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CAPE KIWANDA SINKHOLES AND THEIR FORMATION, TILLAMOOK COUNTY, OREGON

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2023

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DISCLAIMER

WHAT'S IN THIS REPORT?

This report evaluates the formation of two sinkholes during 2023 at Cape Kiwanda, Tillamook County, Oregon. The goal is to provide guidance to the Oregon State Parks and Recreation Department (OPRD) on recent and historical coastal changes as well as potential future impacts taking place at Cape Kiwanda.

Cover: View southeast overlooking Cape Kiwanda and Pacific City

L. Gabel, 12 Aug 2011

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EXECUTIVE SUMMARY

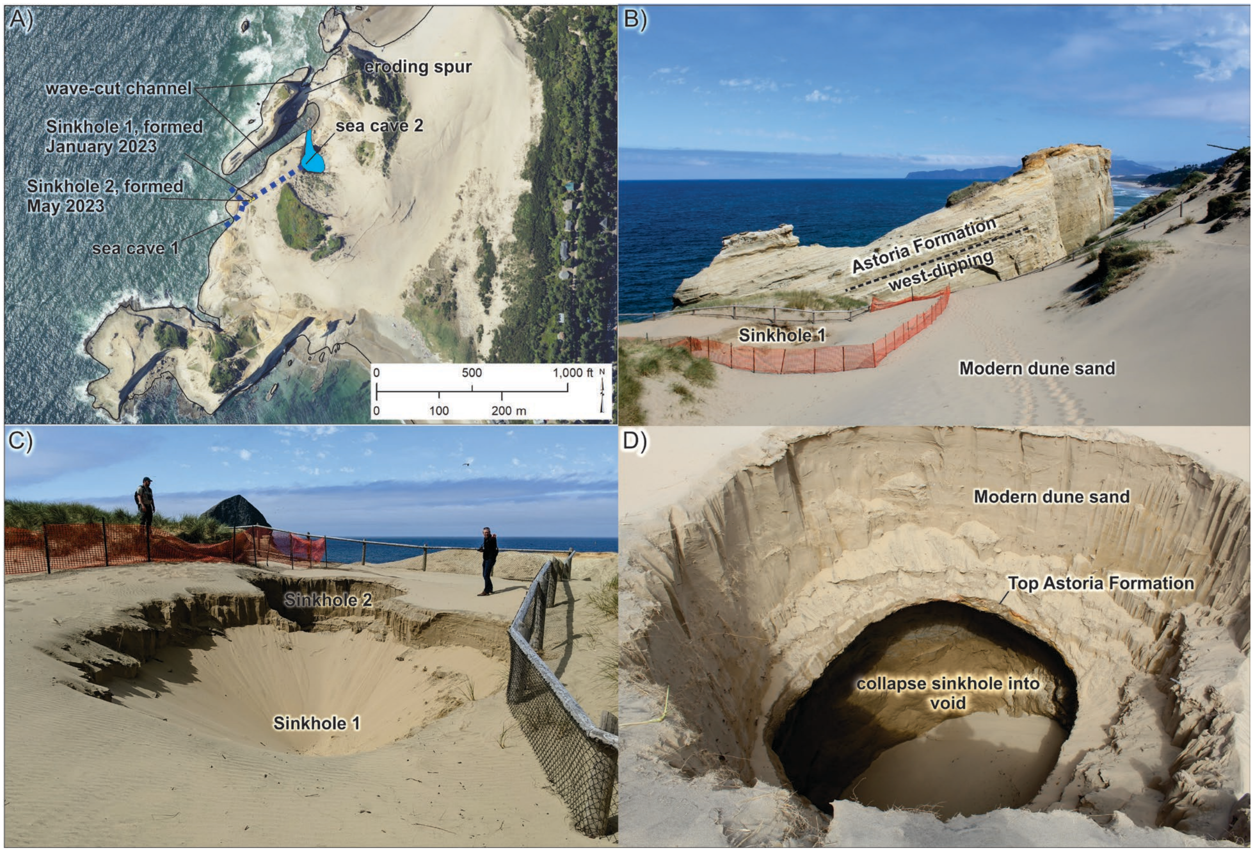
This report provides an evaluation of two sinkholes that developed at Cape Kiwanda early in 2023, including possible causes and potential future impacts at the site. The sinkholes ranged in width from ~4.5 to 10 m (15 to 33 ft), while the smaller sinkhole had an estimated depth of ~5 m (16 ft); both sinkholes contained some of the overburden making determination of the actual true depths impossible. We hypothesize that the sinkholes preferentially formed along a vertical joint in sandstones in the Astoria Formation. Chemical weathering (dissolution) of the underlying rock along a joint created a void, which ultimately resulted in a collapse sinkhole. Due to the rapid speed in which this part of Cape Kiwanda is presently eroding and the presence of a large cave system at sea level directly below the sinkholes, we recommend that Oregon State Parks and Recreation Department establish a new fence line approximately 15 m (50 ft) south of the two sinkholes.

1.0 INTRODUCTION

This report provides an evaluation of sinkhole development at Cape Kiwanda, including possible causes and potential future impacts at the site. Cape Kiwanda is located in southern Tillamook County, adjacent to the community of Pacific City (**Figure 1**). The Cape is popular with tourists, with numerous trails that crisscross the headland allowing visitors ample opportunities to enjoy the spectacular vistas of Cape Kiwanda's unique geology, the Pacific Ocean, as well as views of Haystack Rock. However, due to its popularity, there have been a number of fatalities, mostly from falls due to people having wandered too close to the edge of the numerous steep cliffs that plunge into the ocean. Beginning in early 2023 a new hazard, consisting of two sinkholes, developed along a section of the northwest corner of Cape Kiwanda (**Figure 2**). This report evaluates the possible causes of the sinkholes and discusses potential future implications of sinkhole development at Cape Kiwanda.

