Extremely High Polish on the Rocks of Uplifted Sea Stacks along the North Coast of Sonoma County, California, USA

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Abstract
Remnant sea stacks on an uplifted, Pleistocene, wave cut terrace, on the north coast of Sonoma County, north of San Francisco California, have localized mirror-like polish on their surfaces which extends over areas up to 4 meters high. Scanning electron microscope (SEM) and atomic force microscope (AFM) images of this polish, and comparison with wave polish from the cliffs below the terrace, and known elephant rubs, indicate that the polished surface was most probably made by large Pleistocene mammals rubbing themselves against the rock. The AFM images demonstrate the extreme planar nature of the mirror surfaces.

Key words

Introduction
The low cliffs of the coast of Sonoma County, California, are composed almost entirely of metamorphic rocks of the Mesozoic Franciscan Complex. South of the Russian River the cliffs are topped by a single very distinct uplifted wave cut terrace from which rise a few remnant sea stacks (Figure 1).
Figure 1. Uplifted remnant sea stacks along the coast north of San Francisco, California. Stack 1 is the nearest large sea stack. Stack 2 is in the middle ground. Stack 3 can not be seen behind Stack 2. Stack 4 is on the horizon on the left.

This terrace is believed to be Pleistocene. In several places, the rocks are polished to a surprising bright shine from below the present ground surface to a height of as much as 4 meters. Examination of these polished surfaces by light microscope, scanning electron microscope, and atomic force microscope reveals the parallel micro-scratches characteristic of polish by the rubbing of animals. Only a mammoth or mastodon or the long necked Rancholabrean camel would have been tall enough to polish these rocks (Parkman, 2002). The polished rocks have similar microscopic features to polish on rubbing posts made by modern elephants. The surface
characteristics differ markedly from the polish formed by waves or wind, or any other likely process.

Setting

The Franciscan Complex rock units, which outcrop along the Sonoma County Coast, 75 km north of San Francisco (figure 2), are largely metamorphic, including blueschist, serpentine, and jasperoid chert. Other common lithologies include sedimentary rocks, mostly greywacke and highly deformed shale. The complex is extremely heterogeneous, and varies greatly over short distances.

The Sonoma Coast is characterized by a wide wave cut terrace which has been uplifted about 5 meters. It is likely that this terrace was formed by the last major high stand of the sea during stage 5e about 122,000 years ago (Shackleton and Opdyke, 1973; Borkhardt, 1993). This is consistent with specific age determinations for what appears to be the same uplifted terraces at
Point Reyes peninsula, 20 kilometers south of the site (Souourner and Grove, 1997). That terrace was uplifted and partially covered by the unconsolidated fluvial Millerton formation, which is about 130,000 ± 12,000 years old, although Sloan (2001) has hypothesized that the terraces with the highly polished sea stacks are only about forty thousand years old.

Between Bodega Bay and Jenner, a distance of 12 km, there are roughly 164 large, active sea stacks in the waters directly off shore, but only 5 uplifted sea stacks. North of Jenner and south of Bodega Bay there are no uplifted sea stacks for many kilometers. The polished uplifted sea stacks are mostly blueschist and chert. They have vertical and overhanging sides and have few signs of weathering or spalling. The top surface of the soils at the base of the polished uplifted sea stacks is roughly horizontal. Excavations around the base of one of these rocks have shown that it is polished about two meters below the present soil surface. This shows that the topsoil around the polished uplifted sea stacks was deposited after the polishing episode. This soil is Rohnerville loam, a clayey, mixed isomesic, Typic Tropohumult. It has moderately thick clay films (Miller, 1972). It is likely that an ultisol such as this is several tens of thousands of years old. The uplifted sea stacks, which are not polished, have sides of less than 70 degrees, and have an apron of weathered and spalled material around the bases. The soil on this apron is a very young, completely undeveloped lithic entisol.

The most prominent remnant sea stacks are all west of California State Highway 1 at Sonoma Coast State Beach (figure 3).
Figure 3. Location of the four highly polished stacks with respect to the Russian River and the Coast.

