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Mountains Unseen: Developing a Relief Map of the Hawaiian Seafloor

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The Seafloor Map of Hawai'i, *a medium-scale relief map intended for lay audiences, posed production and design challenges typical of ocean-bottom mapping in general. The biggest problem was incomplete bathymetry data marred by artifacts. Fixing these bad data—filling voids and removing background noise—involved techniques similar to those used by cartographers for terrain mapping. Map design posed another challenge: how to depict a region on Earth that humans will never see. The* Seafloor Map of Hawai'i *uses plan oblique relief, which reveals the seafloor features with three-dimensional offset, a technique borrowed from* National Geographic *maps painted by Heinrich Berann and Tibor Tóth. Other challenges included selecting depth tints and relief colors based on the idea of cartographic realism and determining the names of seafloor features, many of which are unofficial and inconsistently identified.*

INTRODUCTION

The volcanic Hawaiian Islands are among Earth's most prominent mountains when measured from their bases on the ocean floor. The summit of Mauna Kea on the island of Hawai'i rises 10,000 meters, 1,100 meters taller than Mount Everest's height above sea level. Its sprawling neighbor, Mauna Loa, ranks as one of the most massive single mountains on Earth (Kaye and Trusdell 2002; Sager et al. 2013). Yet with 60 percent of their total height hidden beneath the Pacific, most people do not comprehend the size of Hawai'i's mountains. This paper discusses the *Seafloor Map of Hawai'i*, a new map that attempts to remedy this misperception. It depicts the Hawaiian Islands in their entirety from seafloor to summit with consistent detail throughout.

The *Seafloor Map of Hawai'i* overcame the challenges of representing seafloor topography derived from digital data on a regional, medium-scale map (1:897,000). General readers who do not use nautical charts or peruse scientific reports on oceanography are the target audience. The aim was to produce a "user-friendly" wall map of the Hawaiian seafloor that is the equivalent of a physical reference map for land. Accomplishing this posed questions: do data manipulation and relief presentation techniques developed for terrestrial mountains also apply to the ocean bottom features? And, do the relief presentation techniques employed for small-scale seafloor maps, such as those found in *National Geographic* atlases, apply to larger-scale maps?

Compared to terrestrial mapping, the cartographic literature provides little information on how to present seafloor relief. For example, Eduard Imhof (1982, 205) enthuses about the potential of seafloor relief depiction:

> ***Newer maps reveal and depict forms of astonishing variety. It would seem to be the natural next step to map submarine relief in three-dimensional shaded form in a similar manner to the land surface.***

Yet, a few sentences later he dismisses the subject, ending the discussion:

> ***Oblique hill shading, if used for underwater relief forms—and, hence, areas which are normally hidden both from light and our view—tends to produce unrealistic effects. In general it is probably more significant to provide good information on the depths of***

> ***the ocean floor than to portray the shapes there upon. (205)***

More recent literature is similarly meager. Although examples of seafloor maps painted by skilled artists are available for reference, information on completely digital production methods is not. For example, former *National Geographic* artist Tibor Tóth offers samples of his beautiful seafloor art on his blog (Tóth 2009). Tóth also describes the "head-scratching situation" of rendering ocean bottom relief from digital data that were "full of serious imperfections." His solution was to finish the work by hand:

> ***It is conceivable that to someone with only computer based cartographic background this might have looked like a hopeless situation. To me this was where the years of conventional relief painting experience kicked into gear. With the help of the amazing pressure sensitive WACOM tablet, and the various tools afforded by Adobe Photoshop (airbrush, smudge/dodge tools, and various filters), I produced a refined intermediate image.***

The problem is that few cartographers have Tóth's artistic ability or the time to devote to illustrating seafloor relief. Futhermore, compared to Tóth's maps of entire oceans, manually producing medium-scale seafloor maps takes considerably more time because of the greater detail. Considering that water covers 71 percent of Earth's surface, and that the body of bathymetry data is slowly growing, a discussion on digital production is overdue. Hawai'i, with its extreme undersea topography, plentiful medium-resolution data, and general interest to readers, offers a useful case study (Figure 1).

Figure 1: *The* Seafloor Map of Hawai'i *measures 87.4 × 64 cm when printed and covers 433,000 square kilometers of area.*