Figure 1. Map showing the location of Cape Kiwanda and key place names.

Figure 2. Sinkholes at Cape Kiwanda. A) Map of Cape Kiwanda showing the locations of the two sinkholes and related features; B) View looking north toward Cape Lookout and westward dipping (~15°) Astoria Formation, with sinkholes located in the orange fenced area; C) View looking west over the sinkholes toward Haystack Rock; and D) View looking into the most recently developed sinkhole (sinkhole 2). The upper layer consists of approximately 2.5 m (8 ft) of modern dune sand (evident by the freshness of the sand color and presence of dune grass roots, overlying a weathered crust (iron-oxide staining) that likely reflects the top of the Astoria Formation at this location. Below the crust one can differentiate alternating bands of weathered sand, characterized by thin iron-oxide stains. Note also the dark brown sand that comprises the interior of the sinkhole, which appears saturated with water. Iron-oxide staining of the sand is indicative of water movement within the various sedimentary layers.



2.0 GEOLOGY

The geology of Cape Kiwanda consists of middle Miocene sandstone and siltstone of the Astoria Formation (**Figure 3**, orange shading). These rocks are ~15 million years old and were laid down during a period of time when the Pacific Ocean extended over much of western Oregon (Lund, 1974). Although not shown here, the largest outcrops of Astoria Formation can be found in various road cuts near Cape Lookout and Cape Meares.

At Cape Kiwanda, the Astoria Formation consists of approximately 91 m (300 ft) of west-dipping (~15°), massive, dark-gray to tan, medium- to fine-grained, arkosic sandstone and siltstone (**Figure 2B**, Schlicker and others, 1972); arkosic sandstone indicates that the rock contains ~25% feldspar-rich igneous (granite) rock with the remainder being mostly quartz. The Astoria Formation contains abundant fossils and sandstone concretions, while basaltic pebbles may be found high in stratigraphic section.

Over the past 2.6 million years (Quaternary) windblown sand has been deposited on top of the Astoria Formation (**Figure 3**), with the oldest deposits located atop Cape Kiwanda. These deposits provide evidence of the former greater extent of dunes that were deposited when Haystack Rock was connected to the mainland (Schlicker and others, 1972). Intermixed within these older sediments are sandy deposits that have accumulated over the past 15,000 years (Late Pleistocene and Holocene). The most recent sand deposits are reworked beach deposits that are presently accumulating over much of the headland through eolian (wind) processes. Where the headland abuts against the ocean, waves coupled with fluctuating tides are eroding and wearing away the sandstone, producing wave-cut channels, sea caves, arches and rockfalls. These erosive features as well as the Holocene dunes sitting on top of the Astoria Formation can be seen in oblique photographs of the headland (**Figure 4**).

Figure 3. Generalized geologic map of Cape Kiwanda draped on a 2009 1-m (3 ft) Lidar Digital Elevation Model (DEM) hillshade (geology from Schlicker and others, 1972).