There are three main stacks. Stack 1 is a 20 meter tall stack of glaucophane blueschist, which has very few joints (N 38° 25.772', W 123° 06.940'). The uplifted sea stack is fractured, with several distinct stacks rising up from the terrace. Most of the sides are near vertical and some are
overhanging. It is a popular practice site for local rock climbers who call it “Sunset Rocks”. There are numerous large, highly polished surfaces on these stacks, some of which reach up nearly 4 meters. Stack 2 is 32 meters tall, and is composed of actinolite schist, and other, more friable mica schist. It is 400 meters south of stack 1. There is less polish on this stack. The polish extends up about 2.5 meters. Stack 3 is a glaucohpane blueschist boulder approximately 40 meters southwest of stack 2. The boulder is 10 meters in diameter and 3 meters high. The leeward side is polished to a height of about 2.5 meters.

2 kilometers south of Sunset Rocks is a small uplifted sea stack (stack 4 at N 38° 25.639’, W 123° 06.750’) of metamorphosed jasperoid chert which is polished in places to a brilliant shine. It is 2 meters high and 4 meters in diameter. This rock is not characteristic of the common local radiolarian “ribbon” chert. It has been isoclinally folded and fractured. Some of the fractures have been filled with well crystallized quartz veins which are also highly polished.

The lee sides of the stacks are generally more polished than the windward sides. The lower two meters are generally more polished than higher up on the rocks, and the corners and edges where two or three faces meet are often more polished that the flat surfaces between. The sharp apexes, below 3 meters high, of many of the rocks, are the most highly polished corners of all.

The active sea cliffs below the uplifted wave cut bench are fairly well polished. The pebbles on the beach and in the nearby Russian River are also polished, but none of these water polished surfaces are as brightly polished as the uplifted sea stacks. Many of the latter are mirror perfect, and reflect identifiable images. The sea and river scour polish never does that. The sea scour also only extends a meter or so up the sea cliffs.

Microscopy
Figure 4. SEM image of faint parallel scratches on the highly polished rock magnified about 300 times.

Figure 4 shows a scanning electron micrograph (SEM) of the surface of the actinolite schist from a polished area. It is magnified about 300 times, and shows distinctive long thin parallel, and subparallel groves which resemble artificial scratches which one can make on a rock with a harder object. This is the classic characteristic of animal rubs (Schoewe, 1932, 219). Figure 5 shows a 60 by 60 nanometer (nm, 10^{-9} meter) surface segment from the same sample, but magnified almost 1,300,000 times in the atomic force microscope (AFM).
Figure 5. AFM image of mirror polish shows extremely low microtopography of a few hundred nanometers in an area 60 nanometers square.

The vertical axis is greatly exaggerated; it shows 6600 nm, but the maximum relief in the picture is extremely smooth, with irregularities of a few hundred nm. The surface of unpolished actinolite schist on active sea cliffs below the uplifted terrace has local relief of millimeters or centimeters. This suggests that the polishing has smoothed the surface by four or five orders of magnitude.

Until now, the degree of polishing was usually studied using the reflection of light. This has given engineers a numerical tool, but it is not easy to interpret the meaning of these numbers. There are several substantial critiques of these traditional engineering techniques for quantifying the degree of polish using albido (Manley, 1993; Erdogan 2000, Perry et al., 2001). The AFM offers a significant improvement. It is easily to perform, reproducible, and easily interpreted.

Figure 6 shows the surface of a polished pebble from the active beach at the base of the cliff below the uplifted sea stacks. The surface is marked with circular grooves made as the pebbles, in the swirling waves, rotate and scratch the surface of the sea cliff and associated boulders, during glancing blows.
The surface is also covered with powdery looking, white circular areas from 0.2 to 1.5 microns (200 to 1500 nm) across. These are percussion pits made by direct blows of pebbles on the sea cliff or on other pebbles. The minerals in these pits have been crushed. This is most obvious in the large pit on the upper right side of the image. There is no doubt that these wave polished surfaces are very different from the mirror polish on the uplifted sea stacks.