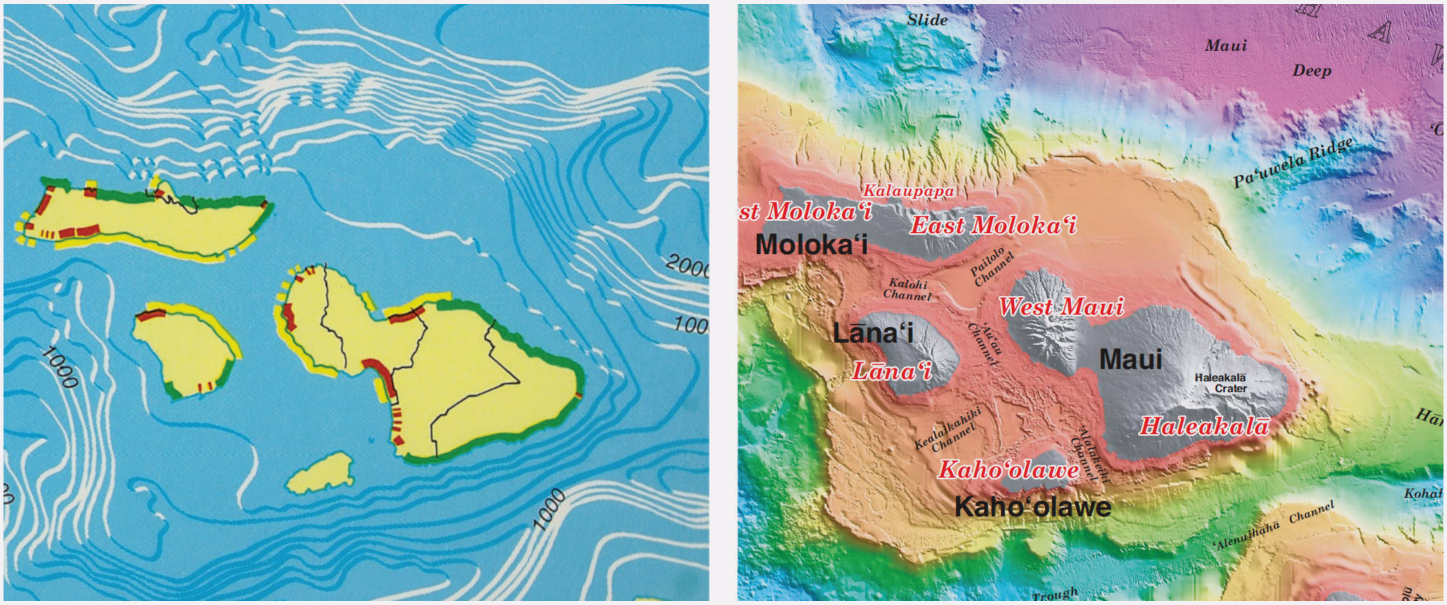

Figure 2: Excerpts of "Bathymetry and Shorelines" from the 1973 Atlas of Hawaii *(left), and 2003* Hawaii's Volcanoes Revealed *(right). The pen and ink 1973 map depicts major features remarkably well compared to its 2003 digital counterpart.*

The desire to depict the ocean bottom on maps of Hawaiʻi is not new. It started with the first published maps of the islands—the coastal charts made by Cook, Kotzebue, Wilkes, and other early explorers—which used depth soundings (Fitzpatrick 1987). More extensive seafloor maps of Hawaiʻi started appearing after the mid-20th century and became more common with the growing availability of bathymetry data from deep waters near the islands. Select examples are the "Bathymetry and Shorelines" map in the *Atlas of Hawaii*[1] (Moberly 1973) that employs the Tanaka method of illuminated isobaths (Tanaka 1950) at 1200-foot (366-meter) intervals (Figure 2, left). Cover art in the second edition of the *Atlas of Hawaii* (1983) features an oblique view from the east of the island chain emerging from the ocean depths. Manually plotted bathymetric profiles are the foundation for this airbrushed art by Everett Wingert. In 1985, Raven Maps published *Hawaii*, a state wall map with shaded relief, bathymetric tints (depth colors), and Raven's signature hypsometric tints on land (Raven Maps & Images 1985). This was followed by *Hawaiʻi* from *National Geographic* (2002), featuring ocean floor relief painted by hand in a style similar to the ocean plates found in their atlases and magazine supplement maps (see Figure 7 for atlas map examples).

The USGS map, *Hawaii's Volcanoes Revealed* (Eakins et al. 2003) achieved a milestone by depicting the Hawaiian seafloor from digitally rendered bathymetric data (Figure 2, right). The map was a little ahead of its time, however. Large areas of the seafloor, including key areas next to the islands, derive from low-resolution data, creating a discordant patchwork that detracts from its appearance. For example, the seafloor adjacent to the southeast coast of Maui is coarser than its surroundings (Figure 2, right). The map's design is also an issue. As is often the case on ocean bottom maps made by scientists, a rainbow color scheme represents bathymetric zones; for example, shallow water is tinted warm red. The light source for the shaded relief originates from the northeast instead of the more conventional northwest, which increases the likelihood of readers perceiving the relief as inverted (Imhof 1982). The overall appearance of *Hawaii's Volcanoes Revealed* is that of a research visualization, not a finished map.

In contrast, the *Seafloor Map of Hawaiʻi* introduced here is a general reference map. Because of its online distribution, designing a map that could attract and hold the attention of a broad range of readers was a key consideration. Even the choice of *Seafloor Map of Hawaiʻi* as the title strives for efficient web search results. Once retrieved, the map's aim is to entice readers to explore, pausing occasionally to read text blurbs that explain Hawaiian seafloor features. The immediate message to readers is that most of Hawaiʻi lies beneath the waves and only with a map can one visualize what is there.

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[1] Several cited publications spell Hawaiʻi without the ʻokina diacritical mark, which is now standard.

Making the *Seafloor Map of Hawai'i* was a long-planned project that depended on the public release of high-resolution bathymetry data for the ocean bottom adjacent to the Hawaiian Islands, which finally occurred in May 2011. The map took five weeks to produce as a part-time project in late 2011 and early 2012. As is typical of digital map production, data and design issues intertwine, although I will treat these issues separately so as to focus the narrative.

BATHYMETRY DATA OVERVIEW

Finding and manipulating data to make the *Seafloor Map of Hawai'i* exemplifies the issues confronting global seafloor mapping as a whole: the ocean is huge, bathymetric surveying is painstakingly slow, and the available data are often poor or incomplete. Because water is a poor conductor of electromagnetic energy, techniques used to gather elevation data on land do not work for the ocean bottom. Even the surface of Mars, millions of kilometers from Earth, has more complete and detailed elevation data than the seafloor only a few kilometers below the ocean surface (Smith 2004).

The only complete global bathymetry dataset currently available derives from satellite altimetry measurements. Based on radar emitted from a satellite, this method detects slight variations in the sea surface height, compensating for waves and tides, to estimate the seafloor topography far below. (Sandwell and Smith 1997). Satellite altimetry data give a coarse snapshot of the seafloor at 2-arc second (~5-kilometer) resolution. It is the basis for the seafloor in the ETOPO2 world elevation dataset (National Geophysical Data Center 2006), and it is used as filler for areas with missing data in higher-resolution datasets, including SRTM30 Plus (Scripps Institute 2013), and GEBCO (2013).

Since the 1970s, multibeam echo-sounders, a type of sonar towed by survey ships, have collected much higher resolution data. The time that a sound wave takes to reach the bottom and return determines the depth, taking into account the ship's constantly changing position on the surface. Continuous multibeam surveys record depths in swaths that become wider and detect more ocean bottom as the water deepens. Multibeam surveys are costly and time-consuming undertakings, however. After decades of effort, surveys are complete for less than 10 percent of the world seafloor, and they often appear randomly located with gaps in the coverage. It is estimated that the remaining 90 percent will take 120 ship-years of survey time to systematically complete using this same technology (Becker et. al. 2009). Broad continental shelves will take the most time to survey because of the relatively narrower multibeam swaths in shallow waters. Despite these difficulties, multibeam bathymetry is now available from the NOAA National Geophysical Data Center for most of the seafloor adjacent to US coasts, including Hawai'i (National Geophysical Data Center 2013a).

