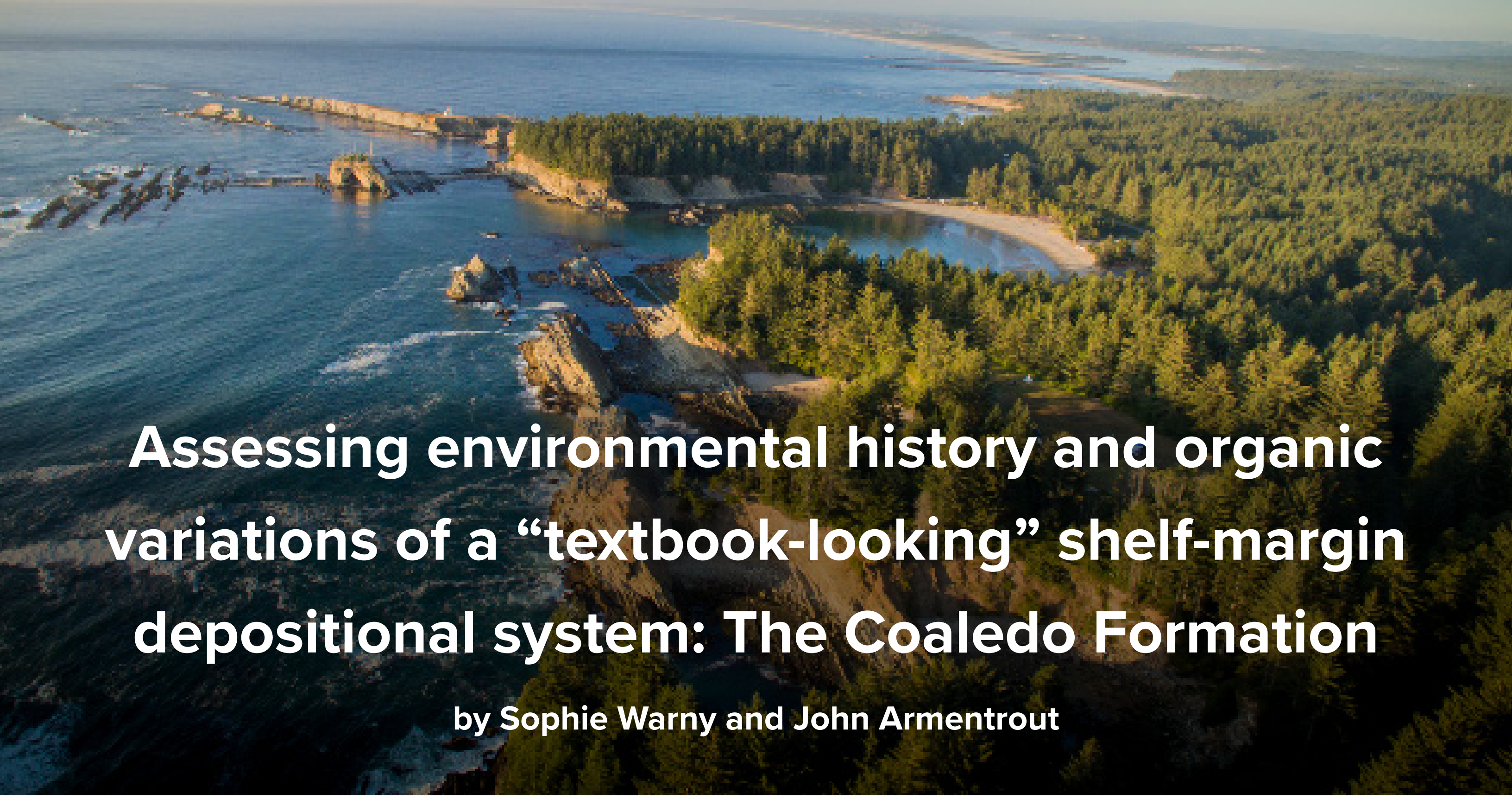


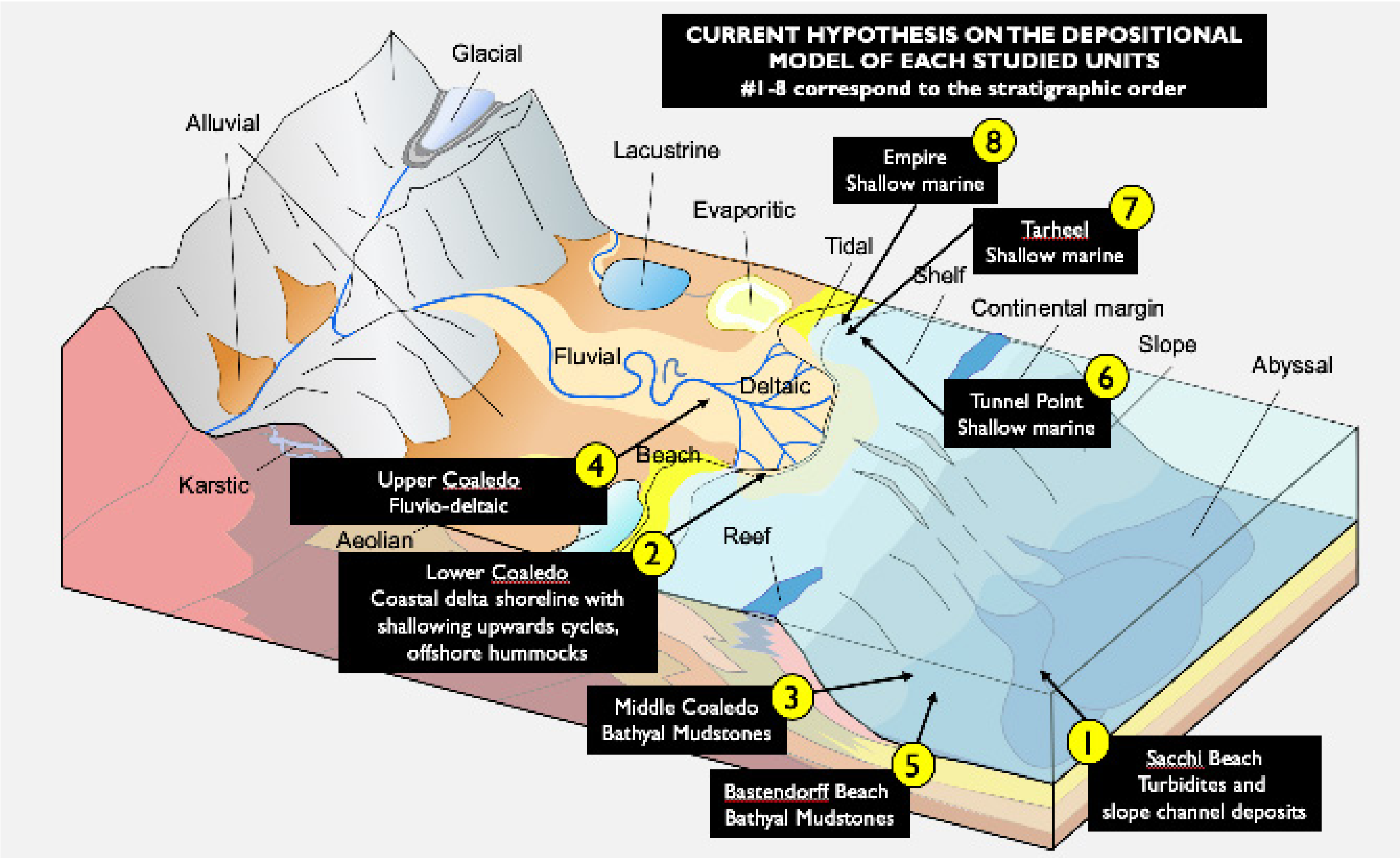
Assessing environmental history and organic variations of a "textbook-looking" shelf-margin depositional system: The Coaledo Formation

