are dominated by locally available, morphologically acceptable (though not necessarily ideal) lithic materials. However, quartz-cemented, quartz-rich sandstone (quartzarenite) cobbles, petrologically distinct from typical sandstone of San Diego County, were present as flat multifacial manos at four sites in the southern part of the county on the western side of the Peninsular Ranges. This distinctive sedimentary cobble material comprised up to 28% of the handstones at an Archaic site in Otay Mesa (CA-SDI-8654; Kyle et al., 1990) on the coastal plain. One quartzarenite cobble mano was found at a site (CA-SDI-14283, Robbins-Wade et al., 1996) in the western foothills of the Peninsular Ranges. Similar quartzarenite material was later identified as handstones in Wallace's (1962) collections from CA-SDI-949 and CA-SDI-967 in Indian Gorge within the Anza-Borrego Desert State Park. The sites lie near or on ethnohistoric Native American trail routes (Cline, 1979) linking the coast and the desert. Two additional specimens were identified in a collection from near the Borrego Spring in the desert.

The restricted spatial distribution of this unusual cobble material raised questions about the geological origins and possible transport of the raw material and/or tools made from it. Because the tool raw material in this case is water-worn cobble rather than quarried material, it is necessary to consider and distinguish between natural versus cultural transport. Natural transport, such as by rivers, may move the material from the point of geological origin to the source location(s) where it was collected. Therefore, the distribution of quartzarenite cobble tools may reflect the presence of a previously unrecognized ribbon-shaped resource exploited according to an embedded procurement strategy. People may also have transported the material some distance from the source where it was collected so that both natural and cultural processes, such as a targeted procurement strategy, played a role in the distribution of the artifacts recovered by archaeologists. In this study we employ three techniques to directly investigate the geological origins and source location(s) of the quartzarenite cobble tools: thin section petrography, U–Pb geochronology, and Hf isotope geochemistry. We consider the diagnostic value of the three techniques for characterizing resource distributions of sedimentary cobble material and related procurement strategies, and more broadly, for sourcing other archaeological materials made of sedimentary and metasedimentary rock.

2. Theory

2.1. Regional geology and culture history

San Diego County encompasses four distinct physiographic zones from west to east roughly paralleling the coastline (Jahns, 1954). Each has its own lithic resources and ecological communities.

1. The northern *coastal* zone is about 13 km wide with elevations rising to about 180 m. The northern coastline consists of steep cliffs of Eocene age sandstone interrupted in places by marshy lagoon habitats. The southern coastal zone has been pulled apart between the active Rose Canyon and Descanso faults creating San Diego Bay and a broader coastal plain that extends 20 km inland. The environment is marked by sandy beaches and tidal flats, and includes Otay Mesa. The coastal plain geology is dominated by a huge Eocene alluvial fan/fan delta with abundant rhyolite and dacite volcanic clasts brought from the modern-day Sonora, Mexico area during pre-Gulf of California times (Abbott, 1999). These multitudinous ultra-resistant volcanic clasts have been reworked and reshaped by waves and redeposited in younger sedimentary rock bodies.
2. The *foothills* zone lies between the coast and high mountains. It is a zone of hills and inland valleys cut by rivers and smaller streams flowing westwards from the Peninsular Ranges. The foothills are composed primarily of igneous rocks of the Lower Cretaceous Santiago Peak Volcanics and the plutonic rocks of the Peninsular Ranges batholith.
3. The Peninsular Ranges *mountain belt* rises to approximately 1800 m, reaching their highest elevations in the north part of the county (Larsen, 1948). The mountains are composed primarily of Cretaceous tonalite, granodiorite and gabbro with some outcrops of Lower Mesozoic Julian schist.
4. To the east, the mountains drop off sharply to the Anza-Borrego *desert* floor, the western margin of the Salton Trough. The Salton Trough is a major topographic depression (as much as 61 m below sea level) that extends north from the Gulf of California and represents the northern end of an active rift valley and a continental plate boundary. A complex geologic history is exposed in the trough, including Ordovician metasedimentary strata, the oldest rocks in the San Diego region (Abbott, 1999).

Vegetation patterns and animal habitats are diverse, but generally correspond to physiographic zones, with grassland, sagebrush, and chaparral in the coastal zones trending to

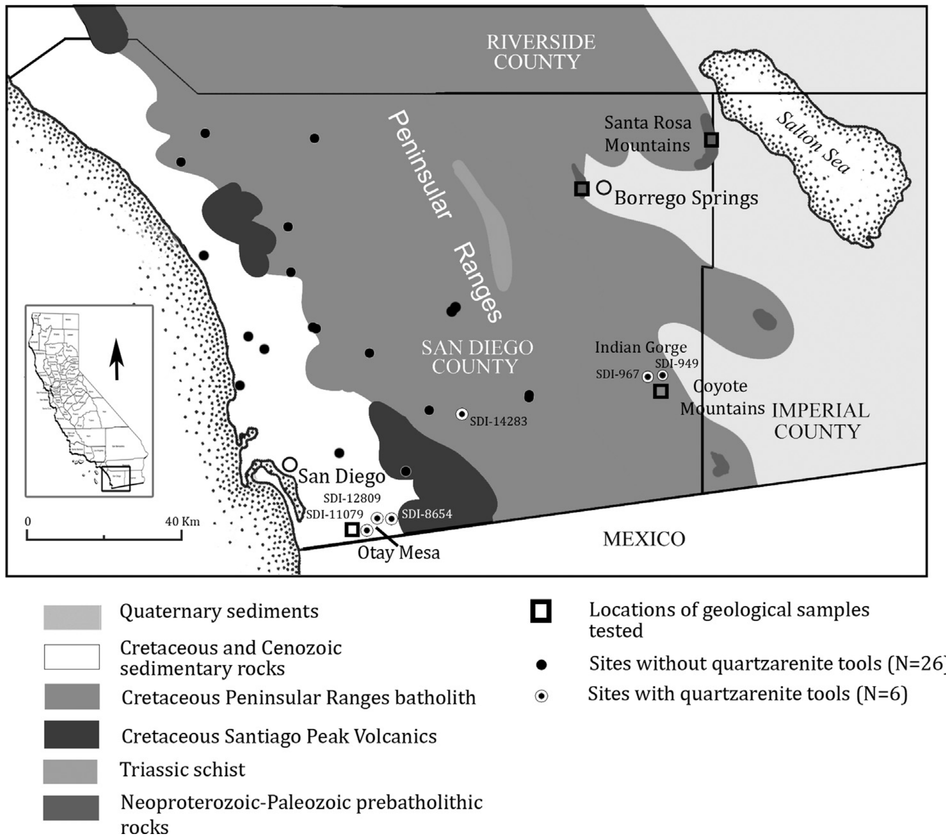

Fig. 1. Map showing generalized geology of San Diego County and locations of studied archaeological sites and tested geological samples.

woodland-grass, pine-fir, and pinyon-juniper as elevation increases. Desert habitats include creosote bush-bur sage and palo verde-cactus shrub, with smoke tree, mesquite, and acacia in washes and native palm trees near natural springs and oases. Throughout Holocene time, the San Diego area has had a mild Mediterranean climate with rainy winters and dry summers.

Human occupation of the San Diego area dates from the early Holocene, at least 10,000 years ago. The earliest sites may now lie submerged off the present-day coastline, which is two to six km farther east than during the late Pleistocene (Masters and Gallegos, 1997). Throughout this time frame, hunter-gatherer groups utilized the diverse resources of the different physiographic zones, though with apparently shifting strategic emphases. The generally accepted cultural history consists of three main phases preceding European contact. Assemblages of the earliest phase, the Paleo-Indian period, are comprised of chipped or flaked stone technologies exemplified by the “San Dieguito” tradition or complex. The appearance of grinding implements, or “milling stones”, no later than about 7000 BP, marks the beginning of the Archaic or “Millingstone” period (Erlandson, 1994). “La Jolla Complex” and “Pauma Complex” tool kits associated with the Archaic period have been differentiated and may reflect coastal versus inland adaptations and/or different cultural origins (True, 1980). However, both are thought to provide evidence for a transition from a “San Dieguito” subsistence strategy based on hunting and gathering of expedient plant species (e.g., pine nuts) to one emphasizing more diversified collecting and more intensive plant processing with a focus on small seeds (Erlandson, 1994; Sutton, 1993). Archaic period sites include coastal and inland valley habitation sites and smaller resource processing and camp sites. Late Prehistoric period (about 2000–200 BP) habitation sites are larger than Archaic period sites and exhibit a greater diversity of artifact types, suggesting increasing complexity and reduced mobility (e.g., Byrd and Reddy, 1999; Christenson, 1990; Laylander, 1997). Pottery and small triangular points are markers for this period. Many Late Prehistoric resource processing and habitation sites are located in the upland and mountain zones near granitic boulder outcrops and oak-grassland habitats. At the time of first European contact, most native groups in California were using stone mortars and pestles to grind acorns into flour (Kroeber, 1925). It has generally been assumed that acorns were a primary staple during the centuries of the Late Prehistoric period that preceded the Historic or post-contact period (1769 CE–present) in the San Diego area. During the winter and spring, social groups moved down from the mountains to the desert to utilize foods like mesquite beans. Unlike other parts of the southwestern U.S., there is no definitive evidence that agriculture was practiced in San Diego County until its introduction by the Spanish (Laylander, 1997; Shipek, 1993 suggests a level of plant manipulation). The use of stone grinding tools by indigenous groups including Luiseño, Juaneño, Kumeyaay, Cahuilla, and Cupeño Indians continued after European contact into the early 20th century and later in some parts of the area.