HAWAI'I DATA

The *Seafloor Map of Hawai'i* comprises bathymetry data from several sources. The cartographic challenge was patching together these disparate data to create a seafloor map that looked seamless. Map production involved rendering multiple pieces of terrain art from these data sources in Natural Scene Designer Pro and compositing the results in Adobe Photoshop.

The primary dataset was the Main Hawaiian Islands Multibeam Bathymetry Synthesis, version 19 (Hawaii Mapping Research Group 2011), a product of the University of Hawai'i at Mānoa, School of Ocean Earth

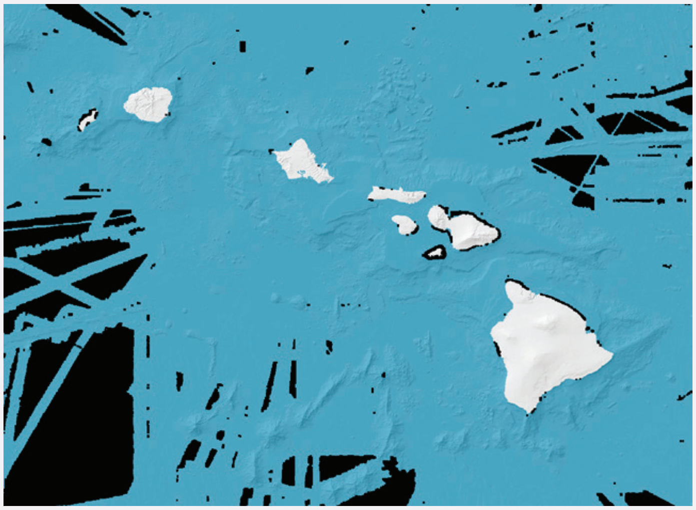


Figure 3: SOEST Main Hawaiian Islands Multibeam Bathymetry Synthesis, version 19, combines multibeam bathymetry (blue) with USGS DEMs on land (light gray). Black indicates gaps in the bathymetry coverage.

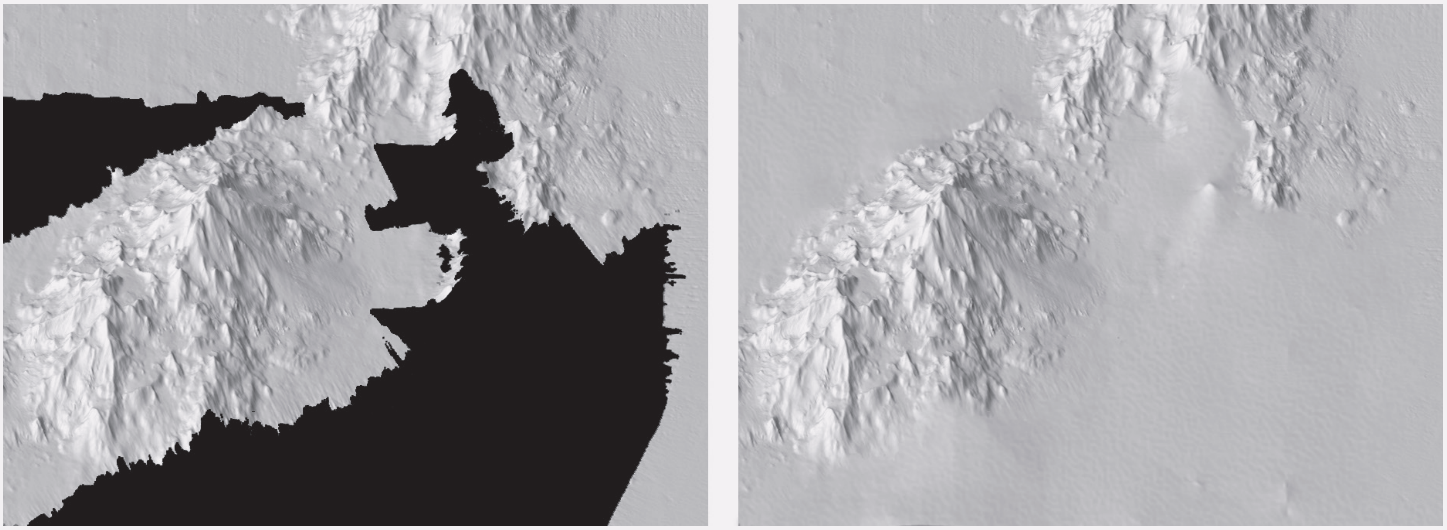


Figure 4: Filling gaps in the SOEST data (black area, left) involved filling in areas with coarser satellite altimetry data from a NOAA DEM (right).

Science and Technology (SOEST). It offers mutibeam bathymetry obtained from many surveys merged with USGS Digital Elevation Model (DEM) coverage on land at a spatial resolution of 1.8 arc seconds (43 meters). The SOEST data are far from perfect, however. Gaps in the data account for 12 percent of the total area of the *Seafloor Map of Hawai'i*. These include narrow strips next to the island shorelines and larger gaps in deep waters on the map periphery (Figure 3, black areas).

DATA MANIPULATION

Filling the gaps in the SOEST data was achieved using methods similar to those used with Shuttle Radar Topography Mission (SRTM) data. This popular elevation dataset of land areas on Earth is also plagued with numerous gaps, vexing cartographers who need to make seamless shaded relief maps. There are two methods of plugging the gaps: by interpolating nearby elevation values or using a second dataset, if one is available (Tait 2010). For the SOEST data, a second DEM developed for the NOAA Tsunami Inundation Program (National Geophysical Data Center 2013b) provided the solution. This DEM, a composite made from multiple sources to provide unbroken seafloor coverage, also had problems. Terrestrial elevation data were absent. More troublesome, the overall quality and resolution of the NOAA DEM were less than that of the SOEST data. For example, shallow areas derived from multibeam data displayed terracing artifacts.

Gaps were filled by rendering both data sources as shaded reliefs and compositing them in Photoshop. A layer mask on the SOEST relief allowed the NOAA relief to show through where there were gaps, thus creating a shaded relief with continuous coverage. Feathering the edges on the layer mask diffused the abrupt seams between the two reliefs. In deep areas, giving the satellite altimetry data a barely perceptible pebble texture further facilitated the blending (Figure 4).