by Sophie Warny and John Armentrout

Understanding how ancient shelf-margin sedimentary systems were deposited in response to climatic and tectonic forcings is key to predict how modern-day delta depositional environments will respond to modern-day changing climates. These shelf-margin depositional systems are also petroleum reservoirs and thus this topic is of interest to both academic and industry researchers. The principle analogues documented in publications include shelf-margin systems in the Ainsa Basin of Spain, West Siberia Basin of Russia, Spitsbergen Archipelago of Norway, and Magallanes Basin of Chile. The Coaledo Formation and Beds of Sacchi Beach, outcropping on the southern Oregon coast, provide an outstanding North American field analogue, yet, there have been few studies since the excellent work of Robert Dott Jr. and his students in the 1980's. This 2303m succession includes shoreface to slope gravity-flow sandstones encased in deep marine mudstones. The delta front channel facies include down-slope slump blocks overlain by a distributary channel complex with lateral shoreface parasequences of probable 200kyr cyclicity. These accessible cliff-face outcrops of continuously exposed strata provide an outstanding field example of sedimentologic organization and deformational overprint of shelf-margin deltaic facies. This continental margin succession affords an opportunity to analyze issues of tectono-eustasy and paleoclimate by linking the megafloral record of central Oregon to the Pacific Margin marine record for comparison with global oceanic paleontologic and isotopic history.

The first week of August 2019, our group from the **LSU Museum of Natural Science** and the Department of Geology and Geophysics (**Sophie Warny** and new graduate student **Allison Barbato**) joined three other members of the multidisciplinary "Coaledo Team" lead by John Armentrout (a sequence stratigrapher and sedimentologist, linked to the University of Oregon) to gain familiarity with the structural geology and depositional facies, and to collect samples for Allison's Master's project. In addition to John Armentrout, the "August" expedition included Kristin McDougall, a senior foraminifer specialist at the United States Geological Survey (USGS) and Laird Thompson, a structural Geologist (retired from Mobil). We focused our efforts around Cape Arago, Sunset Bay and Coos Bay where the sediments of the Eocene Coaledo Formation are beautifully exposed along the southwestern coast of Oregon. The sediments provide a spectacular marine record of forearc sedimentation, ranging from

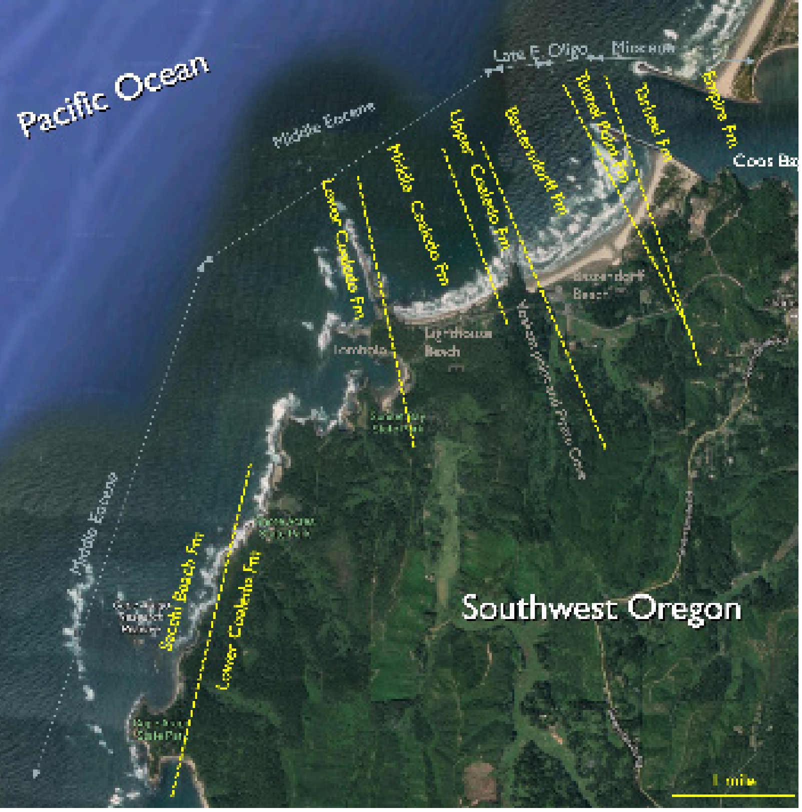
Title Photo: This drone photo shows the area of Sunset Bay State Park where the Eocene Coaledo Formation crops out along scenic headlands and bays of the Cape Arago area near Coos Bay, Oregon (photo by Rocky Johnson).