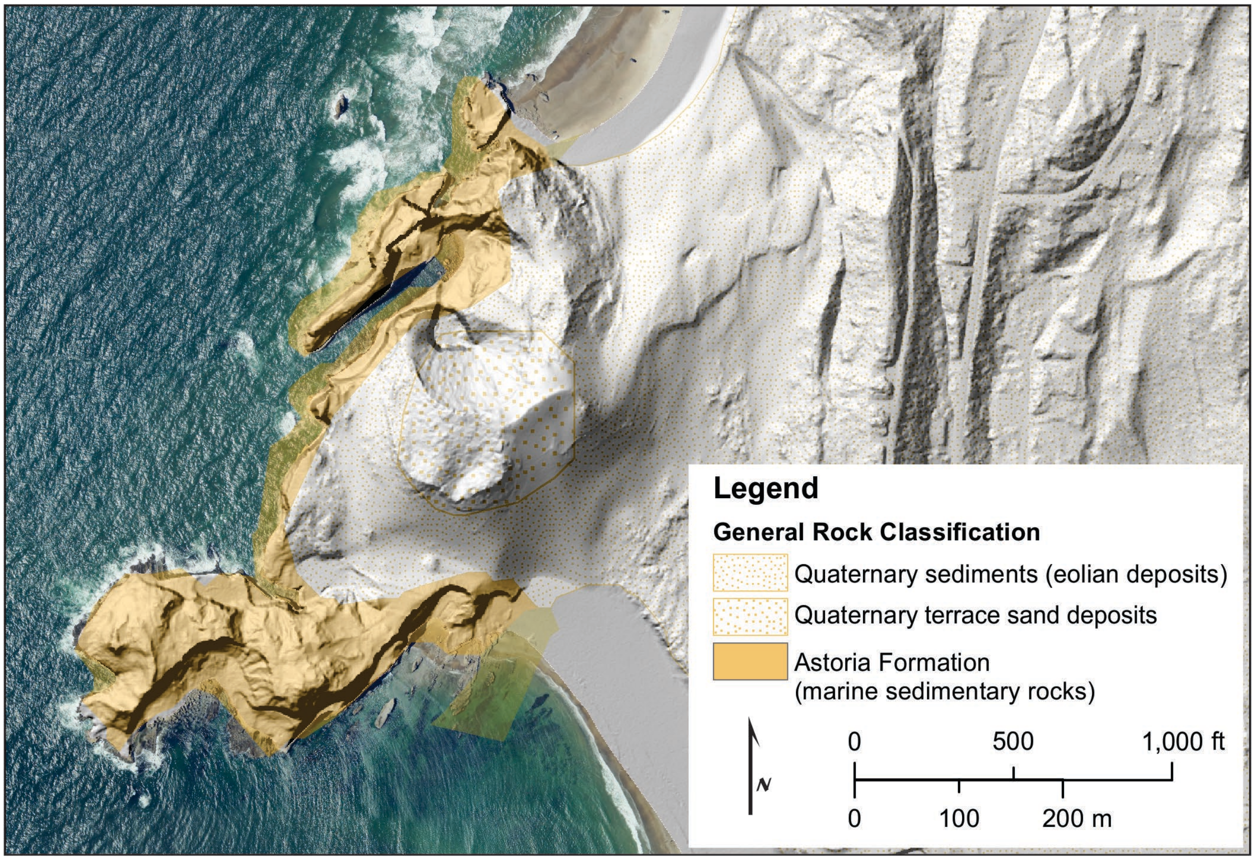


Figure 4. Oblique aerial views of Cape Kiwanda taken in A) November 1974 (Photo credit: Kinney, State Highway Division) and B) in August 2011 (Photo credit: L. Gabel, DOGAMI).

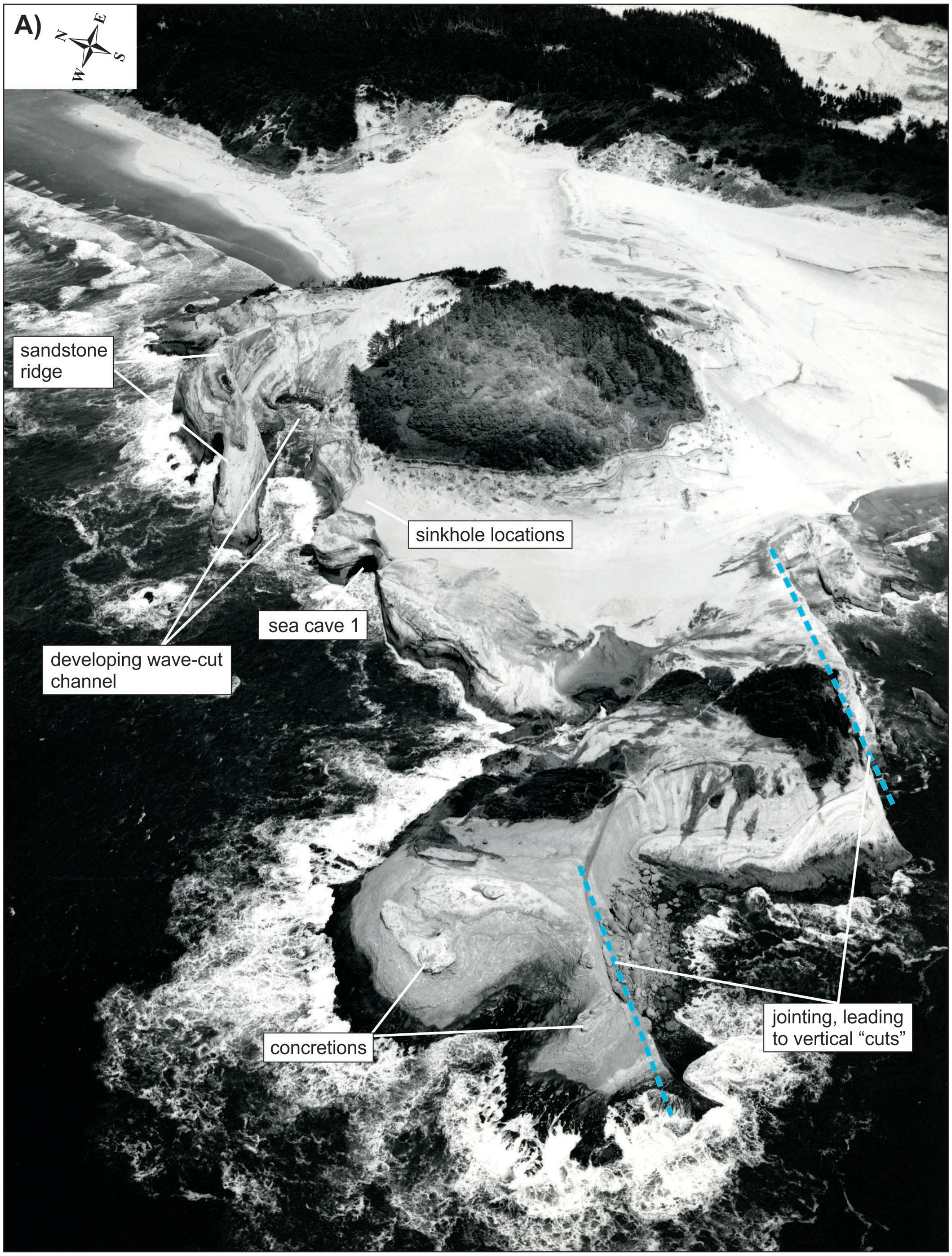
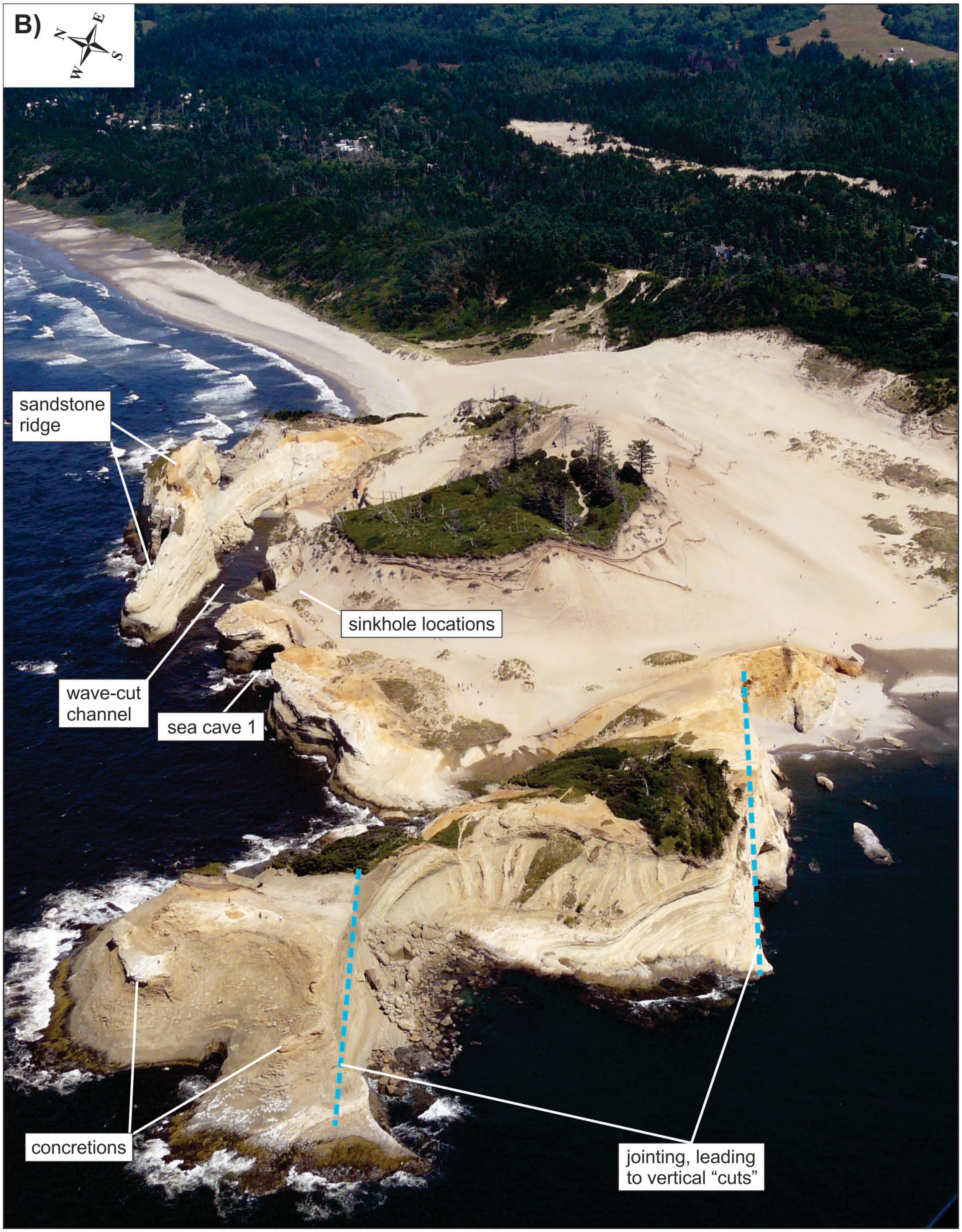