Even where no gaps existed, the SOEST data required considerable manipulation to make it presentable on the *Seafloor Map of Hawai'i*. The main issue was noisy artifacts embedded in the multibeam bathymetry, the result of surveys conducted over several decades merged as a single dataset. The "Frankenstein" stitches between these different data are often more noticeable than the topography itself, especially on abyssal plains (Patterson 2008). Even data deriving from a single multibeam survey often has a noisy texture that disguises subtler seafloor features.

Generalizing these noisy data made it more acceptable for mapping. Reducing the resolution from 1.8 to 6 arc seconds (43 to 144 meters) and applying smoothing to the data in Natural Scene Designer Pro removed most artifacts (Figure 5). Eliminating the larger artifacts required additional manual touchups. In Adobe Photoshop, placing a blurred copy of the relief on a layer below the original and painting repeatedly with a soft brush on a layer mask erased the worst imperfections. Challenges with this technique were distinguishing seafloor features from artifacts and minimizing damage to features when making touchups. When the identity of an artifact was in doubt, the compromise solution was to diminish instead of remove it. A technique similar to that described above was used to make CleanTOPO2, a small-scale bathymetry dataset of Earth (Patterson 2013).

Fortuitous circumstances also minimized the visual impact of coarse-resolution data on the final map, which occurs mostly in the southwest corner of the map. This area is now conveniently covered up by the map legend. Elsewhere on the map, notes inform readers where areas of generalized seafloor data occur.

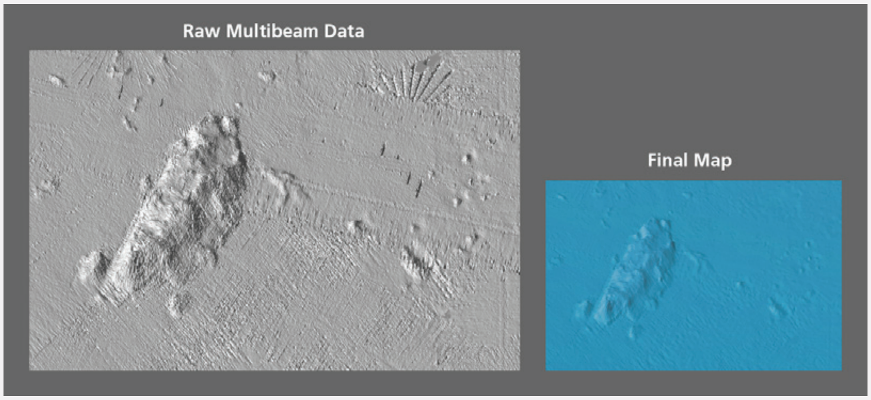


Figure 5: Raw multibeam data contain numerous artifacts (left) that data manipulation partially removed (right). Printing the final map at smaller scale and in blue further minimized the artifacts.

DESIGN OVERVIEW

Making the *Seafloor Map of Hawai'i* posed design challenges that apply to all seafloor maps regardless of scale. Unlike other remote and inhospitable areas on Earth, such as high mountains visible from valleys below, maps of the seafloor depict places that will never be fully seen in their entirety. Light penetrates ocean water to a depth of 200 meters, and perpetual darkness cloaks what lies beyond. What is seen of this dim, alien world is limited to close-up glimpses from deep-sea submersibles. How then should the seafloor appear on a map when we can only imagine what it looks like?

One design approach is to use cartographic realism, which draws inspiration from natural world observations for depicting physical features on maps (Patterson 2002). For example, tree canopies are green, as are forested areas on maps. What hampers applying cartographic realism to seafloor maps is our limited exposure to views of the seafloor. Mud flats and sandy shoals primarily exposed at low tide suggest that the ocean bottom is uniformly soft and all its relief variation is gentle, and should be reflected as such on maps. The reality is not so simple, however. Although the continental shelves and abyssal plains where sediments collect are indeed gentle, many other areas are not. For instance, the undersea cliffs, canyons, seamounts, and lava slopes near the Hawaiian Islands often exceed the ruggedness of adjacent areas on land (Figure 6). Portraying these features on the *Seafloor Map of Hawai'i* required a change from the "land-dweller" mindset. A gently sloped ocean bottom would not do.

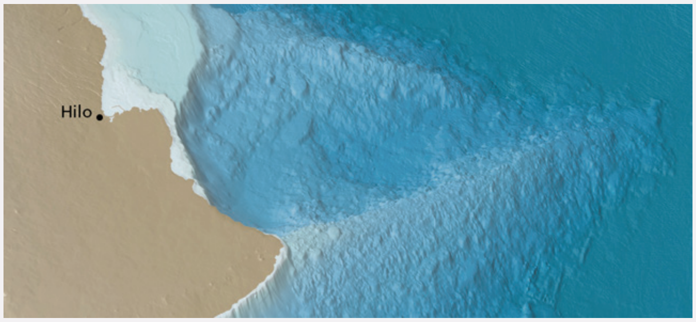


Figure 6: Detail of the Seafloor Map of Hawai'i *without most labels. The seafloor east of Hilo, composed of pillow lava, is more rugged than the broad shield volcanoes that characterize the land.*

Color is another topic of debate for seafloor mapping. Using rainbow colors such as those found on *Hawaii's Volcanoes Revealed* (Figure 2, right) is one approach that has been traditionally used if visualizing nuanced depths trumps all else. Given the lack of light in the deep ocean, and the tendency of dark tints to be perceived as lower in elevation, one could rationalize portraying the bottom as dark gray and black. Beyond making an avant-garde design statement, the problem with these monochromatic tints is having only 256 grayscale levels to depict depths ranging from 0 to -10,900 meters. Graphically speaking, it is a stretch. Printing black shaded relief on black depth tints also presents challenges.

As a practical matter, most ocean bottom maps, including the *Seafloor Map of Hawai‘i*, depict depths with gauzy blue tints progressing from light shallows to dark depths (Figure 6). Slightly varying the hue alleviates the problem of having enough tonal range to represent the depth range. A light to dark blue color sequence mimics the way we see deepening water from boats, bridges, or when swimming. There are also graphical advantages. Because blue is the most visually recessive hue and dark values appear lower, readers will likely perceive the bathymetry as occupying the lowest areas on a map. Blue depth tints blend harmoniously with gray shaded relief. Additionally, in terms of attracting an audience, it helps that—according to a Rutgers University study—blue is overwhelmingly the most popular color (2013).