This figure illustrates the depositional facies of the Middle Eocene to Pliocene formations of the Coos Bay Basin we are testing. The deposition initiated with the (1) slope siltstones and associated channel and turbidite sandstone of the Beds of Sacchi Beach overlain by (2) progradational 'coaly' sandstones of the Middle Eocene Lower Coaledo. Transgression followed (possibly delta lobe avulsion) and deposition of (3) bathyal silty-mudstones of the Middle Coaledo overlain by the (4) prograding Upper Coaledo deltaic sandstone and conglomerate. Conformably overlying the Upper Coaledo are (5)Late Eocene-Oligocene Bastendorff shales of bathyal biofacies, again suggesting transgression (? avulsion). Gradationally overlying the Bastendendoff are Oligocene neretic sandstones of (6) the Tunnel Point Formation. During the latest Oligocene-earliest Miocene the basin was folded before deposition of the unconformably overlying (7) neretic Tarheel Formation. Folding again occurred in the middle Miocene followed by the subsequent deposition over the unconformity of (8) the Late Miocene neretic Empire Formation sandstone. Pliocene deformation again folded the basin resulting is truncation of all of the strata that are most recently overlain by Pleistocene marine terrace deposits.

turbidite to shoreface sandstone encased in deep-water siltstone and mudstone.

Results from this Master's thesis should allow us to evaluate the depositional history of the Middle Eocene Coaledo Formation in much greater details. With the addition of modern geochemical analyses, we will be able to test the hypothesis that the Coaledo Formation is a shelf-margin delta deposited during a global sea-level lowstand. Indeed, shelf-margin deltas typically deposit at relative lowstands of sea level when distributary systems incise to the shelf edge, and are often associated with significant bypass of coarse-sediment into the basin deep. The lowstand shelf-margin deltas prograde over deep-marine mudstones, and are then subsequently transgressed by deep marine mudstones as sea level rises. But shelf-margin delta may also form during highstand if there is sufficient sediment flux to prograde to the shelf edge. Many shelf-margin deltas are deposited during late lowstand when initial rise in sea level results in vertical aggradation of coarsening-upward parasequences. This results in high-preservation of laterally variable facies partitioned by marine flooding surfaces. This contrasts with highstand deltas that are deposited during a slow rise to eustatic stillstand followed by an initial fall in relative sea level. That progression of eustatic changes usually results in a change in stratigraphic architecture from aggradational to progradational of parasequences. The working hypothesis so far is that the Coaledo Formation consists of two cycles of deltaic progradation, each encased in previously interpreted bathyal mudstones. The dramatic



This figure shows a view of our current interpretation of the distribution of formations we sampled and the principle geographic names of the localities visited.

paleo-water depth changes associated with the two intervals of shallow marine Coaledo deltaic sandstone, each encased in very deep-water mudstone, has been interpreted from benthonic foraminiferal biofacies analyses. Based on the paleowater depths, it has been proposed that the Coaledo Formation is an outer-shelf to slope delta, and it is that hypothesis that is being tested by the research effort encompassing this palynological study. The large-scale proposed paleowater depth changes have been attributed to either tectonic deformation or to distributary avulsion. These hypotheses, previously proposed by the Robert Dott's team, will include a new age model based on zircons, updated biofacies interpretation from several fossil groups, and integration of paleowater depths from both sedimentologic and biofacies analysis. The provincial biozone ages will be updated using magnetic anomaly patterns, and radiometric dating of interbedded volcanic tuffs (by some of our other team members).

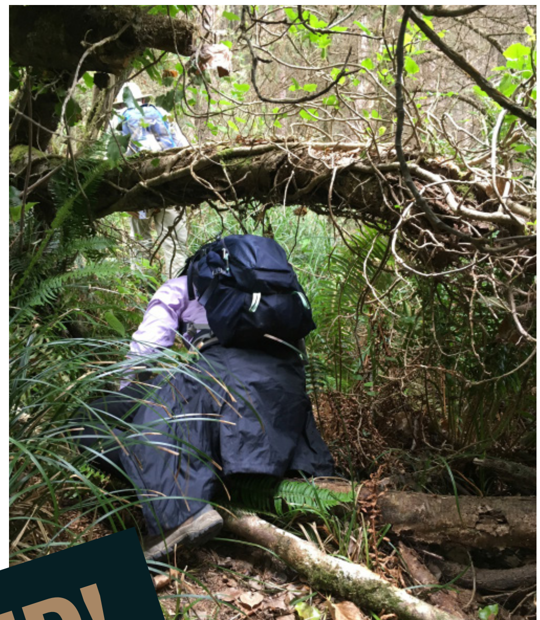
The sampling was a success!