2.2. Archaeological context of non-local appearing sandstone cobbles used as handstones

Examination of handstones from archaeological sites in the Otay Mesa area of southern San Diego County with a 10× hand lens (conducted as part of a larger county-wide study of a total of 748 handstones and 89 netherstones including fragments from 30 sites, Fig. 1) revealed quartz-cemented, quartz grain-rich sandstone (quartzarenite) as cobble material (Fig. 2). These quartzarenite cobble handstones were previously identified in site reports by archaeologists as manos made of granitic or quartzite rock, i.e.

materials of local geological origin. The tools (weights up to 1.5 kg) are ovoid-to-round, ranging from 7 to 13 cm in length and 6.5 to 12 cm in width, and flattened in profile (2.5–6 cm in thickness). Most of the quartzarenite handstones have a naturally rough-textured surface (Fig. 3). Hand lens inspection indicates that this lithic material was not derived from local bedrock sources. Sands deposited in southwestern California during Mesozoic and Cenozoic (66 Ma to present) time accumulated within a tectonically active regime featuring steep topography and bedrock close to depositional basins; this results in quartz-poor sandstones. In California, there has not been sufficient time for chemical weathering to destroy feldspar and lithic grains, and not enough distance of geological transport to physically destroy weak grains of sand. Therefore, the quartzarenite cobbles used as handstones and found at archaeological sites in this area appear to be non-local, i.e. they must have been transported to the area by natural and/or cultural processes. The non-local appearing quartzarenite handstones occurred in context with handstones made of other lithic materials that reflect the coastal plain geology of southern San Diego County (Table 1). Notably abundant in these assemblages are tools made from volcanic (mainly dacite, rhyodacite, and rhyolite) cobbles representing the Eocene alluvial fan/fan delta. The volcanic cobbles have a naturally smooth surface that appears to have been intentionally roughened by pecking prior to use (Fig. 4). Plutonic rocks, especially gabbro, are proportionately more abundant in the handstone assemblage of CA-SDI-14283. The sample set from CA-SDI-14283 is very small ($N = 5$), but the high frequency of plutonic rocks is similar to sample sets from other study sites in the foothills and Peninsular Ranges mountain belt and is consistent with the mountain belt geology.

The study site with the highest proportion (18 items, or 28%) of the non-local appearing quartzarenite in its grinding tool assemblage is CA-SDI-8654. Known as the Kuebler Ranch Site, this site was occupied about 7000 years ago (based on ^{14}C dates) and is one of many from this time frame situated on Otay Mesa (Gallegos et al., 1998; Kyle et al., 1990). A variety of archaeological features and materials attest to the use of CA-SDI-8654 as a habitation site, either for an extended period or for recurring seasonal visits. These include a living floor, hearths, cobble tools, handstones and netherstones, hammer stones, cores and debitage, flake tools, *Olivella* shell beads, and other worked and unworked shell and bone. The Kuebler Ranch Site is close to a perennial spring and surrounded by oak, coastal sage scrub, and chaparral. *Olivella*, a marine shell, provides evidence of travel to, or social contact with, the coastline, presently 20 km to the west. Coso Range obsidian found at the site indicates contact and/or trade with the Great Basin region, east of the Sierra Nevada Mountains. A tourmaline crystal originating from the Peninsular Ranges is further evidence of movement and/or social exchange networks linking Otay Mesa with other parts of the San Diego region and beyond during the Archaic period. The large outcrop of felsic volcanic rock (Santiago Peak Volcanics) near CA-SDI-8654 may have made this location especially attractive to Archaic populations. This stone has excellent flaking properties (Dietler, 2004) and was used to make a variety of chipped stone tools, including projectile points, gravers, and punches. Many of the grinding tools were used for food processing and, along with charred seeds found at the site, are interpreted as indicating a growing reliance on plant foods (compared with the earlier Paleo-Indian period). The handstones found at CA-SDI-8654 made from quartzarenite cobbles show attributes consistent with stone-on-stone food processing (Adams, 2014). Another Archaic period site on Otay Mesa, CA-SDI-11079, had the second largest number of non-local appearing quartzarenite cobble tools (5, or 5% of the ground stone assemblage) among the studied sites. This site, known as the Remington Hills site, is located about 10 km west of CA-SDI-8654. The Remington Hills site is a habitation site occupied between about 7000 and 9000 years ago (based on ^{14}C dates; Kyle et al., 1998). Coso Range obsidian was also found at CA-SDI-11079.

Two Late Prehistoric sites on the western side of the Peninsular Ranges also had cobble handstones made of non-local appearing quartzarenite. Habitation site CA-SDI-12809 is located on Otay Mesa and associated with the ethnohistoric village of *Otai* (^{14}C-dated to about 500 years ago and probably occupied earlier; McDonald et al., 1993). Habitation site CA-SDI-14283 is located next to the Sweetwater River and has extensive bedrock milling features centered on a granitic exposure at an elevation of 414 m (Robbins-Wade et al., 1996). These sites had one quartzarenite cobble handstone each. Non-local appearing artifacts at Late Prehistoric sites may have been scavenged from Archaic sites rather than collected from their natural source locations. Otay Mesa and mountain locations are known to have been connected by trail networks during ethnohistoric times (Sample, 1950).

East of the Peninsular Ranges, handstones made of the non-local appearing quartzarenite cobbles were identified in assemblages from CA-SDI-949 (Cat #90) and CA-SDI-967 (Cat #114) in Indian Gorge within the Anza-Borrego Desert State Park. These sites are

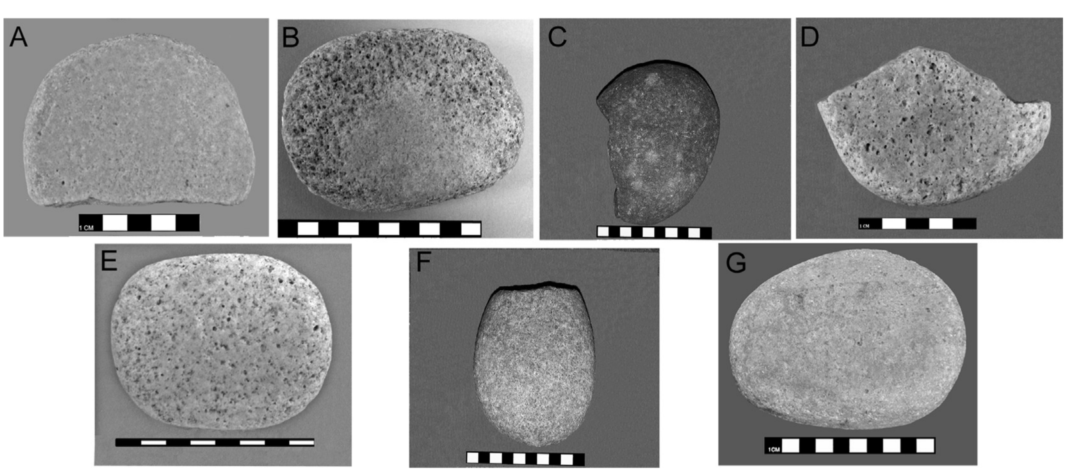

Fig. 2. Examples of non-local appearing sandstone cobble handstones found at San Diego County sites. A, Duvall collection #625-60-324; B, CA-SDI-949 Cat#90; C, CA-SDI-8654 Cat#1934; D, Duvall collection #625-60-352; E, CA-SDI-967 Cat#114; F, CA-SDI-8654 Cat# 1062; G, SDI-14283 Cat#320. These specimens are composed of quartz grains cemented by quartz, i.e. mineralogically they are quartzarenites. Texturally they are coarse- to medium-grained sandstone, moderately- to moderately-well sorted with rounded sand grains.