Figure 7 shows a portion of a SEM image of a surface from the rubbing post from the elephant enclosure at the Johannesburg Zoo, in South Africa.
Figure 7. SEM image of faint parallel scratches on the highly polished wood from the rubbing post in an elephant pen magnified about 60 times.

It was polished by the animals rolling in the mud and then rubbing themselves on the post. The open, irregular grooves which trend toward the upper left side of the image are the wood grain. The parallel, linear, shallow grooves which trend toward the upper right side of the image are scratches caused by particles of sand and silt on the skin of the elephants as they rub themselves on the post. Similar results were found from a sample of the post from the rhinoceros pen.

Discussion

We believe that the most likely cause of the mirror-like polish on the uplifted sea stacks of the Sonoma Coast is animal rubbing. Cows and sheep are still polishing rocks in this region today. However, they are not tall enough to have polished rock surfaces 4 meters high. Furthermore, although not specifically dated, the buried polished surfaces must be much older than the 200 years during which there have been cows and sheep in this region. It is well established that Rancholabrean megafauna lived in this region until about 10,000 years ago.
(Edwards, 1990). The tusk, lower jaw, and tooth of a mammoth (Mammuthus columbi) was found at Bodega Head, within sight and just to the south of the polished uplifted sea stacks (West, James, personal communication, 2001). Other fossils of large mammals found nearby in Sonoma and Marin Counties include remains of other mammoths, mastodons (Mammut americanum), giant ground sloths (Glossotherium harlani), giant camels (Camelops hesternus), and bison (Bison latrifons and Bison antiquus) (Jefferson, 1991, 50; Savage, 1951, 283).

In eastern and southern Africa, rubbing stones are relatively common in the savanna and grassland areas (Ouzman, Sven, personal communication, 2001).

They stand as monuments to ancient itches. Rocks rubbed to a shine by massive rhino rumps. Boulders polished to brightness by itching elephants. Stones worn smooth with the scratching of buffalo and bushpig. Rubbing stones glint in desert and forest, savanna and grassy highland, all over southern Africa (Skead 1976, 21).

Stack 1 in our study area is adjacent to a seep which has probably been active throughout the Pleistocene. The modern Asian elephants (Elephas maximus) and African elephants (Loxodonta africana) especially like to rub on trees and rocks after wallowing in mud (Stewart, 1998, 5). Ectoparasites encased in the drying mud are removed by the rubbing action which benefits the animals. It is possible that the seep was an animal wallow which encouraged the use of the adjacent rocks, and caused their high polish over a matter of perhaps a hundred thousand years.

Long ago, Walter Schoewe listed many hypothetical causes of rock polish: wind blown sand abrasion, wind blown ice abrasion, water wave scouring, river water current scouring, sea water current scouring, glacial ice scouring, frost action, dissolution, chemical precipitation, desert varnish, organic secretions, bioturbation, plant rubbing, animals rubbing, and various human activities (1932, 212). Some of these processes are no longer considered to cause polishing. Dissolution, for example, produces matted and usually pitted surfaces, not polish. Frost action splits rocks and makes them rougher, not smoother. One may add only a few more recently recognized hypothetical processes: gastrolithic polishing (Manley, 1993), landslide scouring, wind blown dust abrasion, rock joint formation, and pyroclastic flow (Grunewald et al. 2000).

Schoewe (ibid.) hypothesized that rock polish could be caused by the waving of trees in the wind. This seems reasonable, given hundreds of thousands of years, but it has never been reported in the literature. We believe it would cause scratches which are concentric, not straight scratches such as we see at this site. Nor would polish be concentrated on stack edges and corners as it often is on the uplifted sea stacks.

The only other common natural polishing process observable along the Sonoma Coast is wave driven scour which clearly causes a very much less polished surface, and is characterized by percussive pitting and circular scratching, which is not found on the highly polished uplifted sea stacks (figure 6).