Allison collected 88 samples spanning many of the mud layers found along the ~2300m of outcrop. Her sampling strategy was to focus on mudstones and other similar fine-grained layers that were sometimes difficult to access. The rare mudstones have a superior chance over sandstones to provide for optimal palynological yields. Now that she is back at the CENEX lab at LSU, Allison will split the samples three ways to conduct three different types of analyses.

First, she will conduct a classic palynological analysis. Samples will be processed to extract all organic-walled microfossils from the sediments. These should include dinoflagellate cysts (marine palynomorphs), and pollen and spores (terrestrially-derived palynomorphs). Dinoflagellate cyst analysis will provide biostratigraphic control and paleo-environmental data on the marine facies correlative to local known events and for regional paleo-oceanographic comparison with global events. Analysis of pollen and spores will provide details on past vegetation, type of environments and climate. These organic microfossils will allow us to assess changes of vegetation between subdelta environments and within cycles of both bathyal-to-outer neritic and inner neritic-to-shoreface sedimentation.

Comparison of marine vs. terrestrially-derived microfossils will be interpreted in a sequence stratigraphic framework to evaluate eustatic cycles. Sampling of muddy lithofacies in multiple cycles, both laterally and vertically, will allow documentation of changes in palynological assemblages both within the shallowing cycles and between the distributary front and delta margin facies. It is anticipated that variations will include marine, coastal plain and upland floral components. By integrating the palynomorph assemblage patterns with those data from foraminiferal, molluscan and elasmobranch biofacies, we should have multiple parameters for identifying discrete depositional settings.

Second, Allison will conduct the organic petrographic evaluation of the maturity of the organo-facies via a Thermal Alteration Index (TAI) study which consists of quantifying the degree of heat and pressure applied to the rock post deposition and, by measuring the vitrinite reflectance (Ro) in the samples, which consist of measuring the percentage of incident light reflected from a polished surface of vitrinite in an



Unlike our fellow curators, we often have no ideas what we are sampling and adding to the collections while we are in the field. We estimate the ages sampled and environment types, so we have best guesses, but no confirmation of the fossil yields until we are back in the lab and we extract the microfossils. Only then, do we know if our field campaign was successful.

Top and middle photos: From experience, we know that we have to look for the finest-grain sediments. Sands usually have a terrible yield in palynomorphs. The outcrop below (bottom photo) contains abundant sand layers. Although breath-taking, these rocks are likely barren in pollen, spores or dinocysts. Instead, as seen to the left, we looked for the most eroded layers to collect the palynological samples.

Bottom: The outcrop below is composed of depositional cycles of lateral to lowermost Lower Coaledo facies of stacked channel-complexes. The channel-complexes are sand-filled river distributaries abandoned and filled as the river-distributaries switched (avulsed) across the coastal plain. These are not ideal for palynological sampling.

MUD WANTED!

organic-rich sample. This will be done with the help of Thomas Demchuk at RPS.

Third, Allison will perform geochemical analyses to evaluate the total organic content (TOC) of the sediment to assess the amount of organic carbon present in the rock, to characterize the potentially varying organic facies within the deltaic system and confining deeper-water marine mudstones.

To understand how we can have 'stack' cycle upon cycle like seen in the top photo on page 28, one needs to consider two working hypotheses 'forcing' this cyclicity. One hypothesis uses the Mississippi River as a model, with the lateral switching of river-fed depositional lobes. Each lobe consists of a shoaling-upward facies cycle and as the delta compacts and subsides, new space becomes available for another shoaling upward cycle to be deposited. A second hypothesis is the cycles are climate or tectonically 'forced', with constant subsidence of the basin margin filled by pulses of increased sediment supply due to more rapid uplift and erosion of the adjacent mountains. This uplift and erosion provides an increase supply of sediment resulting in rapid progradation of the shoreline. One goal of the Coaledo Project is to integrate multiple data sets to identify the most probable geologic process resulting in the depositional cycles.