Fig. 3. Quartzarenite handstone (CA-SDI-8654 Cat#1465). Note rough texture that results in a naturally abrasive working surface.

among a group of 28 short-term seasonal campsites recorded by Wallace (1962) during surveys in 1960. Indian Gorge runs along the southern edge of the Tierra Blanca Mountains, which consist of white-colored, quartz-rich granite. Coarse sand on the floor of the wash is weathered from the surrounding granitic pluton. Artifacts found at the sites, some of which include boulder milling features, are chipped stone, ceramic sherds, and handstones made from the local granitic material, in addition to the two quartzarenite cobble handstones. Clasts of the local granitic material are more angular in shape and more friable than the quartzarenite cobble tools. The presence of ceramics places these sites within the Late Prehistoric cultural period. Cline (1979) has documented ethnohistoric Kumeyaay trail routes along washes through the Tierra Blanca mountains, linking the coastal plain and the desert. Two additional quartzarenite cobble handstones were identified in a collection of unprovenienced artifacts from near the Borrego Spring (Duvall collection, Cat#625-60-324; Cat#625-60-352).

2.3. U–Pb geochronology

U–Pb geochronology by Laser Ablation-Multicollector-Inductively Coupled Plasma-Mass Spectrometry (LA-MC-ICPMS) has evolved rapidly over the past ~20 years to become a nearly indispensable method for the investigation of sedimentary rocks and their source regions (Gehrels, 2011). Zircon is an important mineral for U–Pb geochronology because of its durability and widespread occurrence in common igneous, metamorphic and sedimentary rocks of the continental crust. Furthermore, additional information relating to the source of zircon crystals is recorded by hafnium isotopic compositions. Recent advances have improved zircon U–Pb geochronology so that crystallization ages from igneous rocks can be determined with a typical uncertainty of ~1.5% (2σ) and Hf isotope compositions can be determined to within 1–2 epsilon units (2σ) (Cecil et al., 2011).

Detrital zircon provenance studies are among the most important applications of U–Pb geochronology with about 40,000 analyses of detrital zircon grains conducted each year on samples from many parts of the globe (Gehrels et al., 2008). LA-MC-ICPMS allows for efficient data acquisition and the generation of large data sets. The number of zircon ages acquired from a sample is a function of the complexity of the age distribution and the questions being asked (Fedo et al., 2003; Andersen, 2005). Typically, ~100 grains per sample will be analyzed in sedimentary provenance studies in an effort to identify at least the main age groups present (Gehrels et al., 2008). Data are commonly presented as relative age probability or age–distribution diagrams. Major age peaks and their proportions indicate the different magmatic contributions to the sample, characterizing the sample and helping to trace the provenance and dispersal patterns of the zircon grains. Large reference databases have been established for some regions, including sandstones exposed in the Grand Canyon and Colorado Plateau of Arizona (e.g., Timmons et al., 2005; Dickinson and Gehrels, 2003, 2008a,b; 2009a,b) and northwestern North America (e.g., Gehrels et al., 1995, 2009). A database of detrital zircon ages is available from http://www.geochron.org/detritalsearch.php, which allows for "sourcing" by matching the age spectra of unknowns to the age spectra of sampled rock outcrops.

While it is clear that detrital zircon geochronology is a powerful tool for reconstructing regional geologic histories and for sourcing zircon-containing rocks (e.g., Davis et al., 2010; Dickinson et al., 2009; Doe, 2010), archaeological applications have so far been limited. Most recently, U–Pb ages of detrital zircons in sands used as temper for pottery production in the Solomon Islands were critical for identifying the particular island source of the temper sands, providing more specific data than comparative petrography (Tochilin et al., 2012). The current study explores the potential of U–Pb geochronology as a method for identifying the geological origins and sources of another category of archaeological materials: those made of sedimentary and metasedimentary rock.

2.4. Hf isotope geochemistry

Hf isotope analyses conducted on detrital zircons yield information about the source materials that were melted to create the magma in which the zircon crystals formed. The critical ratio is $^{176}Hf/^{177}Hf$, which changes over time due to the decay of ^{176}Lu to ^{176}Hf (^{177}Hf is non-radiogenic). Measurement of $^{176}Hf/^{177}Hf$ is challenging due to isotopic interferences among ^{176}Yb, ^{176}Lu, and ^{176}Hf, but analysis by LA-MC-ICPMS yields isotopic ratios of appropriate precision and accuracy. The methods utilized in the study have been described by Cecil et al. (2011) and Gehrels and Pecha (2014).

Hf isotopic data are generally presented in terms of epsilon units, which portray deviations of measured values from the Chondritic Uniform Reservoir (CHUR). Epsilon Hf values are plotted against crystallization age because the Hf isotopic composition at the time of crystallization is of most interest. A critical reference on an Epsilon Hf-age plot is the evolution of the depleted mantle (DM), which represents an end-member situation in which a magma was generated entirely from melting of mantle materials. Epsilon Hf values are lowered from the Depleted Mantle array by incorporation of continental crust during magma generation. The degree to which an epsilon Hf value is lower than DM is a function of the age of the crustal material (older is more negative) and the proportion of this material in the final magma. Common terminology is that epsilon Hf values (at the time of crystallization) that are within 5 units of DM are referred to as juvenile (Bahlburg et al., 2011), which indicates that the magma was generated largely from mantle material or crust that was recently extracted from the mantle. Values more than 12 epsilon units below DM are referred to as evolved because the magma must have been generated in large part from older continental crustal materials. Epsilon Hf values between 5 and 12 units below DM are referred to as intermediate.

Table 1
Handstone lithic type frequencies at study sites on the western side of the Peninsular Ranges with non-local appearing quartzarenite cobble handstones.

	Otay Mesa			*Foothills*
	SDI-8654	SDI-11079	SDI-12809	SDI-14283
	$N = 65$	$N = 95$	$N = 25$	$N = 5$
Plutonic rocks:				
Diorite	5	–	–	–
Gabbro	6	–	12	60
Granite	5	1	8	–
Granodiorite	–	–	8	–
Quartz diorite	–	2	–	–
Quartz monzonite	1	–	–	–
Plutonic subtotal	**17**	**3**	**28**	**60**
Metamorphic rocks:				
Quartzite	–	20	8	–
Metamorphic subtotal	–	**20**	**8**	–
Sedimentary rocks:				
Calcium carbonate-cemented sandstone	–	3	–	–
Clayey medium sandstone	–	1	4	–
Quartz-cemented sandstone	8	5	8	–
Breccia angular chert grains, quartz cement	1	–	–	–
Quartz-rich, quartz-cemented sandstone (quartzarenite)	28	5	4	20
Sedimentary subtotal	**37**	**14**	**16**	**20**
Volcanic rocks:				
Andesite	1	3	–	–
Andesite breccia	–	2	–	–
Basalt	–	1	–	–
Breccia	1	–	–	–
Dacite	8	20	12	–
Dacite breccia	–	5	–	–
Latite	–	1	8	–
Pyroclastic	–	2	–	–
Quartz latite	8	12	8	–
Rhyodacite	17	3	–	–
Rhyolite	11	12	16	20
Trachyandesite	–	2	–	–
Trachyte	–	–	4	–
Volcanic subtotal	**46**	**63**	**48**	**20**
Total	100	100	100	100

Of critical importance during Hf studies is the analysis of zircon grains of known isotopic composition to verify that all measurements and corrections are robust. For this study, zircon standards FC1, 91500, Plesovice, R33, Temora, and Mud Tank were analyzed (DR Table Hf), and all yield weighted mean values that are within 2 epsilon units of the reported values. This external precision is consistent with the average uncertainty of all unknown analyses of 2.5 epsilon units (2σ). The current study is the first application of Hf isotope geochemistry to archaeological material.

Also critical for provenance analysis based on Hf isotopic data is the availability of similar data sets from potential source regions. In this case, relevant Hf isotope data are available from sandstones of Neoproterozoic and Cambrian age in southeastern California and northwestern Sonora (Wooden et al., 2013; Gehrels and Pecha, 2014).

3. Material and methods

3.1. Geological sampling locations and procedures

Although any location within the social interaction sphere of the Archaic sites as indicated by associated archaeological materials is a potential candidate for investigation, in this study we focused survey and sampling on possible sources closest to the sites. These are pre-Cretaceous metasedimentary rock on the eastern side of the Peninsular Ranges that appear similar to the quartzarenite cobble handstones and Neogene (23–2.5 Ma) conglomerates and cobble terraces near the archaeological sites. Sampling locations included:

1. Quartz-rich metasedimentary strata from the eastern Peninsular Ranges near the town of Borrego Springs and at the foot of the Santa Rosa Mountains near the Salton Sea.
2. Indian Gorge, including north and south forks of Indian Valley in the vicinity of CA-SDI-949 and -967;
3. Carrizo Creek and Sweeney Pass cobble-rich river terraces south of Indian Gorge (metasedimentary rocks of the Jacumba and Coyote Mountains; cobbles in the Tertiary [65–2.6 Ma] Canebrake Conglomerate, Fig. 5);
4. Miocene (23–5.3 Ma) conglomerate of the Table Mountain Gravels at Jacumba;
5. Otay Mesa near the Cactus Street site (CA-SDI-11424), the Remington Hills site (CA-SDI-11079), and the Kuebler Ranch site (CA-SDI-8654). Although much of the area in the vicinity of these archaeological sites has been disturbed by development, remnants of cobble-conglomerate formations could be identified in some places (Fig. 5).