HEINRICH BERANN'S INFLUENCE

The last fifty years have seen a sizeable number of small-scale ocean bottom maps published for general audiences, which provided design references for making the *Seafloor Map of Hawai‘i*. The pioneer in this effort, Austrian artist Heinrich Berann, painted a series of ocean maps in the 1960s and 1970s for *National Geographic* and the US Navy based on data compiled by Marie Tharp and Bruce Heezen (Lawrence, 1999). It is perhaps not a coincidence that the artist who popularized alpine panoramas, a map genre that merges with landscape painting, set the early standard for seafloor maps (Figure 7).

Berann drew on his artistic background to paint highly distinctive ocean bottom maps (1968; 1977). His minimalist color palette presents a world of contrast: land areas basking in sunshine set starkly against the blue-gray ocean bottom, a somber underworld. Depth tinting is barely present. Berann instead paints the mid-ocean ridges, rents in Earth's crust producing new seafloor rock, in dark gray, in contrast with the ocean basins that are lighter blue. The three-dimensional topography exaggerates features on the ocean bottom more so than those on land. The ocean appears as if drained of water, exposing its chiseled continental shelves, deeply etched canyons, soaring seamounts, and fractured mid-ocean ridges to the reader.

Of the 12 ocean-bottom maps painted by Berann, eight use a light source originating from the southeast (lower right) to illuminate seafloor features, the rest use a southwest (lower left) light source. Like his alpine panoramas, illumination striking seamounts and other high features casts shadows across the seafloor. This is of course impossible so far below the surface, but so too is seeing the ocean bottom without water. The upcoming section on bathymetric tints discusses an alternative to depicting drained oceans.

More recently *National Geographic* has modified Berann's style, led by Tibor Tóth, a former staff artist and now retired freelancer for that organization. For several years conventional shaded relief had replaced three-dimensional relief depiction on National Geographic seafloor maps (Figure 7, third from top), but now three-dimensional relief is popular again (Figure 7, bottom). Compared to Berann's pieces, Tóth employed less vertical exaggeration, used brighter colors, and did not darken the mid-ocean ridges.

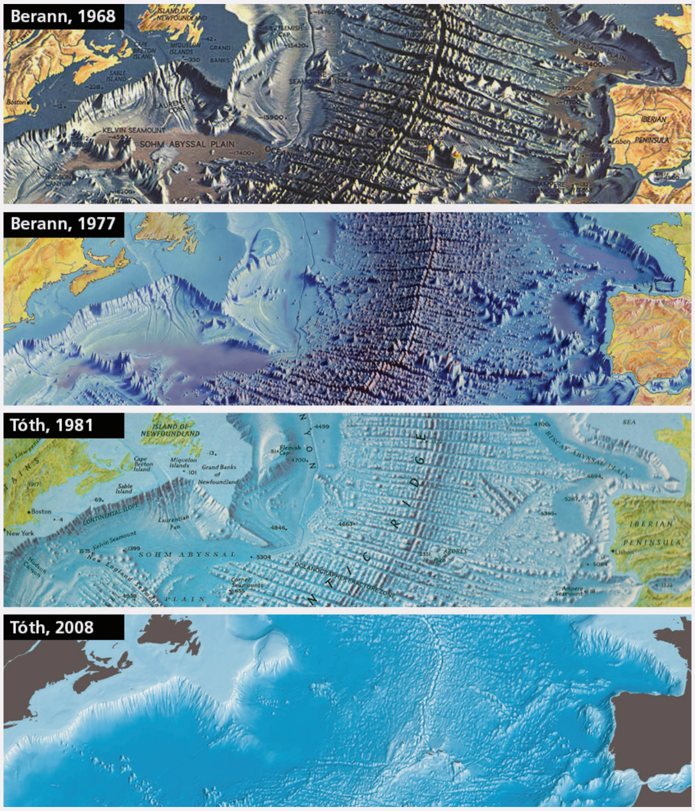


Figure 7: Small-scale ocean bottom maps. Examples courtesy of National Geographic, *except for Berann, 1977, published by the US Office of Naval Research.*

Tóth's work also shows Berann's strong influence, including restrained use of depth tints, the presence of cast shadows (Tóth applies these with a lighter touch), and a preference for southeast lighting, although he acknowledges that southwest illumination works just as well (Tóth 2009). More significantly, Tóth also painted seafloor topography. His method in recent years was to render digital bathymetry as a three-dimensional relief and then paint over it in Photoshop using a Wacom tablet and stylus (Tóth 2008; 2009). He painted not of preference but because of the necessity to remove imperfections or to add detail to poor-quality bathymetry data, especially at larger scales.

Although the design of the *Seafloor Map of Hawai'i* borrows heavily from both Berann and Tóth, it differs from them most noticeably in using only digital methods for relief presentation.

PLAN OBLIQUE RELIEF

Plan oblique relief is a type of projection that gives an impression of three-dimensional relief rendered from digital elevation models (DEMs). One of the parameters of plan oblique relief projection is a vertical offset, which produces an appearance similar to the terrain depicted in panoramas. It depicts mountains projecting upwards toward the top of the map and valleys downward (Jenny and Patterson 2007). By contrast, conventional shaded relief assumes that the position of the reader is directly above the map and depends entirely on light and shadows to model the terrain features (Figure 8).

There are tradeoffs to using plan oblique relief. On the positive side, it brings drama and realism to maps. Readers see terrain with a vertical dimension and in partial profile much like mountains appear from a scenic overlook or out of an airplane window. The relatively simple undersea topography of Hawai'i—conical seamounts, blocky landslide debris, and steep-sided terraces around the islands—is suited to plan oblique relief presentation. These features appear to pop up from the ocean floor.

Lighting is another advantage. Because plan oblique relief illumination comes from either the front left or front right, compared to back left with conventional shaded relief, shadows fall on slopes facing away from the reader. This makes the terrain and overall map lighter, improving the readability of labels. The lighter relief also combines well with dark bathymetric tints in deep areas.