We wish Allison tons of success with her project and we are delighted that this project gives us the opportunity to collaborate with the diverse community of paleontologists and geologists of the Coaledo Project Team.

More pictures from this trip can be seen on the following pages.

Top: To get to the Qochyax Island tombolo takes a bit of effort. After a quarter mile of brushy trails, there is a 60 foot 'bank' (cliff) to descend. We all survived both entry and exit to the study area.

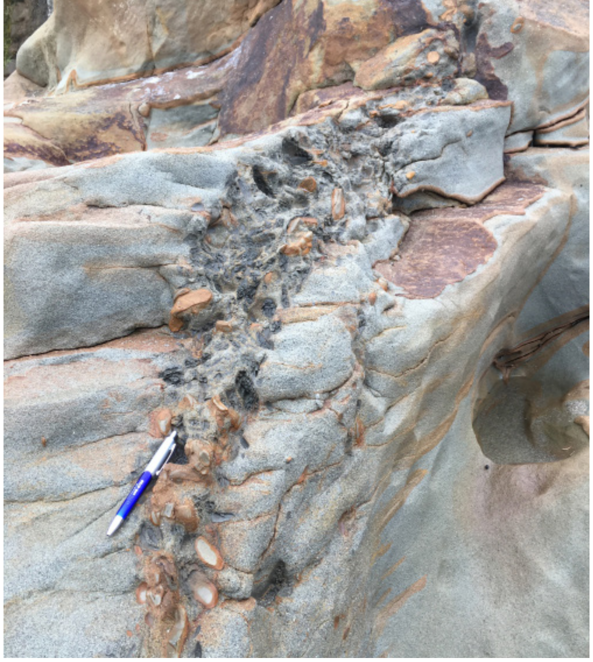
Bottom: Within the Upper Coaledo section is a 1.5 meter thick coal bed (black layer below sandstone), correlated with the Beaver Hill Coal Seam. Could it be correlated with the Middle Miocene Climatic Optimum? This is an exciting question to investigate for Allison.

It is quite ironic that, while we cannot see the microfossils we are collecting (but we hope are present in the mud), creatures long gone leave a very visible trace in the form of fossilized burrows.

Top: Modern clam (pholad) bored boulders as comparison. [Yoakum Point Cove, Yoakum Point State Park]

Bottom Left: Part of the reward to getting to the tombolo outcrop is discovery of Teredo-clam bored fossil-wood, a clear indicator of marine condition but of no help in estimating paleowater depths as water logged wood sinks. [Qochyax Island Tombolo, Sunset Bay State Park]

Bottom Right: This sandstone is highly burrowed, perhaps supporting a shallow water-type environment in clearly well oxygenated conditions. [Qochyax Island Tombolo, Sunset Bay State Park]



Field work in the Coaledo formation provided data on a suite of sedimentary structures, a wonderful way for the rocks to tell us their stories.

Top Left: Occasional small channel-forms filled with mudstone ripups and coalified wood clasts.