A total of 52 geological samples were collected in the field based on hand specimen visual similarity to the quartzarenite handstones. Multiple samples were collected from each location to represent local variability. Sampling in the field and mineral separation procedures followed guidelines established by the Arizona LaserChron Center to minimize the possibility of contamination.

3.2. Petrographic thin section study

A petrographic thin section study was conducted of selected quartzarenite handstones ($n = 7$) and a subset of the geological samples ($n = 10$). Geological samples selected for thin section study included the metasedimentary basement samples (QSR86 and QS22) as well as cobbles that were most similar in appearance to the quartzarenite handstones.

3.3. U–Pb detrital zircon provenance analysis

Based on the thin section analysis, two quartzarenite handstones and four geological samples were selected for U–Pb geochronology at the Arizona LaserChron Center. Detrital zircons from quartz-rich sandstone previously collected from the Rancho San Marcos Formation in northwestern Baja California (Lothringer, 1983) were also analyzed due to compositional similarity with the quartzarenite handstones. Sample preparation and analysis included the following steps:

1. Zircon grains were extracted from samples using conventional methods of crushing and pulverizing, followed by separation with a Wilfley or GEmini table, heavy liquid separation using diiodomethane, and a barrier-field (Franz LB-1) magnetic separator.
2. Grains were mounted in epoxy along with a Sri Lanka zircon standard of known age, sanded and polished.
3. Ages of zircon grains were determined by U–Pb geochronology using LA-MC-ICPMS (Gehrels et al., 2006, 2008). Analysis involved ablation of approximately 100 zircon grains from each sample alternating with analyses of the Sri Lanka standard.
4. The analytical data were reduced using a LaserChron Center Excel macro and relative age–probability plots generated using Isoplot (Ludwig, 2008). Age spectra were compared using the K–S statistical test (Press et al., 1986).

Fig. 4. Selected handstones from CA-SDI-8654. Left: Rhyolite mano (Cat#2185) shows evidence of pecking to roughen the working surface prior to use. Note the distinct margin between the prepared surface and the naturally smooth edges. Right: Quartzarenite mano (Cat#1465) has a naturally rough surface. Both are made from discoidal cobbles that have been rounded and shaped by waves prior to use.

3.4. Hf isotope detrital zircon provenance analysis

Zircon crystals from the two quartzarenite handstone samples analyzed by U–Pb geochronology were also analyzed for Hf isotopes at the Arizona LaserChron Center utilizing techniques described by Cecil et al. (2011) and Gehrels and Pecha (2014). Reliable Hf isotope information was acquired from 53 grains from Sample 1062 and from 54 grains from Sample 1934. These same grains had been previously analyzed for U–Pb age, and the Hf ablation pit was located on top of the U–Pb ablation pit. This is done to raise the likelihood that the Hf data are acquired from the same domain as the U–Pb age. Grains were selected to represent

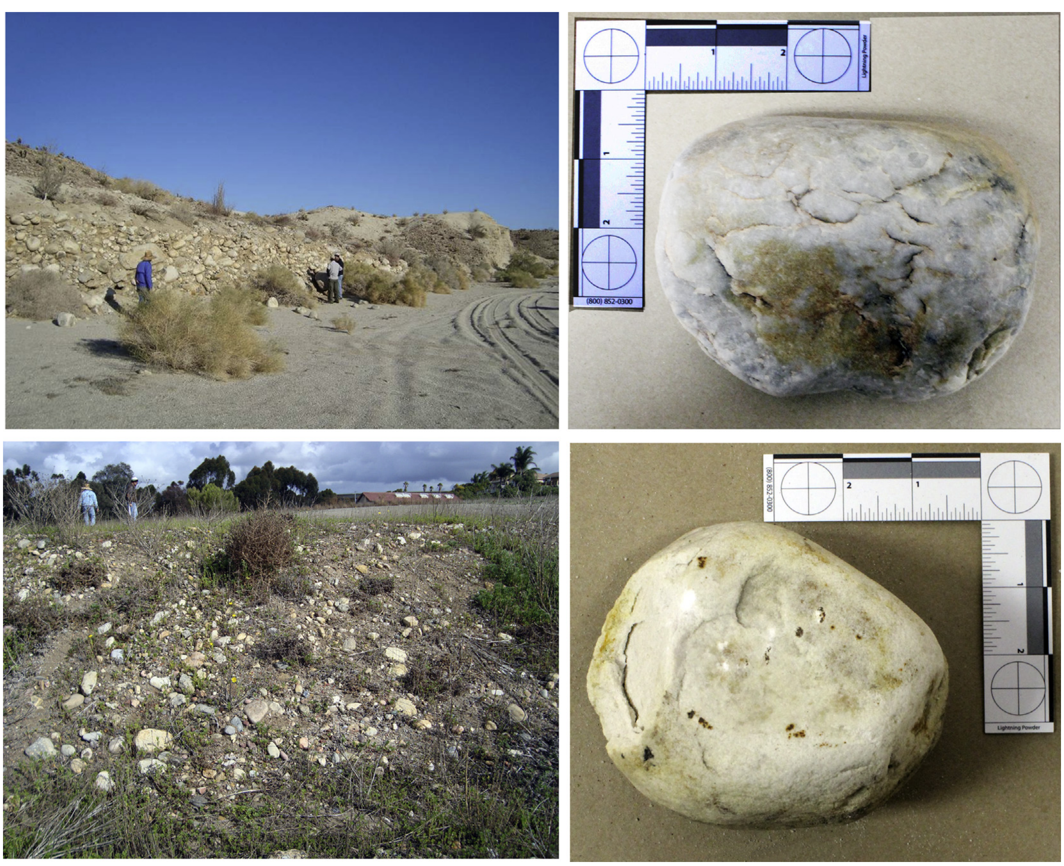

Fig. 5. Top: Carrizo Creek cobble terrace, approximately 4–7 km south/southeast of Indian Gorge sites CA-SDI-949 and CA-SDI-967; cobble Sample 13. Bottom: Otay Mesa cobble field, 200 km southwest of the Remington Hills site CA-SDI-11079; cobble Sample 44.

Table 2
Thin section analysis of sedimentary cobbles and cobble handstones.

Sample name	Description	Location/archaeological context	Framework	Matrix	Cement	Porosity	Quartz	Feldspar	Other lithics	Grain size/Sorting/Rounding	Maturity	Sedimentary structures
13	Cobble	Terrace above Carrizo Creek, near Sweeney Pass (Jacumba Mtns)	90	0	10 Quartz overgrowths	0	100	0	Trace chert	Lower-medium/moderately-well/subrounded to rounded	Super-mature	
44	Cobble	SW of Remington Hills site CA-SDi-11079	85	0	15 Quartz overgrowths	0	98	Trace	Trace chert	Medium/well/subrounded to rounded	Super-mature	
1062	Flat bifacial mano	CA-SDi-8654 Block A, Unit 10 Level 60–70 cm	90	0	10 Quartz overgrowths	0	99	0	1 Crushed polycrystalline quartz, quartzite; trace others	Coarse/moderate/rounded	Super-mature	
1934	Flat bifacial mano	CA-SDi-8654 Block A, Unit 46 Level 70–80 cm	90	0	10 Quartz overgrowths	0	100	0	0	Medium/Moderate-well/rounded	Super-mature	Elongate grain orientation
320	Flat bifacial mano	CA-SDi-14283 Unit 1 Level 40–50 cm	87	0	10	3	100	0	0	Medium/moderate/subrounded	Super-mature	
90	Flat bifacial mano	CA-SDi-949 Surface	82	0	18 Quartz 6%; Calcite 12%	0	100	0	Trace chert	Medium/moderate/rounded	Super-mature	
114	Flat bifacial mano	CA-SDi-967 Surface	90	0	10 Quartz overgrowths	0	100	0	Trace chert	Medium/moderate/rounded	Super-mature	
324	Flat bifacial mano	Duvall surface collection from near the Borrego spring	90	0	10 Quartz	0	100	0	Trace chert	Medium/moderate/rounded	Super-mature	Laminated; finer and coarser laminae
352	Flat bifacial mano	Duvall surface collection from near the Borrego spring	90	0	10 Quartz overgrowths	0	100	0	Trace chert	Medium/moderate/rounded	Super-mature	

each of the main age groups present in each sample, and CL images were further used to identify grains that lacked internal zonation, inclusions, or fractures.