The Sonoma coast line follows and is caused by the San Andreas fault. There are a few places where movement along small faults have caused small shiny surfaces in the rocks of the cliffs below the uplifted wave cut terrace. Slickensides and other small fault features are not scratches, but complexly structured microgrooves and ridges, entirely distinct from the simple scratches on the mirror polished uplifted sea stacks, none of which have the crescentic markings, steps, fractures, trains of inclined planar structures, trailed material, or asymmetric cavities found on fault surfaces (Doblas, 1998).
There are many landslides along this coast, and landslide sole fractures are, in rare cases, smoothed and even grooved (Fan, 1997), but these would not be vertical and overhanging as is the case of these uplifted sea stacks. Neither faults nor landslides could polish corners.

The joints in the Franciscan rocks which make up the uplifted sea stacks are unusually widely spaced, often three to five meters apart. This is probably one of the main reasons that these rocks became sea stacks while the more highly jointed rocks nearby were weathered and eroded. Many of these joints are smooth, and somewhat shiny. However, they have a local relief of several millimeters, and could not be confused with the mirror-like polished surfaces.

There have never been glaciers in this region. It is possible that wind blown sand or dust have polished surfaces in this region. The polished sea stacks do not resemble the effects of dust polishing, which creates complexly curving lines called flutes (Whitney, 1973, 1979). Windblown sand or ice polishing is never mirror-like, and in the microscope would show the same percussive pits seen in the wave scoured surfaces (figure 6).

It has been suggested, perhaps not seriously, that ancient native peoples polished these rocks by hand. People have polished large stellae in ancient Orkney, Scotland, and in Peru. That cannot be disproved by our results, but this would be a unique activity unknown in the rest of the world. Melting by igneous processes (Murphy, 2000) or forest fires could cause a sort of smoothing which might be confused with polishing, but SEM images show that the mineral grains are intact and were not melted. The development of desert varnish, or organic secretions or chemical precipitation of calcite or silica could smooth a surface, but thin sections show that these processes have not occurred.

Conclusions

Although, at first, it seemed unlikely, we conclude that the highly polished uplifted sea stacks along the Sonoma County coast south of the Russian River and north of Bodega Head were probably caused by the rubbing of large mammals against them during the Pleistocene. The signature in SEM images of these surfaces is extremely similar to SEM images of rubbing posts from elephant and rhinoceros enclosures in a zoo. AMF images of the polished rocks show they are planar on an extremely fine scale. The highly polished uplifted sea stack rocks look very different from wave polished rocks of the same lithology, developing at the base of the cliff below the uplifted sea stacks.

There are only a few cases in the literature of careful studies of rub rocks (Schoewe, 1932; Lang, 1941, 1947; Koby, 1942) and no reports of studies with a SEM or AFM. It appears that these modern instruments provide new powerful tools for characterizing and differentiating polish caused by different natural processes. We believe that AFM images are a significant improvement over reflected light albedo measurements for the characterization of polished surfaces.

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Captions for illustrations Parkman et al.

Figure 1. Uplifted remnant sea stacks along the coast north of San Francisco, California. Stack 1 is the nearest large sea stack. Stack 2 is in the middle ground. Stack 3 can not be seen behind Stack 2. Stack 4 is on the horizon on the left.

Figure 2. The San Francisco Bay region with site located south of the mouth of the Russian River.

Figure 3. Location of the four highly polished stacks with respect to the Russian River and the Coast.

Figure 4. SEM image of faint parallel scratches on the highly polished rock magnified about 300 times.

Figure 5. AFM image of mirror polish shows extremely low microtopography of a few hundred nanometers in an area 60 nanometers square.

Figure 6. SEM image of wave polished rock with impact pits and crescent shaped scratches caused by glancing blows by wave turbulence.

Figure 7. SEM image of faint parallel scratches on the highly polished wood from the rubbing post in an elephant pen magnified about 60 times.