On the down side, plan oblique relief can hide parts of a map. As in any 3D image, there is a front side and back side to objects. In the case of plan oblique relief, south slopes face the reader and are more visible than steep north

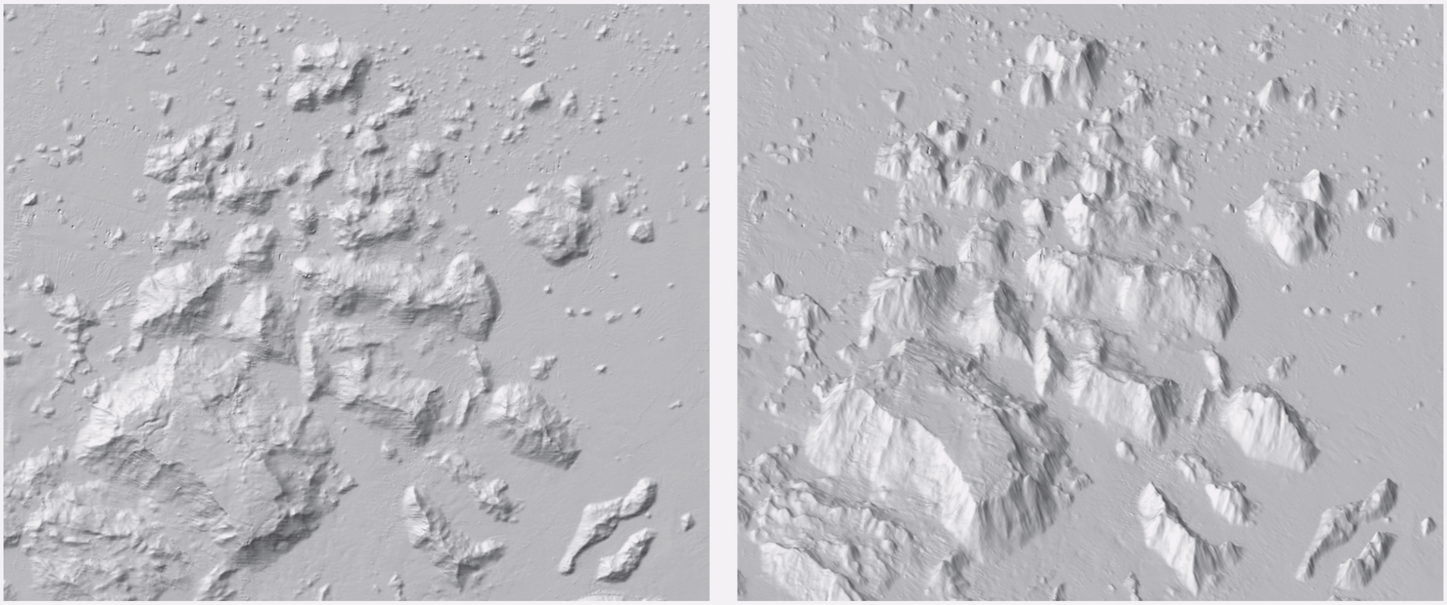


Figure 8: Conventional shaded relief of the Nu'uanu Slide (left) compared to plan oblique relief (right). Note that illumination originates from the upper left on the shaded relief and lower left on the plan oblique relief.

slopes, which can disappear from view. This issue, however, is less critical on the empty seafloor than on land as there are no roads, towns, rivers, etc. to obscure. In addition, seafloor features do not experience aspect-related weathering. Unlike terrestrial mountains in the northern hemisphere that have dramatic north faces due to glaciers, seafloor features are apt to be equally interesting on all sides.

Map lines are another problem with plan oblique relief. For example, latitude and longitude lines on a plan oblique relief map would not appear as a grid but would mirror the topography, going up and down with the changing elevation. Because a rectangular grid would only apply at sea level, a small area on the *Seafloor Map of Hawai'i*, it is not used. A related problem is that map georeferencing and reprojection is not advisable. For example, transforming plan oblique relief from a cylindrical to conic projection would tilt the three-dimensional topography inward. Like the panoramas that they mimic, plan oblique relief maps are pictorial.

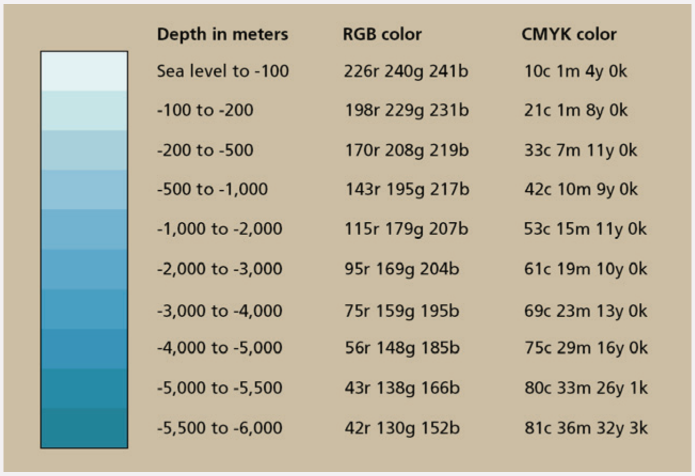
The *Seafloor Map of Hawai'i* uses plan oblique relief rendered with a beta version of Natural Scene Designer Pro 6.0. The pitch setting in this software application, ranging from -10 to -90 degrees, determines the amount of vertical exaggeration. For the Hawaiian seafloor, a pitch setting of -25 degrees yielded more vertical exaggeration than the default -45 degrees, but much less than that found on Berann's smaller-scale maps. Light originates from the west-southwest (245 degrees) at an angle of 45 degrees above the horizon. This light direction purposely departs from Berann's favored direction from the southeast (lower right). By selecting a light source closer to that of conventional shaded relief (northwest or upper left), the intent was to present the relief in a manner most familiar to readers. The Hawaiian Islands trending from southeast to northwest also render very well with perpendicular light coming from the southwest. The light angle at 45 degrees above the horizon generates fewer shadowed slopes than those of Berann's maps. Cast shadows also are not present on the *Seafloor Map of Hawai'i*, giving it a lighter overall appearance.