4. Results and discussion

4.1. Petrography

4.1.1. Artifact thin sections

The handstones from CA-SDI-8654 at Otay Mesa (Table 2, Samples 1062 and 1934; Fig. 6C, F) are mineralogically and texturally mature quartzose sandstones made up of well-rounded and well-sorted monocrystalline quartz grains cemented by quartz (Fig. 6C, F). These rocks are supermature quartzarenite sandstones following the terminology of Folk (1968). The mineral composition of the framework grains is visually estimated to be $Q_{100}F_0L_0$ (Quartz, Feldspar, Lithic fragments in percentages). A few grains of siliceous chert (lithic fragments) are present.

Pure quartz sands of this type result from extensive chemical and physical weathering usually emanating from multiple recycling of quartz from early sedimentary source rocks. Quartzarenite sandstone is widespread within late Precambrian (or Neoproterozoic, prior to 541 Ma) and early Paleozoic (541–252 Ma) sediment of the Cordilleran miogeocline – the ancient passive rift margin of southwest North America (Dickinson, 2004). The distal edge of the Cordilleran miogeocline was intruded by the eastern Peninsular Ranges batholith (Gastil, 1993). Here the miogeoclinal rocks are exposed in a belt extending from the San Jacinto Mountains in the north, southwards through the Santa Rosa Mountains/Borrego Springs area and into Baja California.

The handstones from CA-SDI-14283 in the western foothills of the Peninsular Ranges (Table 2, Sample 320; Fig. 6G) and from sites east of the Peninsular Ranges (Table 2, Samples 90, 114, 324, and 352; Fig. 6A, B, D, E) are very similar to the CA-SDI-8654 handstones in terms of their texture and mineralogy: clay matrix-free, silica-cemented, quartz-rich sandstone with quartz percentages near 100% including a few chert grains. Quartz grains are moderately to moderately-well sorted, sub-rounded to rounded, medium-grained sandstone.

4.1.2. Geological sample thin sections

The cobbles collected from Neogene conglomerate at Otay Mesa (Sample 44) and from Holocene river-terrace gravels in the desert (Sample 13) are both similar to the quartzarenite handstones; i.e., they consist of sorted, rounded, medium sand-size grains of quartz cemented by quartz (Table 2; Fig. 7D, E). Minor post-depositional recrystallization is reflected by some quartz grains with deformed outer surfaces showing long- or concavo-convex contacts. Sedimentary textures are still well-preserved.

Prebatholithic miogeoclinal sandstone from the eastern Peninsular Ranges near Borrego Springs and the foot of the Santa Rosa Mountains were also sampled (Samples QS22 and QSR86), as previously mentioned in Section 3.1, to evaluate their potential as a source of the handstone material. The prebatholithic samples have similar bulk compositions but the samples at these localities have undergone extensive metamorphic recrystallization that involved growth of metamorphic garnet and mica and the formation of a prominent metamorphic foliation (Fig. 7A, B). These metamorphic quartzites are distinctly different from the rock used for grinding tools. Based on this textural comparison, it is possible to conclude that the geologic origins of the cobbles used for the quartzarenite handstones must lie elsewhere, either north or south along strike form locations, or farther to the east. The Rancho San Marcos quartzarenite locality in northern Baja does preserve the original sedimentary texture (Lothringer, 1993) (Fig. 7C) and, for this reason,

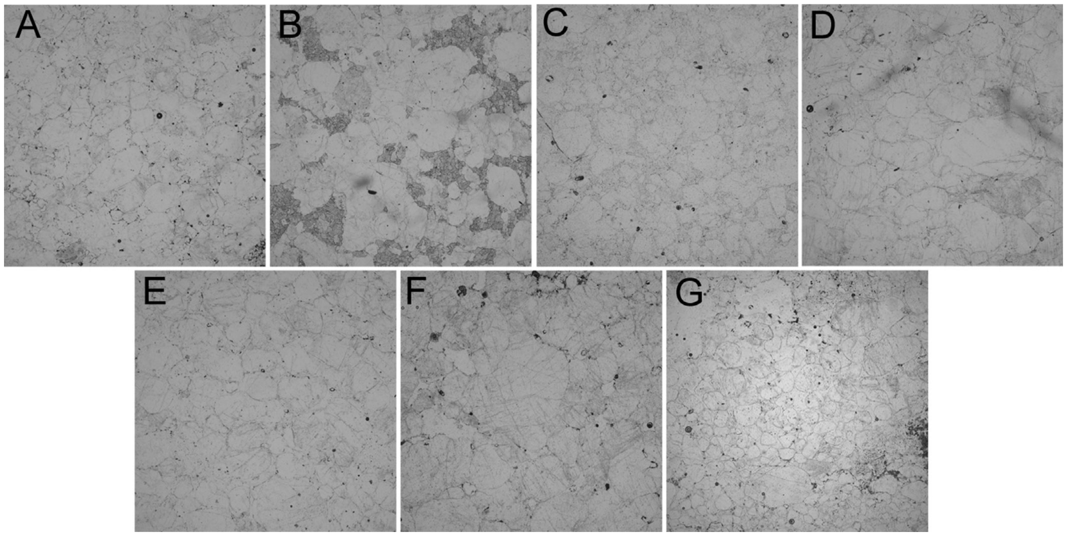

Fig. 6. Thin section photomicrographs of selected non-local appearing sandstone cobble handstones found at San Diego County sites. Plane polarized light,×40 magnification, field of view = 5.5 mm. A, Duvall collection #625-60-324; B, CA-SDI-949 Cat#90; C, CA-SDI-8654 Cat#1934; D, Duvall collection #625-60-352; E, CA-SDI-967 Cat#114; F, CA-SDI-8654 Cat# 1062; G, SDI-14283 Cat#320. Note the similarity of the quartz sand grains surrounded by quartz cement. Rock B has 6% quartz overgrowth cement on sand grains plus 12% calcite cement.

has potential based on texture alone to be a source of the handstone material.

4.2. U–Pb geochronology results

Detrital zircon results from this study are displayed as relative probability age spectra in Fig. 8 (see Table 3 for sample descriptions and Fig. 9 for locations). A compilation of zircon data from NeoProterozoic-Cambrian miogeocline (passive margin) quartzarenite sandstone is included in the figure for comparison. Relative age probability plots combine the individual U–Pb ages and their uncertainties into a single compound curve. The areas beneath the curves are normalized to equal areas, which aids visual comparison of the different age spectra. Inspection of the age distribution curves in Fig. 8 reveals close similarities and some differences between the CA-SDI-8654 quartzarenite handstones and potential source rocks.

All of the samples, including the handstones, show broadly similar Neoproterozoic-Cambrian- detrital zircon age distributions. They all share in common a southwest Laurentia signature with dominant peaks representing the Mojave province (~1.6–1.8 Ga, 2.0–2.3 Ga), Yavapai-Mazatzal (mainly ~1.6–1.8 Ga), Mesoproterozoic (~1.34–1.48 Ga), and the Grenville province (~1.0–1.3 Ga). The results show that the CA-SDI-8654 handstones, as well as Otay Mesa cobble 44 and Carrizo Creek cobble 13 were derived from a NeoProterozoic-Cambrian miogeoclinal source. Small components of Cretaceous zircon in the Anza Borrego (QS22) and Santa Rosa Mountains (QSR86) quartzite samples likely reflect either Cretaceous metamorphic zircon associated with high grade