Figure 4 (cont.). Oblique aerial views of Cape Kiwanda taken in A) November 1974 (Photo credit: Kinney, State Highway Division) and B) in August 2011 (Photo credit: L. Gabel, DOGAMI).



2.1 Sinkhole Formation in Sandstone

Sinkholes are defined as depressions in the ground that have no natural external surface drainage (e.g., a creek outlet) and they occur when a subsurface cavity becomes too large to support the overlying rock (**Figure 2C and 2D**). Their development may be gradual, occurring slowly over many years to decades, or sudden. In the latter case, the sinkhole forms rapidly such that the land surface remains intact until support from below fails and the hole opens up. These are termed "collapse sinkholes."

Sinkholes are most commonly found in carbonate ("karst") rocks where circulating groundwater dissolves the bedrock (e.g., limestone). Although less common, sinkholes may form in sandstones through a combination of chemical dissolution as well as from mechanical erosion due to moving water (Sasowsky and Alexander, 2020). Because sandstones contain large amounts of quartz, the chemical dissolution of quartz requires significantly more water when compared with dissolution of carbonate rocks. According to Sasowsky and Alexander (2020) sinkhole development in sandstone requires the potential for high hydraulic gradients (and/or a long period of time) and a lithology that allows for the chemical breakdown of the rock. In the case of Cape Kiwanda, some of this water could come from groundwater movement within the sandy deposits as iron-oxide staining of various sand layers is indicative of moving water. Sinkhole formation may also be enhanced by other characteristics of the underlying geology, including the presence of jointing and fissures in the rock. In these types of geology, infiltration of water into the ground may preferentially dissolve the rock along a joint, penetrating deeper into the main body than in adjacent areas, where in time it creates a void. Eventually, the overlying material loses its supportive strength and collapses into the void beneath it.

3.0 METHODS

A variety of approaches were used to evaluate the changes taking place at Cape Kiwanda, including assessing historical changes derived from aerial imagery, serial lidar surveys of the coastline, and a field reconnaissance of the headland that took place on 18 May 2023.