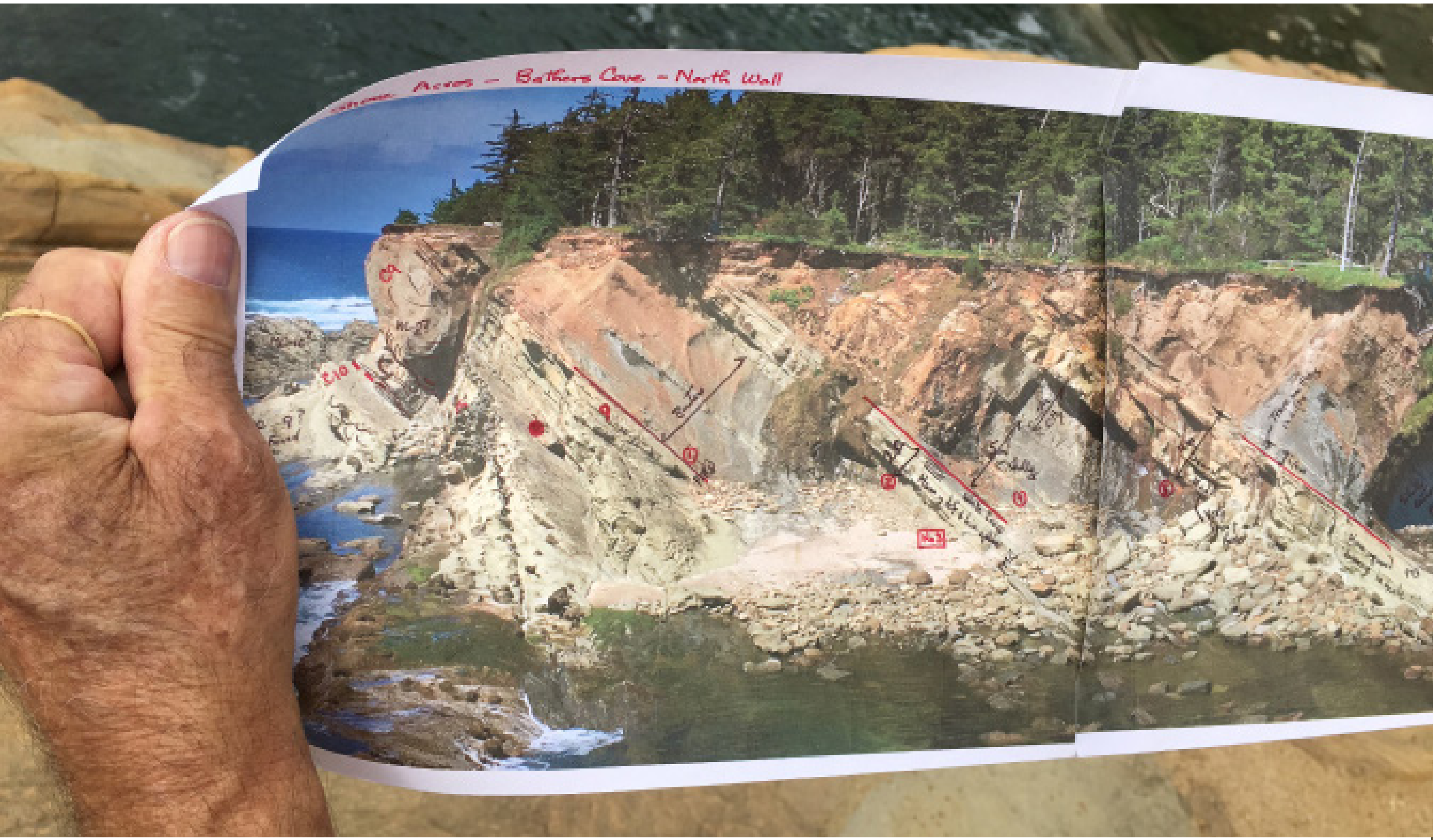
Top Right: The sandstone is typically hummocky or trough-cross bedded as in this photo, illustrating the high wave energy of shallow environments.

Middle Left: This photo shows multiple hummocky cross-stratified fine to medium-grained sandstone, with the thickest very-light colored unit Allison stand upon being an amalgamated set of hummocks.

Middle Right: Hummocky beds with scour as the sand is 'lifted' by waves and then settles as more hummocky strata.

Bottom Left: Toward the top of Middle Coaledo the occurrence of tabular foresets and hummocky cross-bedded sandstones suggest shallowing. This facies transition grades upward into the very sandy and conglomeratic Upper Coaledo at Yoakum Point.

Bottom Right: Ripple laminated surfaces most probably related to near-shore storm deposits.



Top: This photo shows three coarsening-upward mud (gray)-to-sand (reddish-tan) cycles along the north shore of Bathers Cove.

Bottom: The Bathers Cove cycles are sketched-in on this photomosaic.

Although macrofossils are not part of our study, it is always exciting to see the diversity in outcrop and learn from the clues they give us.

Top: Crepidula cluster at Fossil Point.

Middle Left: Some of the muddy sandstones contain abundant fossils, here of the gastropod *Turritella*, the modern relatives of which range in water depths from 20 to 200 meters.

Center: Gastropod in the Empire Formation (a younger Miocene-age formation).

Middle Right: *Patinopecten coosensis* in Empire Formation.

Bottom Left: Warny and Barbato are grateful for the guidance in the field by Armentrout and Thompson (center). We got too excited by all the mud found in the cove behind that outcrop and forgot about the tide! (Photo: Kristin McDougall)