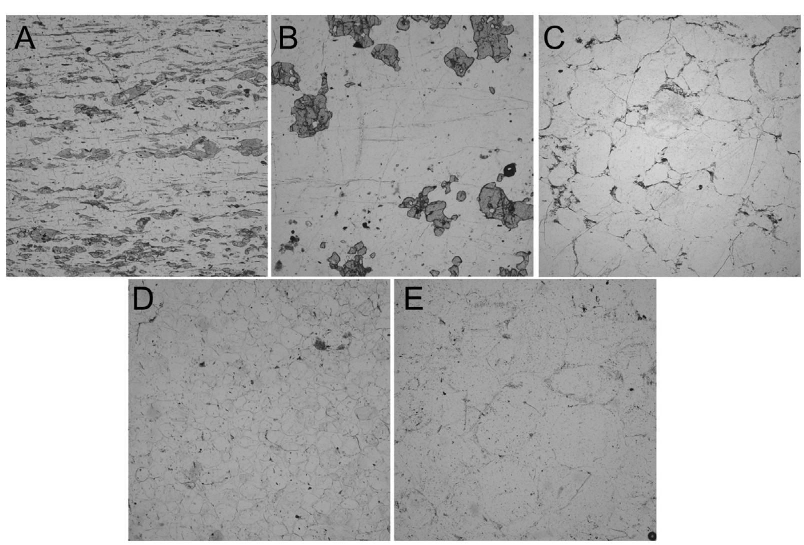

Fig. 7. Thin section photomicrographs of geological samples selected for U–Pb geochronology. Plane polarized light,×40 magnification, field of view = 5.5 mm. A, quartzite outcrop Sample QS22; B, quartzite outcrop Sample QSR86; C, olistolith Sample Rancho San Marcos; D, cobble Sample 44; E, cobble Sample 13. These five samples have similar but not identical detrital zircon age spectra. A and B are no longer sedimentary rocks – they have been metamorphosed. A shows pronounced layering and growth of oriented micas. B shows even higher-grade metamorphism with growth of new minerals. C, D and E are sandstones – quartzarenites very similar to those in Fig. 2 and 6. Note the quartz sand grains, quartz cement, medium grain-size sand, well- to moderately-well sorting, and rounding of grains.

metamorphic recrystallization or veining of samples by Cretaceous batholith rocks. The one Cretaceous zircon grain in handstone 1062 and two Cretaceous zircon grains in the Otay Mesa cobble 44 are likely contaminating Cretaceous zircons that adhered to the outer surface of the samples.

The age spectra from individual samples can be compared mathematically to one another by application of the Kolmogorov-Smirnoff (K–S) statistic (Press et al., 1986). The K–S statistic calculates a *P*-value. If P is > 0.05 there is a >95% confidence that two samples are not statistically different. It does not, however, establish that two detrital zircon populations actually had the same source. Also, even if two samples contain completely overlapping sets of ages, the ages must occur in nearly the same proportions in order for the samples to "pass" the K–S test. The K–S test *P*-values for samples in Fig. 8 are presented in Table 4.

The K–S test reveals that the two CA-SDI-8654 quartzarenite handstones and Otay Mesa cobble 44 have statistically indistinguishable age spectra. These samples also have age spectra that are indistinguishable from QS22, but the latter sample is a metamorphic quartzite with completely different texture. The Rancho San Marcos olistolith quartzarenite sample in contrast has a

Table 3
Zircon U–Pb sample descriptions.

Sample	Latitude	Longitude	Locality	Rock
1062	32.5809	−116.9162	Otay Mesa	Quartzarenite handstone
1934	32.5809	−116.9162	Otay Mesa	Quartzarenite handstone
RSM2	32.1695	−116.4355	Rancho San Marcos	Quartzarenite olistolith
QSR86	33.4058	−116.0587	Anza Borrego - Santa Rosa	Quartzite outcrop
QS22	33.2374	−116.4063	Anza Borrego	Quartzite outcrop
44	32.5647	−117.0402	Otay Mesa Remington Hills	Quartzarenite cobble
13	32.8441	−116.2062	Carrizo Creek	Quartzarenite cobble

WGS84 datum

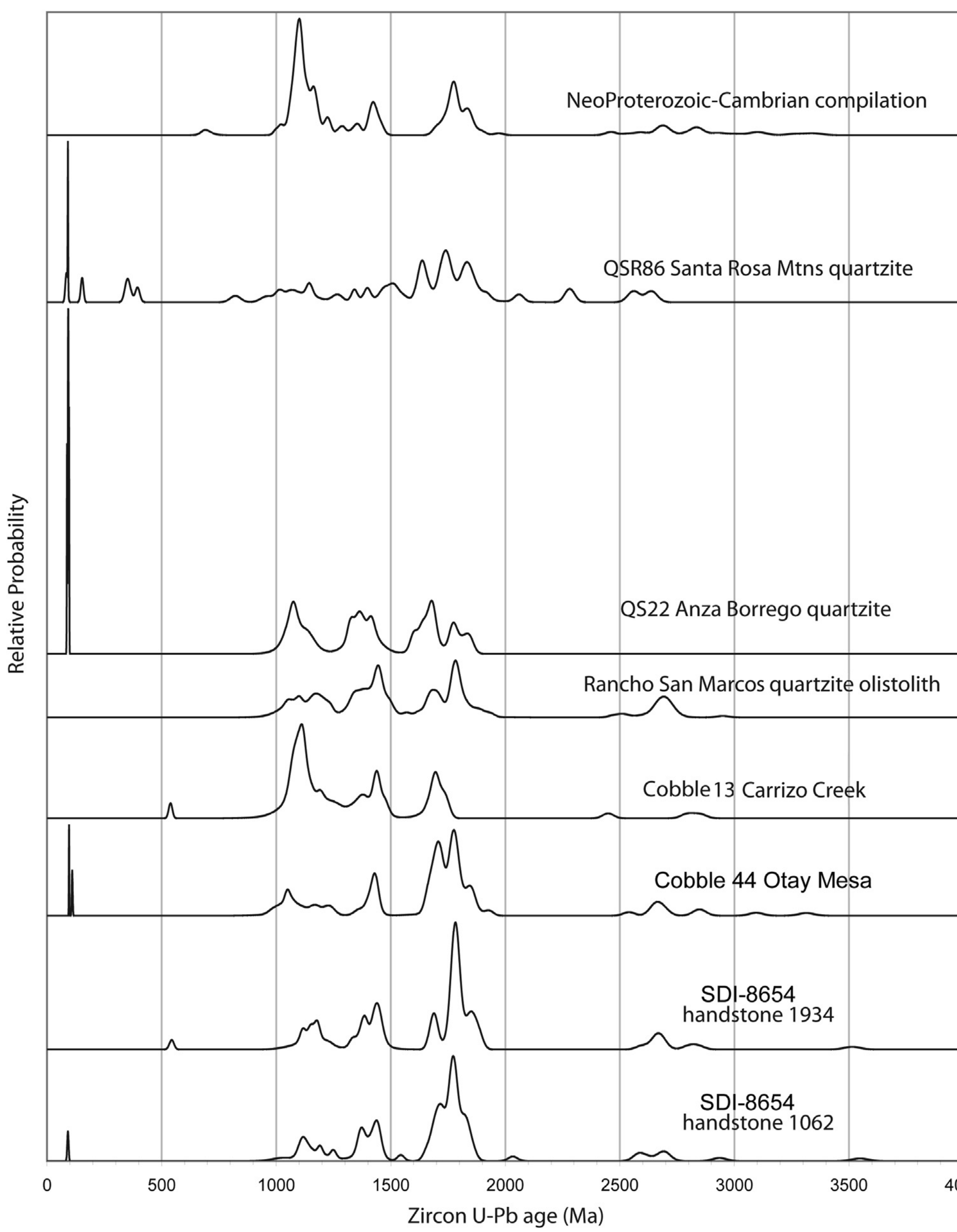

Fig. 8. Relative age probability plot of detrital zircon U–Pb ages for quartzarenite handstones compared to potential sources. NeoProterozoic-Cambrian compilation from Stewart et al. (2001).

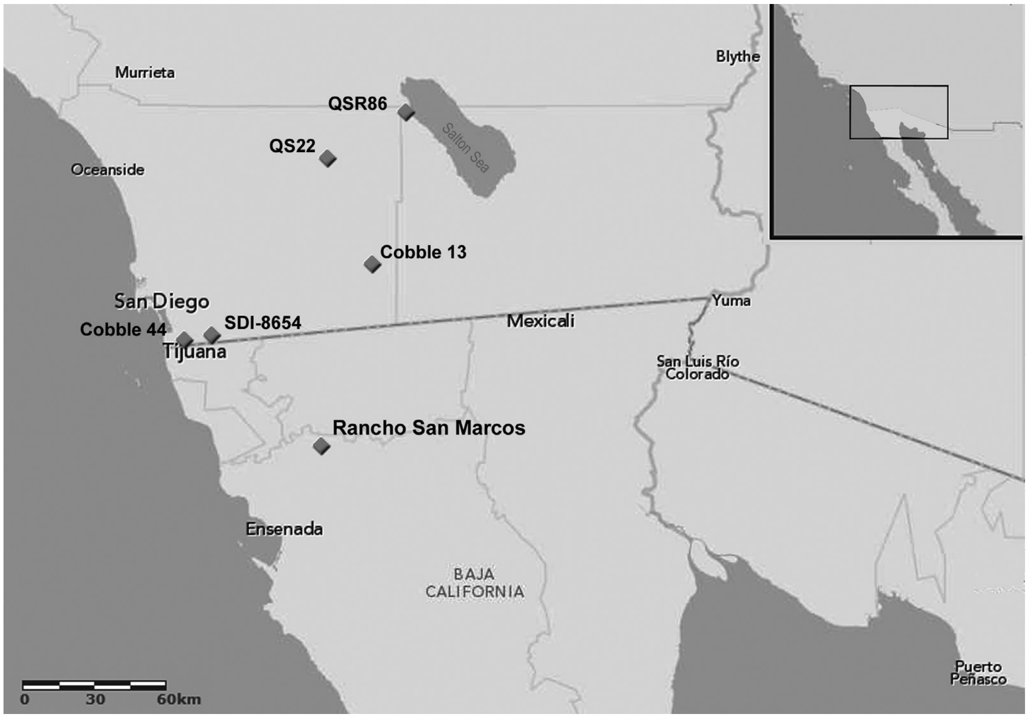

Fig. 9. Map showing locations of samples analyzed by U–Pb geochronology and Hf isotope geochemistry.