The earliest compilation of aerial photographs of the Oregon coast was undertaken in 1939 by the U.S. Army Corps of Engineers (USACE). Unfortunately, the images are stereo (pairs) that have never been rubber-sheeted or orthorectified. Orthorectification is an approach used to process imagery to account for optical distortions (e.g., tilt or relief) with the goal of yielding an image that is planimetrically correct and fixed to a geospatial coordinate system, enabling the data to be viewed and analyzed in GIS. In order to orthorectify the images, the 1939 aerial photographs were added to ArcGIS and processed using the Georeferencing suite of tools. This is accomplished by identifying common ground control points (e.g., road junctions, bridges, buildings, rock outcrops) that can be identified in the 1939 images and in contemporary (e.g., 1995, 2000, 2004, 2009, 2014, 2016) orthorectified images or lidar. Using this approach, Allan (2020) was able to orthorectify a suite of 1939 photos for Tillamook County, enabling comparisons to be made against modern images of the coastline and from lidar. Contemporary photos evaluated here are derived from orthorectified aerial images collected by the National Agriculture Imagery Program (NAIP) under contract for the U.S. Department of Agriculture for the Farm Service Agency.

Lidar collected in 1998, 2002, 2009, 2010, 2014, and 2016 provide additional information that can be used to document the long-term changes taking place at the headland.

4.0 RESULTS

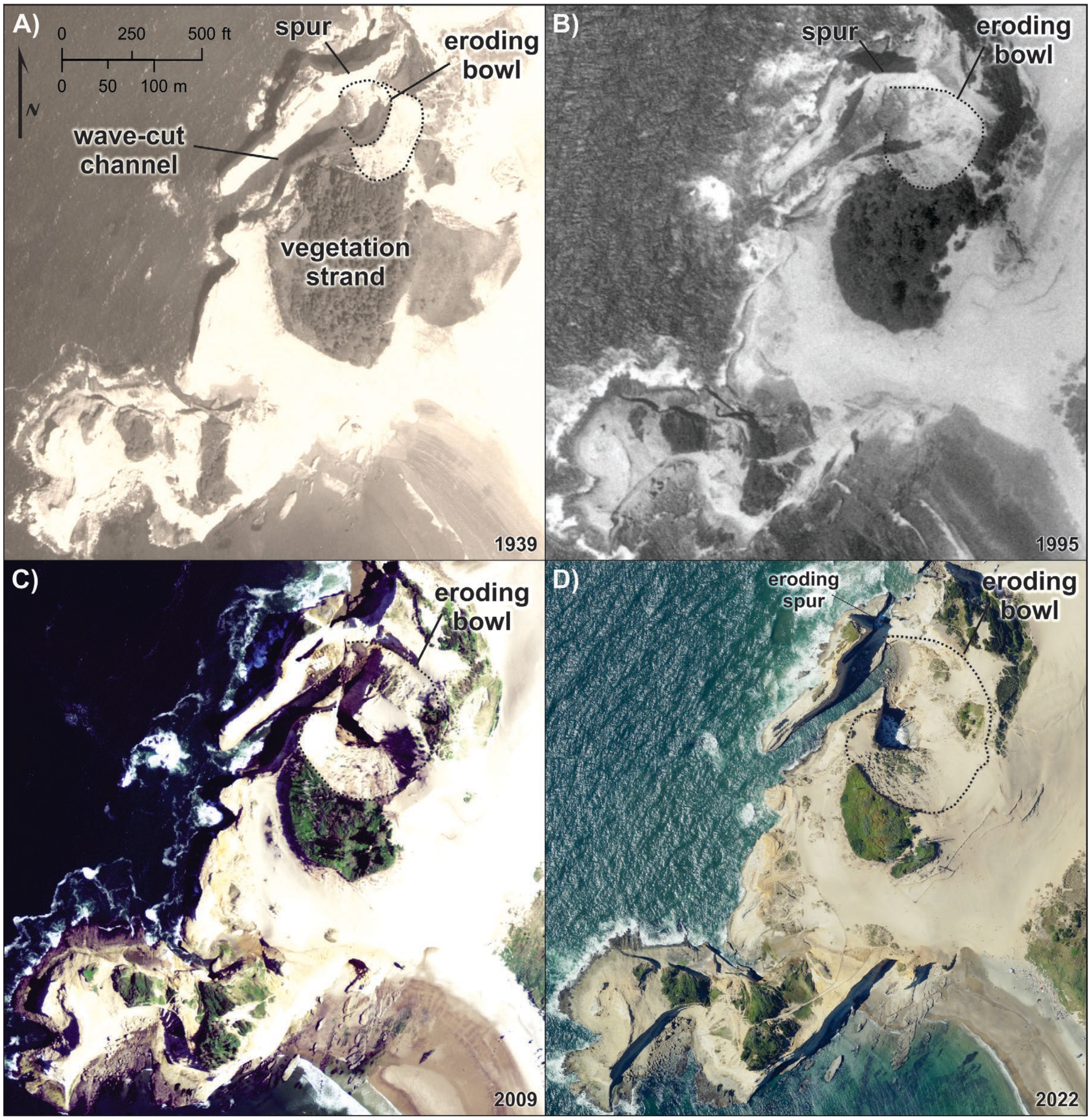
Figure 5 presents a sequence of digitally orthorectified aerial images (1:5,000 scale) of Cape Kiwanda, from 1939 to 2022, demonstrating the powerful role ocean waves have played in eroding and shaping the sandstone headland over the past 84 years. **Figure 6** provides an interpretation of recent geomorphic changes that can be identified from the various images.

One of the most notable changes that has taken place on the headland is the considerable loss in vegetation coverage over time, from a peak in 1939 to the present coverage in 2022 (compare **Figure 5** to **Figure 6A**). The bulk of this loss can be attributed to the developing "erosion bowl" on the north side of the headland (compare **Figure 5A** and **5D**), which has consumed massive volumes of sand, rock, and vegetation over time. Removal of these sediments has been aided by wave and current processes operating within the wave-cut channel, and from within a cave that has developed parallel to the wave-cut channel. Since 1939, vegetation around central Cape Kiwanda decreased by ~66% from 4.6 to 1.6 hectares (11.5 to 3.9 acres). Conversely, vegetation at the far western end of Cape Kiwanda does not appear to have changed significantly over time (Compare **Figure 5**, 1939 to 2022).