BATHYMETRIC TINTS

The *Seafloor Map of Hawai'i* employs very conventional bathymetric tints (depth colors) starting with light blue-green in the shallowest water and progressively darkening to gray-blue in deep areas (Figure 9). Class breaks occur at 1,000-meter intervals, except for extremely shallow and very deep areas that tend toward flatness and therefore have more class breaks for better definition. Depth tints on the *Seafloor Map of Hawai'i* blend continuously into one another, and combine with the relief shading and illumination. The point of the map is to emphasize relative depths.

Selecting tints to represent depths can challenge mapmakers accustomed to working with hypsometric tints. Unlike on land where high elevations are relatively rare, much of the world ocean consists of very deep basins. On the *Seafloor Map of Hawai'i*, for example, the maximum depth is -5,795 meters and depths between -4,000 and -5,000 meters predominate. Finding a pleasing blue tint to represent this depth class was critical, while avoiding gaudy or excessively dark hues that would overwhelm the map when viewed at full size. On the other hand, because the map is distributed online and appears as one of many thumbnail images on search pages, selecting eye-catching colors was an important consideration.

Compared to the subdued hues favored by Berann, the *Seafloor Map of Hawai'i* is brighter and more saturated, partially in consideration of the geographic area being mapped. Hawai'i is not the North Atlantic. A more significant departure from Berann, and to a lesser extent his successor at *National Geographic*, Tibor Tóth, is the prominent use of bathymetric tints. This is largely due to advances in map production. Whereas compositing blended



Depth in meters	RGB color	CMYK color
Sea level to -100	226r 240g 241b	10c 1m 4y 0k
-100 to -200	198r 229g 231b	21c 1m 8y 0k
-200 to -500	170r 208g 219b	33c 7m 11y 0k
-500 to -1,000	143r 195g 217b	42c 10m 9y 0k
-1,000 to -2,000	115r 179g 207b	53c 15m 11y 0k
-2,000 to -3,000	95r 169g 204b	61c 19m 10y 0k
-3,000 to -4,000	75r 159g 195b	69c 23m 13y 0k
-4,000 to -5,000	56r 148g 185b	75c 29m 16y 0k
-5,000 to -5,500	43r 138g 166b	80c 33m 26y 1k
-5,500 to -6,000	42r 130g 152b	81c 36m 32y 3k

Figure 9: Bathymetric tints used on the Seafloor Map of Hawai'i. *The beige background in the illustration is the island color on the map.*

bathymetric tints and the modulated light and shadows of shaded relief is easy to do with digital technology, a traditional artist would face challenges. There are just too many constantly changing colors to depict accurately with an airbrush or paintbrushes.

Now that digital production is the norm, combining bathymetric tints and shaded relief offers both conceptual and practical advantages to mapmakers. Shades of blue becoming darker with depth suggest an ocean filled with translucent water rather than drained (Figure 6). Consequently, readers see a less extreme departure from reality. Darker bathymetric tints in deep areas accentuate the aerial perspective effect, enhancing the apparent three-dimensionality of topography (Imhof, 1982). These darker tints also disguise shaded relief created from poor-quality data in deep waters.

Land areas on the *Seafloor Map of Hawai'i* are muted beige, which downplays the importance of the islands compared to the ocean bottom. The beige nevertheless has enough warmth to provide visual relief from the cool blues everywhere else on the map (Figure 9). Shaded relief on land is slightly blue-gray, which softens its appearance. Lowlands received slight darkening to accentuate figure-ground contrast between the island shapes and shallow water, eliminating the need for shoreline casings. In fact, lines are entirely absent from the map. The island of Hawai'i, which is comprised of shield volcanoes with gentle slopes, received extra shaded relief darkening.

MAP FINISHING

The *Seafloor Map of Hawai'i* comes in two versions, one with spot depths and elevations indicated in meters, and the other in feet. A liberal sprinkling of spot depths focuses attention on key seafloor features, such as seamount summits and deep troughs. The map also identifies island high points. Draping NOAA (2013) nautical charts with depth soundings on the rendered plan oblique relief provided a placement guide. This method, however, often proved inadequate because soundings on the nautical charts did not precisely coincide with relief generated from bathymetric data, which is presumably more accurate. For example, a spot depth might fall mid-slope on a seamount instead of its highest point. Sampling the bathymetry data to obtain spot depths proved a better technique.

Labeling undersea features proved more difficult than those on land. The National Geospatial-Intelligence Agency (2014) maintains the GEOnet Names Server for US and international waters, but the coverage is sparse for Hawai'i. Altogether the GEOnet Names Server accounts for 39 of the 84 undersea place names found on the *Seafloor Map of Hawai'i*, mostly seamounts southwest of the island of Hawai'i. The remaining names are unofficial, largely taken from the USGS map *Hawaii's Volcanoes Revealed*. They typically describe physiographic features and geologic events, such as the Clark 1 Slide west of the island of Kaho'olawe (Figure 10). Other geology-related names include the Moloka'i Fracture Zone, Southwest O'ahu Volcanic Field, Hawaiian Arch, and numerous ridges, slides, and slumps.

Researching undersea feature names for the map revealed varied terminology. For example, some maps identified the Hawaiian Trough, a region of extremely deep water adjacent to the Hawaiian Islands, as the Hawaiian Deep or Hawaiian Moat. In this case, the GEOnet Names Server identified the feature as a trough, which settled the decision. For names not on the GeoNet server, a helpful reference was "Policies and Guidelines for the Standardization of Undersea Feature Names," a document published by the US Board on Geographic Names (2005), which lists definitions of undersea feature designations.

Many large undersea features don't have names. The massive Nu'uanu Slide northeast of O'ahu consists of more than a dozen mountain-sized fragments (Figure 6), only one of which has a name. Even more conspicuous, no name was found for the large seamount northwest of the Kaua'i (partially cropped on the left map margin) that rises almost to the surface. The opposite problem, too many place names, occurs only off the north shore of Moloka'i. Of the one dozen submarine canyons found here, tight space on the map permitted the labeling of only two. Many Hawaiian seafloor features take their names from adjacent places on land. For example, off the northeast coast of Maui, Pa'uwela Ridge takes its name from a point, and Hāna Slump and Hāna Ridge from a town (Figure 10). These appear on the *Seafloor Map of Hawai'i* with diacritical punctuation as approved by the US Board on Geographic Names (2013) for their terrestrial namesakes.