similar sandstone texture to the CA-SDI-8654 quartzarenite handstones but fails the K–S test with *P*-values <0.05 in both cases. The Carrizo-Otay cobble comparison also fails the K–S test with a *P*-value of zero. Visual inspection of the age spectra for these samples in Fig. 8 reveals the difference; although they have basically the same distribution of ages, the proportions of the ~1.1 and ~1.7 billion year peaks are substantially different from one another.

Combining the data from petrography and detrital zircon U–Pb dating indicates that the CA-SDI-8654 quartzarenite handstones were likely collected from cobble sources represented by the Otay Mesa Sample 44, approximately 10 km from the site.

4.3. Hf isotope results

The Hf isotope data acquired from the two CA-SDI-8654 quartzarenite handstones are presented in Fig. 10. The upper portion of this diagram shows the epsilon Hf values determined for the tested zircons at the time of crystallization. Also shown for reference are values from Neoproterozoic-Cambrian sandstones of the passive margin sequence of southwestern North America. The lower portion of the diagram represents the U–Pb age distributions of the two handstone samples in comparison with the Neoproterozoic-Cambrian passive margin strata. The significant overlap of both ages and Hf isotope compositions provides strong evidence that the handstones were derived from these passive margin geological assemblages.

4.4. Geological origins of quartzarenite cobbles and cobble handstones in southern San Diego County

The combined data sets from comparative petrography, U–Pb geochronology, and Hf isotope geochemistry confirm the non-local geological origins of the quartzarenite cobbles that were used as handstones by Archaic and Late Prehistoric people in southern San Diego County. The detrital zircon data establish the age of the quartzarenite to be Neoproterozoic to early Paleozoic. Rocks in this age range are quite uncommon in the San Diego region but increase in abundance eastward into Arizona and Sonora, Mexico. Thin section petrographic analyses eliminate the few outcrops of ancient quartzarenites in the San Diego and Imperial counties region as possible sources of the tool material because those rocks are no longer sedimentary rocks; they were severely altered by metamorphism during emplacement of the Cretaceous Peninsular Ranges batholith. Thus the quartzarenite grinding tools recovered from the archaeological sites and the cobble samples collected nearby must have geological origins outside the tested region, most likely towards the east. The Rancho San Marcos quartzarenite olistolith sample, which does retain a sandstone texture, is eliminated as a possible source by U–Pb detrital zircon provenance analysis.

How did these quartzarenite cobbles arrive in the southern part of San Diego County? During Eocene time, the Ballena River flowed from a distant eastern source in modern-day Sonora, Mexico to the

Table 4
P-values from Kolmogorov–Smirnov test of U–Pb detrital zircon age spectra similarity.

	1062	1934	44	13	RSM	QSR86	QS22	Prot-Camb
1062		**0.646**	**0.926**	0.000	0.008	0.000	**0.288**	0.000
1934	**0.646**		**0.603**	0.000	0.020	0.000	**0.219**	0.000
44	**0.926**	**0.603**		0.000	0.002	0.000	**0.211**	0.000
13	0.000	0.000	0.000		0.000	**0.530**	0.000	0.001
RSM	0.008	0.020	0.002	0.000		**0.066**	**0.337**	0.000
QSR86	0.000	0.000	0.000	**0.530**	**0.066**		0.024	**0.071**
QS22	**0.288**	**0.219**	**0.211**	0.000	**0.337**	0.024		0.002
Prot-Camb	0.000	0.000	0.000	0.001	0.000	**0.071**	0.002	

Values in bold indicate passage of K–S test.
For $P > 0.05$ samples are statistically indistinguishable at 95% confidence level.
P-values calculated using error in CDF using Excel macro of Guynn and Gehrels (2010).
Prot-Camb = compilation of data from Stewart et al. (2001).

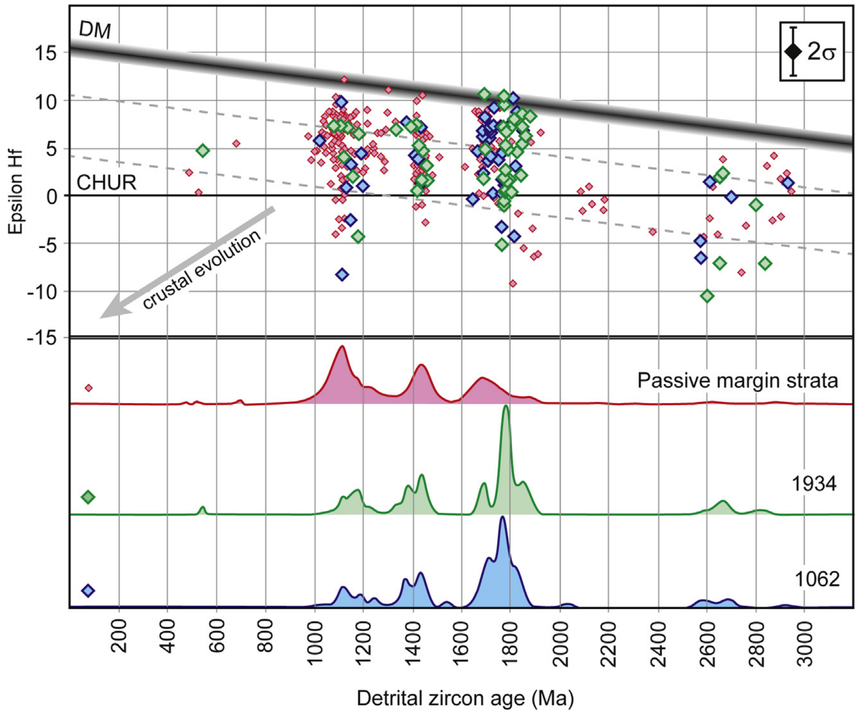

Fig. 10. Upper plot shows epsilon Hf values for detrital zircons from quartzarenite handstone Samples 1062 and 1934 (large squares). Small squares show data from Neoproterozoic-Cambrian strata of the passive margins sequence in southwestern North America (from Wooden et al., 2013; Gehrels and Pecha, 2014). CHUR is from Bouvier et al. (2008). DM is from Vervoort and Blichert-Toft (1999). Gray arrow shows the HF isotopic evolution of typical continental crust assuming present-day $^{176}Lu/^{177}Hf = 0.0093$ (Vervoort and Patchett, 1996; Bahlburg et al., 2011). Gray dashed lines separate fields of juvenile, intermediate, and evolved Hf isotope compositions (from Bahlburg et al., 2011). The average uncertainty of all analyses is shown in the upper right (at 2σ). Lower plot shows U–Pb age distribution of the two quartzarenite handstone samples in comparison with Neoproterozoic-Cambrian passive margin strata (from Wooden et al., 2013; Gehrels and Pecha, 2014).

San Diego region (Fairbanks, 1893; Minch, 1972, 1979; Minch and Abbott, 1973; Abbott and Smith, 1978; Steer and Abbott, 1984). The dominant clast types carried by the river were ultradurable rhyolites and dacites. Referred to as “Poway clasts”, these acted as a ‘ball mill’ to grind and physically disintegrate weaker clasts during flood transport (Abbott and Peterson, 1978). Only the most durable clasts survived the long-distance travel; these may include some heretofore unrecognized quartzarenite clasts.