A second notable feature identified in **Figure 5** and in the oblique photos (**Figure 4**) are structural controls within the sandstone, including the wave-cut channel and sandstone ridge to the north of the vegetation strand. The wave-cut channel probably developed in response to wave erosion into a joint, fissure or other vertical sedimentary weakness in the sandstone. Over time, waves would have worked away at these lines of weakness, perhaps initially forming a sea cave that progressively opened up, elongating in the line of the weakness. Eventually the top of the cave collapsed downward, opening up the channel. North of the main wave-cut channel identified in **Figure 4** and **Figure 5** is a sandstone ridge that has remained intact, possibly because it contains rock that is more resistant to wave erosion. Nevertheless, part of the eastern end of this sandstone ridge has eroded over the past two decades as a new, smaller channel develops (**Figure 2A**). Erosion there has occurred rapidly over the past decade and is a testament to the varied characteristics of the local geology and its responses to wave erosion. Finally, linear-like vertical "cuts" in the sandstone on the south side of the headland (**Figure 4**) can similarly be attributed to structural controls within the Astoria Formation. It is noteworthy that these features are orientated in a manner that is very similar to the wave-cut channels to the north (**Figure 2A**). The variation in these types of geologic characteristics, erosion responses, and geomorphology demonstrate the heterogeneity of the sandstone that makes up the headland, which has ultimately guided its evolution.

Figure 6B and **6C** shows the evolution of the erosion "bowl" since 1939. As can be seen in **Figure 6C** and **Figure 5A**, the area of the "bowl" in 1939 had a more limited extent, being confined to the landward end of the wave-cut channel and was no more than about 50 m (165 ft) in width. Using lidar and aerial photos, we can see that the "bowl" broadened significantly over time with the largest change occurring sometime between 2002 and 2010; as of 2022 the "bowl" had reached a diameter of ~150 m (500 ft). From 2010 to 2022 the erosion "bowl" did not change markedly. The authors were able to access the "bowl" as part of our field reconnaissance and observed that much of this area is highly active, characterized by evidence of landsliding (slope instabilities), including rockfalls (along the bluffs just east of "b" in **Figure 6D**) and slumping above it (**Figure 6B**). We consider the contemporary headscarp of the "bowl" to be unstable, particularly along its northeastern flank, and recommend the OPRD consider fencing this area.

Figure 5. Sequence of aerial images taken of Cape Kiwanda showing geomorphic changes over time. The 1939 image was flown by the USACE, while the 1995, 2009, and 2022 images were collected by the NAIP.



From within the bowl, we identified a large sea cave (**Figure 7**), which connects to a smaller sea cave ("1") identified in **Figure 2A** and ("b") in **Figure 6D**. We estimate that the sea cave (2) is approximately 117 m (384 ft) in length and is ~15 m (50 ft) wide at the base of the "bowl" near "b" (**Figure 6D**). Due to its orientation and length, we believe this cave system extends directly under the two sinkholes. However, we could see no evidence for a vertical shaft inside the cave that would identify connectivity with the sinkholes above; similarly, one cannot see the sea surface through the sinkholes. Further study of the sea cave (i.e., size, extent, and internal structure) and the overlying bedrock (i.e., identifying areas of weakness such as jointing and studying groundwater movement) could provide a better understanding of the cave system and predict future sinkhole locations.

Figure 6. Geomorphic changes around central Cape Kiwanda.