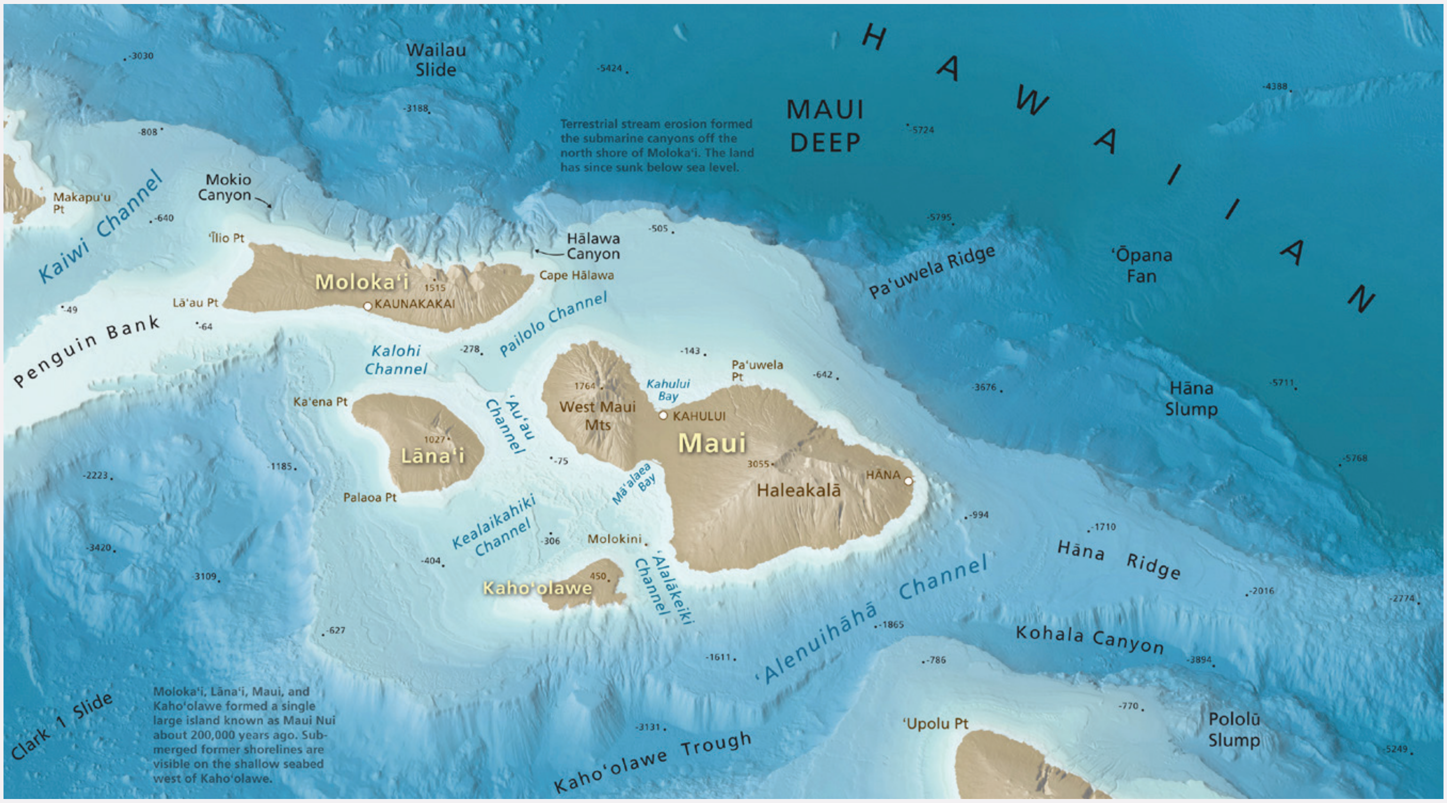


Figure 10: Excerpt of the Seafloor Map of Hawai'i with labels and metric spot depths.

Terrestrial stream erosion formed the submarine canyons off the north shore of Molokaʻi. The land has since sunk below sea level.

Molokaʻi, Lānaʻi, Maui, and Kahoʻolawe formed a single large island known as Maui Nui about 200,000 years ago. Submerged former shorelines are visible on the shallow seabed west of Kahoʻolawe.

Finally, the *Seafloor Map of Hawaiʻi* uses the Plate Carrée or Geographic projection. The bathymetric data used to make the map were originally in this cylindrical projection. Since maps of tropical areas at medium scale have little distortion regardless of the projection used, changing it to another projection was unnecessary.

CONCLUSION

The *Seafloor Map of Hawaiʻi* represents a map type that will slowly become more common with the ongoing collection of high-resolution bathymetry data. It demonstrates that with digital production it is now possible to make medium-scale seafloor maps that take inspiration from the small-scale ocean maps hand painted by artists over the last 50 years. More significantly, digital methods bring unrivalled detail to ocean floor maps and expand the design possibilities. For example, merging bathymetric tints with plan oblique relief brings color and realism to undersea maps that will likely appeal to general audiences. The intent is for readers to see the Hawaiian Islands as an enormous mountain range.

The compilation of this map also calls attention to the problem of incomplete and suboptimal bathymetry data that require considerable manipulation to become presentable on a map. As with all types of mapping, as scale and detail increase, so does the magnification of data problems. The solutions employed by cartographers to fill voids in SRTM data in mountainous areas also apply to bathymetry data. Yet even with these repairs the data are often too irregular and noisy for clean map presentations. The available solutions are not ideal: smoothing bathymetry data, reducing the map scale, printing shaded relief on the seafloor lightly, and emphasizing depth tints. As a last resort and if time permits, touching up the data manually yields a much improved map presentation.

An irony of nearly all seafloor maps, including the *Seafloor Map of Hawaiʻi*, is the inevitable presence of land somewhere on the map. Perhaps to be meaningful to land-bound humans, this is a necessary requirement. It nevertheless brings up the question of how to design seafloor maps without land, which involves issues such as ubiquitous blue tones, a lack of known names, and no land to provide a frame of reference. Considering that most of Earth is underwater, and how few large- and medium-scale maps of the seafloor exist, cartographers still have much work to do—and many discoveries to make.

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