The long-distance Ballena River was disrupted and cut off by active tectonism in the Sonoran Desert region between 36 and 30 million years ago (mya) (Axen et al., 2000). Tectonic quiescence from ~30 to 15–10 mya left the San Diego area receiving lesser amounts of sediments, and then only from local sources. At 15–10 mya, tectonism increased in the Salton Trough with extension and top-to-the-west normal faulting adding elevation to the Peninsular Ranges (Axen et al., 2000). In late Pliocene time (5.3–2.6 Ma), streams moved large volumes of gravels which were mainly deposited in the Tijuana, Mexico region but also included the southern San Diego/Otay Mesa region. The gravels were largely recycled from the Eocene Poway alluvial fan but also included gravels eroded from the Peninsular Ranges. These gravels were deposited during the Northern Hemisphere ice sheet advances and retreats of the past 2.6 million years, thus they were subjected to varying environmental conditions. During glacial advances corresponding with low sea levels, deposition occurred in river valleys. During glacial retreats with high sea levels, ocean-wave erosion occurred with reshaping of clasts.

The gravels deposited in the San Diego/Tijuana region during late Pliocene and Quaternary (2.6 Ma to present) time have been mapped by Kennedy and Tan (1977) and Scheidemann and Kuper (1979). The Pliocene San Diego Formation contains sandstone bodies with marine fossils that interfinger with conglomerate masses. The gravels are described as pebble, cobble and boulder conglomerate in a coarse-grained sandstone matrix up to 75 m thick. The fluvial conglomerate is poorly sorted and composed of ~75% recycled Poway clasts from the Eocene alluvial fan but also includes granitic and metamorphic rocks from the Peninsular Ranges. Conglomerate bodies reworked by ocean waves in Quaternary time have been mapped as Lindavista Formation by Kennedy and Tan (1977) and discussed by Gastil and Higley (1977). Clast sizes are typically measured along three axes: long (L), intermediate (I), and short (S). Poway rhyolite clasts in the river deposits dominantly have rod shapes with dimensions L > I = S. Reworking of some of these rhyolite clasts by ocean waves modified their shapes to disks with dimensions L > I > S creating sizes and shapes suitable for use as manos. The quartzarenite cobble manos found at the Otay Mesa archaeological sites are similar in shape and size to rhyolite clasts found at the same sites (Fig. 4). This suggests that both rhyolite and quartzarenite clasts were shaped by the same river and ocean geological forces and possibly co-occur in the same gravel deposits.

Did humans play a role in transporting the quartzarenite cobbles, either as tools or lithic raw material, to the archaeological sites where they were recovered? The restricted spatial distribution of the quartzarenite cobbles at southern San Diego County archaeological sites may reflect a natural ribbon-shaped resource of recycled quartzarenite clasts from the Eocene alluvial fan, though the presence of quartzarenite cobbles in these deposits has not previously been documented by geologists. People may have selected the quartzarenite cobbles for tools due to their desirable sizes and disk-like shapes as well as their durable, rough working surfaces as part of an embedded procurement strategy. Petrographic and U–Pb detrital zircon evidence presented here show that Archaic people living at CA-SDI-8654 collected quartzarenite cobbles for handstones about 10 km to the southwest. It is probable that the quartzarenite cobble mano found at CA-SDI-14283 in the foothills zone was human-transported to this location because the Sweetwater River drainage catchment does not include any potential sources for miogeoclinal quartzarenite. This makes it unlikely that people could have collected the clast from the riverbed. The disk-like shape of the CA-SDI-14283 artifact (Fig. 2G) further suggests that the cobble was affected by ocean waves like the cobble handstones from CA-SDI-8654. Thus it may have been human-carried upriver about 35 km from Otay Mesa, perhaps during a seasonal migration. The presence of small numbers of quartzarenite tools at the Indian Gorge sites CA-SDI-949 and CA-SDI-967, where immediately available granitic clasts have relatively poor qualities for grinding tasks, indicates at least short-distance human transport of quartzarenite cobbles, from the Carrizo Creek about 4–7 km to the south/southeast. Alternatively, the Indian Gorge quartzarenite handstones may have been carried farther, about 80 km, from the Otay Mesa region on the western side of the Peninsular Ranges. Patterns in variability of U–Pb age spectra of detrital zircons in the samples tested (Fig. 8, Table 4) show that such long-distance transport could be demonstrated by U–Pb detrital zircon provenance analysis of the handstones from CA-SDI-14283, CA-SDI-949, and CA-SDI-967. This can be asserted because the Carrizo-Otay cobble comparison fails the K–S test, showing detectable variation in naturally occurring quartzarenite cobbles along a west-east transect in southern San Diego County.

4.5. Conclusion

Are thin section petrography, U–Pb geochronology, and Hf isotope geochemistry useful techniques for identifying geological origins and resource distributions of sedimentary cobbles exploited as tool material by prehistoric people? As previously described in Section 1, cobble material used for ground stone tools is most likely to be distributed as a continuous source (e.g., a broad alluvial fan) or a ribbon-shaped source (e.g., a river or stream drainage) (Miksa and Tompkins, 1998). A ribbon-shaped source may be considered a moderately-restricted resource but still amenable to the kind of embedded procurement strategies often practiced by residentially mobile societies (Schneider, 1993). A preferred material, such as particularly well-shaped, durable, or rough-textured cobbles, may be more restricted in its natural distribution, occurring in isolated patches as point sources. Artifacts made from such material may then be traceable to the point source(s), providing evidence of a targeted procurement strategy. Accurate characterization of resource distributions is thus important in the reconstruction of technological choices as well as patterns of social group movement and interaction.

This study suggests that a combined approach utilizing comparative petrography, U–Pb geochronology, and Hf isotope geochemistry yields the most accurate characterization of a sedimentary cobble resource distribution. In this case, U–Pb geochronology and Hf isotope geochemistry were important in verifying the Neoproterozoic/lower Paleozoic origins of the sandstone body from which the cobbles used as handstones were derived. The results show that the cobbles could not have been derived from the regionally widespread San Diego area Mesozoic–Cenozoic sedimentary bedrock. The cobbles also were not derived from Neoproterozoic-Cambrian-early Ordovician detrital metasedimentary formations exposed in the San Diego area; this is attested by the metamorphic-grade textural differences apparent in thin section. Therefore, the cobbles must have geological origins outside the region. Preliminary evidence described above suggests that an ancient paleoflow may have resulted in a moderately-restricted ribbon-shaped resource of quartzarenite cobble tool material that was exploited by Archaic and later inhabitants of the region. Neither comparative petrography nor U–Pb geochronology nor Hf isotope geochemistry alone were sufficient to arrive at this conclusion.

Further, the statistically identical U–Pb age spectra of detrital zircons in the two tested quartzarenite handstones from CA-SDI-8654 at Otay Mesa and the Otay Mesa cobble sample demonstrate the potential of this technique for identifying highly-restricted point sources. Sedimentary and metasedimentary strata can have complex age spectra because they derive from alluvial deposition of sands that contain detrital zircons from multiple source rocks. These age spectra then serve as distinct signals of geological origin more precise than comparative petrography (e.g., Tochilin et al., 2012). The U–Pb age profiles of the two Otay Mesa handstones and the cobble sample collected nearby pass the K–S test, while the Carrizo Creek cobble 13 does not, thus implying the presence of a point source that is identifiable by U–Pb geochronology but not comparative petrography. Analysis of U–Pb ages of detrital zircons in additional handstones, such as those identified at the western foothill site CA-SDI-14283, and the Indian Gorge sites CA-SDI-949 and CA-SDI-967 on the east side of the Peninsular Ranges, may definitively show whether cobble tools from Otay Mesa were carried by people eastward across the mountains and into the desert. Recognizing such instances of human-transported cobble grinding tools in mobile hunter-gatherer archaeological contexts, even if they are rare, can provide important information about social group movements, the kinds of activities engaged in during these movements, and possible interactions with other groups.

Although this study focused on sedimentary cobble grinding tools, it further demonstrates that U–Pb geochronology and Hf isotope geochemistry may be useful sourcing techniques for other kinds of archaeological materials made of sedimentary and metasedimentary rock, depending on the spatial scale of investigation. Detrital zircon age spectra for quartzite outcrops in the eastern Peninsular Ranges near Borrego Springs (Sample QS22) and at the foot of the Santa Rosa Mountains (QSR86) are statistically distinct (Table 4). In a previous study, two quartzite samples from the Coyote Mountains (Fig. 1) were also found to have distinguishable U–Pb age spectra (Cosentino, 2009). This indicates that the complexity of U–Pb age spectra of detrital zircons has the potential to lend greater precision to the identification of sedimentary and metasedimentary quarry locations within regions, and the matching of quarried products to their source to determine distribution patterns (e.g., Antelope Hill, Schneider, 1993). Archaeological materials that are amenable to characterization and therefore sourcing by comparison of U–Pb age spectra and Hf isotope compositions of detrital zircons include sandstone vessels, metates or grinding slabs, and mortars, as well as sandstone building materials. The common occurrence of such materials in many parts of the world and in many chrono-cultural contexts points to the broad applicability of U–Pb geochronology and Hf isotope geochemistry in archaeological research.

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