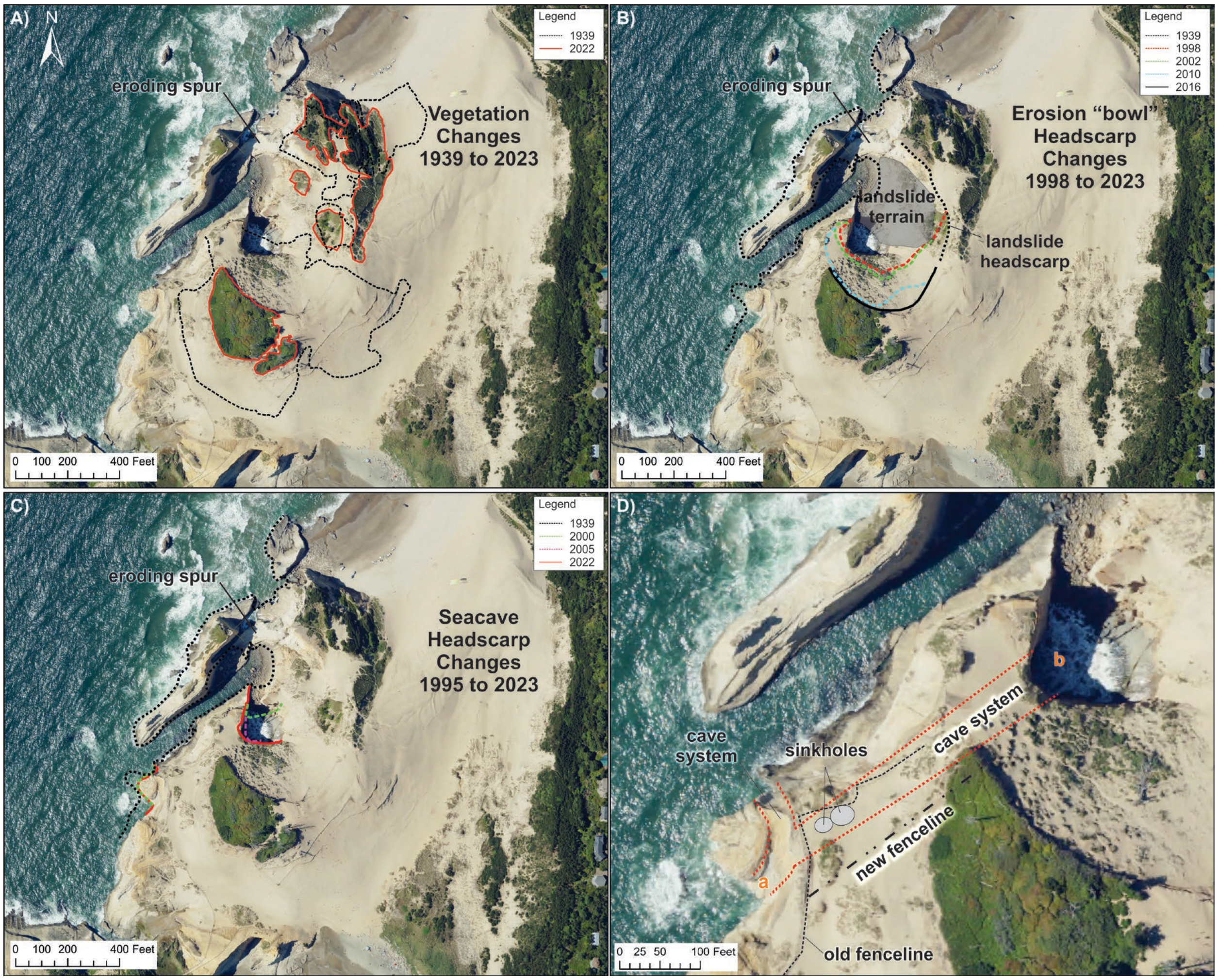


Figure 7. A) Looking down into the developing erosion "bowl"; B) Sea cave that connects to the western end of the headland; view is from location "b" in Figure 6D, looking west (Photo credit: J. Allan, 2023).

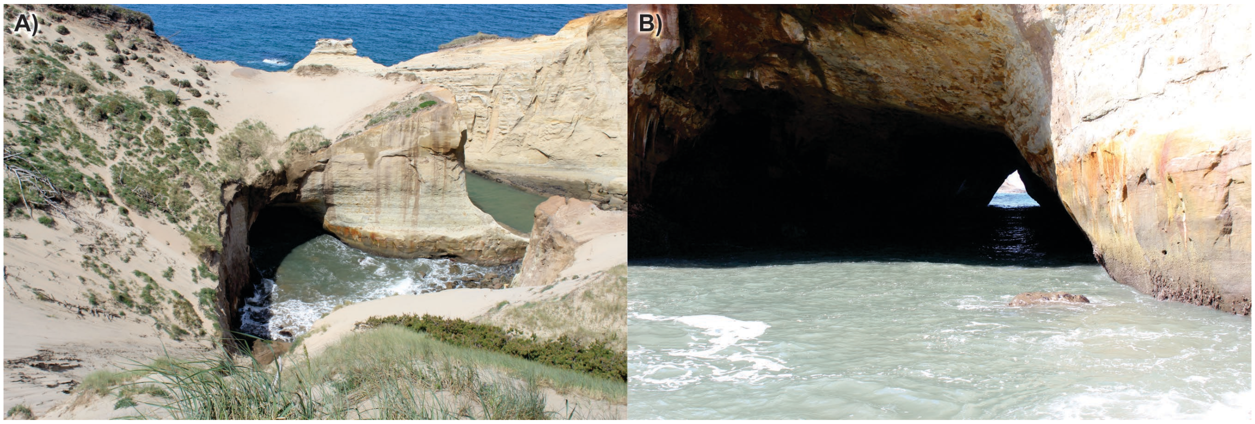


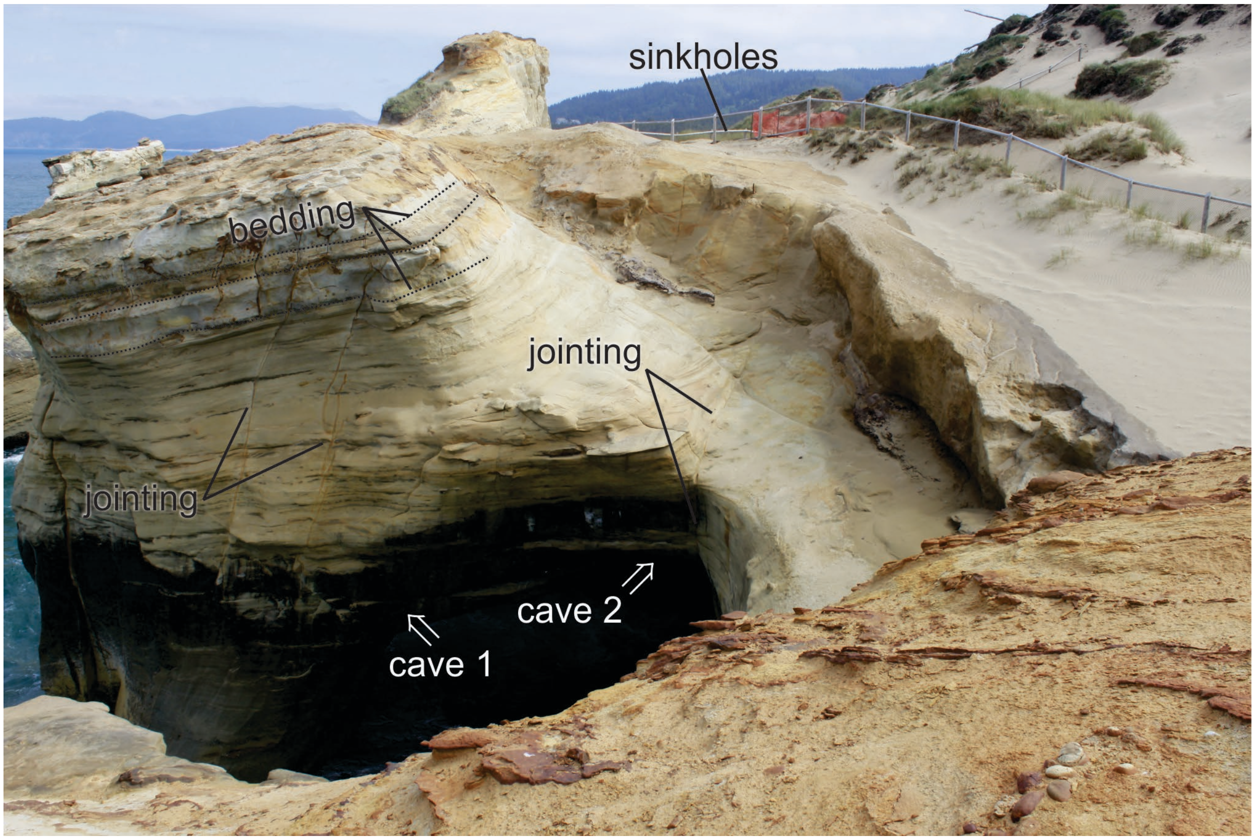
Figure 6C shows changes to the entrance of the two sea caves over time. At location "a" it can be seen that the coastline has not changed significantly over time. In contrast, we can track the general broadening of the erosion "bowl" between 1939 and 2000, and development of a cave entrance near "b". Importantly, it appears the erosion accelerated ~2000 to 2005, with the cave entrance having assumed its current general configuration by ~2005. This would imply that the cave was likely closed at its eastern end prior to 2005. With the eastern end having fully opened up, erosion of the "bowl" accelerated, directly contributing to the landslide failures taking place east of the cave entrance. Since 2005, it appears the rate of erosion around the cave entrance near "b" has slowed, while undermining within the erosion "bowl" continues to make this area highly unstable. Finally, **Figure 6**D provides a schematic of the overall layout of the sea cave and location of sinkholes.

In the absence of any obvious vertical shaft having formed within the sea cave system between "a-b" in **Figure 6D** (meaning ocean water is not visible from the sinkhole), we hypothesize that these are collapse-type sinkholes, in which water may have preferentially dissolved a void within the sandstone, possibly along the same plane as the joint shown in **Figure 8**, which subsequently collapsed downward. The characteristic shape of the sinkhole and internal structure appears to support this idea. The ability to form a void within the sandstone also implies some unique geologic characteristics about the chemical disposition of the sediments below the collapse sinkhole. Hence, the formation of the sinkhole cannot be solely a function of a joint/fissure, but may also have resulted from chemical dissolution. A weakness in the underlying sediment, perhaps within its mineral structure, could have allowed water to preferentially dissolve the mineral, eventually leading to the formation of a void and its eventual collapse. Finally, we cannot rule out entirely mechanical action from the waves below, though this seems highly unlikely when compared with dissolution weathering of the rock strata. For example, the top of the sinkholes is located at an elevation of ~23 m (~75 ft). We can measure the approximate top of the wave runup zone from geomorphic features and erosion cuts near the water line, located at ~8 m (~26 ft) elevation near the caves. If we assume this is the approximate height of the top of the cave, this indicates ~15 m (48 ft) of rock above the cave system, which is a large amount of rock to erode from below.

5.0 CONCLUSION AND RECOMMENDATIONS

This study evaluated two sinkholes at Cape Kiwanda, which formed in January (sinkhole 1) and May (sinkhole 2) 2023. Fieldwork confirmed the presence of a large cave system that extends beneath the two sinkholes. However, we saw no evidence for vertical connectivity between the sinkholes and the cave below. We hypothesize that the sinkholes preferentially formed along a joint and within a saddle (low point in the ground surface) that may have allowed water runoff from higher up to preferentially pond within the saddle. This likely allowed water to progressively dissolve the underlying rock structure, leading to a collapse sinkhole. Given the observed erosion and rapid transformation of this part of Cape Kiwanda over the past 84 years and especially in the last two decades, we recommend that the entire area overlying the cave system be avoided entirely. At a minimum, we recommend establishing a new fence line approximately 15 m (50 ft) south of the existing sinkholes, which should provide sufficient setback to allow for future catastrophic failure of the cave system. In time, we suspect that this part of Cape Kiwanda may eventually form a small sea stack as the western sea cave ("sea cave 1" in **Figure 2A**) collapses, while a wave-cut channel could eventually form along the main east-west cave system ("sea cave 2" in **Figure 2A**), similar to the existing wave-cut channel located immediately north of the developing cave system. Finally, our fieldwork within the erosion "bowl' indicated the presence of active slope instabilities, including rockfalls near "b" in **Figure 6D** and slumping (**Figure 6B**). We recommend building a new fence line (dashed black line in **Figure 6B**) in the northeast to keep people out of the erosion "bowl" as this part of the Cape remains unstable, while maintaining a view overlooking the area.

Figure 8. View from near "a" in Figure 6D looking in a northeasterly direction into the western end of the cave system. Note the vertical jointing in the Astoria Formation sandstone above and to the right of the cave entrance (as well as in several other locations seen to the left), along with weathering (iron-oxide staining) and concentrations in the various sand layers (Photo credit: J. Allan, 2023).



6.0 ACKNOWLEDGMENTS

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