CHAPTER 100

TRACERS OF SAND MOVEMENT ON THE OREGON COAST

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ABSTRACT

The study of sand mineralogy and grain rounding can help answer many questions of immediate concern to coastal engineers or to broader issues of beach preservation. The heavy-mineral contents of sands, together with statistical techniques such as factor analysis, can be used to delineate sediment sources, trace transport paths, and map out patterns of mixing during sediment dispersal. Variations in the degree of grain rounding can similarly be used to trace sand movements, or to obtain additional information concerning the history of the sediment particles.

The techniques of studying sand mineralogies and grain rounding, and the types of problems they can address, are illustrated by research on the Oregon coast. Heavy mineral compositions of Oregon beach sands are the products of mixing contributions from four sources; the Columbia River on the north, the smaller rivers draining the Coast Range, the Umpqua River on the southern Oregon coast, and the Klamath Mountains of southern Oregon and northern California. Numerous headlands now prevent the longshore transport and mixing of sands from these multiple sources. The beach-sand compositions instead reflect along-coast mixing during Pleistocene lowered sea levels when blockage by headlands was absent. At that time there was a net littoral sand transport to the north, evident from the dispersal of Klamath-derived sands. With a rise in sea level and accompanying migrations of the beaches, headlands eventually interrupted the along-coast mixing of nearshore sands. Therefore, the north to south variation in compositions of beach sands is in part a relict pattern inherited from mixing during lowered sea levels. This has been modified during the past several thousand years by some additions of sand to the beaches from sea-cliff erosion and from rivers. However, studies of sediment mineralogy and grain rounding indicate that sands derived from most rivers draining the Coast Range are presently trapped in estuaries and so are not significant sources of beach sand. The Columbia River now supplies sand to Oregon beaches only to the first headland, Tillamook Head. At that headland there is a marked change in mineralogy and grain rounding with angular, recently supplied Columbia River sand to the north and rounded relict sand to the south.

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INTRODUCTION

The mineral compositions of sands and properties of individual particles such as their degrees of rounding can be utilized to trace movements of sediments in the coastal zone. This was illustrated many years ago by the pioneering studies of Parker Trask who investigated the movement of beach sand along the southern California coast (Trask, 1952). Trask was able to demonstrate that the sand filling the harbor at Santa Barbara comes from a distance of more than 160 km up the coast. He concluded this by using the heavy mineral augite as a tracer, a mineral whose source is ancient volcanic rocks near Morro Bay to the north of Santa Barbara. This mineral, together with the lighter quartz and feldspar, moves to the south along the beaches as littoral drift, until it is trapped by the Santa Barbara breakwater.

This simple example from the work of Trask illustrates the potential of applications in the use of the mineralogy of sediments to determine their sources and transport paths. In this example there was a clear application to an engineering problem – shoaling in the Santa Barbara boat basin. However, such techniques can be used to examine a range of questions concerning sources and losses of beach sands: Will dam construction on a river cut off a major source of beach sand?; Are river sands able to pass through estuaries to reach ocean beaches?; Is erosion of cliffs backing the beach a major source of nearshore sands?; Is the sand on the beach able to pass around headlands? Answers to such questions are often important to the proper design of coastal engineering structures, and to the preservation of beaches.

It is unfortunate that coastal engineers seldom draw upon this type of information. Considerable advances have been made in the techniques of studying sand mineralogies and grain rounding since the study of Trask (1952). These advances now permit more refined analyses and interpretations. A general objective of this paper is to illustrate the types of studies that can be undertaken, utilizing examples from the Oregon coast. These examples include the findings of studies which have attempted to determine the sources of beach sands on the central-Oregon coast, and examinations of the exchange of sand between estuaries and adjacent beaches. The Oregon coast is ideal to illustrate the types of investigations that can be undertaken in that all of the questions cited above are relevant to an understanding of beach-sand sources and transport paths.

TECHNIQUES OF STUDY

Heavy minerals such as augite contained within sands are distinguished from the light minerals, principally quartz and feldspars, by their contrasting densities. Laboratory techniques to separate the light and heavy minerals have in the past employed the heavy liquids bromaform (density 2.88 g/cm^3), tetrabromoethane (2.95) and methylene iodine (3.30). These heavy liquids are highly toxic, and so considerable care must be taken in the mineral separations. Fortunately, the use of the much safer sodium polytungstate (3.00) has recently been introduced (Callahan, 1987). Identification of the individual heavy minerals is accomplished with a microscope using standard petrographic techniques. The heavy-mineral separates are mounted on slides in a liquid such as Canada Balsam which has a known index of refraction, and usually some 100 to 300 non-opaque heavy minerals are identified and counted. This yields the percentages of the various non-opaque heavy minerals.

Variations in the degree of grain rounding can also be used to trace sand movements, or to obtain additional information concerning the history of the sand. Roundness is a measure of the sharpness of the grain's corners and edges, and is distinguished from sphericity which is a measure of the degree to which the grain deviates from a sphere. When grains are transported, collisions abrade their sharp edges so that the average degree of rounding progressively increases. In the case of sand-size grains, it has been shown that transport in rivers causes very little abrasion and rounding, and would produce minimal changes over typical river lengths (Kuenen, 1959). On the other hand, the long-term action of surf on beaches can eventually lead to grain rounding. It is difficult to evaluate the time periods required for rounding sand grains on beaches, but most investigators qualitatively assess it as involving thousands of years.

A major problem in studies of grain rounding has been in its quantification. Powers (1953) and Shepard and Young (1961) provide standardized series of grain images ranging in degrees of roundness. Comparisons between grains of the sample and these images allows one to place them in one of six categories ranging from "very angular" to "well rounded", or to assign corresponding numbers 1 through 6. However, this approach is subjective and can be viewed as only semi-quantitative. We have been able to use this approach in studies of Oregon coast sands due to the significant differences in angularity between the fresh river sands and the beach sands which have suffered appreciable abrasion. A more quantitative and reproduceable approach has been introduced by Schwartz and Shane (1969) and Ehrlich and Weinberg (1970) which involves Fourier analyses of the digitized outlines of the grains. The lower harmonics in such analyses relate to the overall shape of the grain, being more of a measure of the grain's sphericity, while the higher harmonics in part reflect the grain's degree of rounding. Studies such as that by Mazzullo et al. (1984) demonstrate that analyzing grain shapes by this approach can yield information on sand sources and transport paths. Techniques have been devised which automatically digitize grain outlines viewed under a microscope, with subsequent derivations of the harmonics of the Fourier analyses. This is necessary in that when the application is to trace sand movements, measurements are required on hundreds of grains in any given sample.

OREGON-COAST MINERAL STUDIES

The Oregon coast provides an ideal location to illustrate the usefulness of studies of sand mineralogy and grain rounding to obtain a better understanding of sources and transport paths of coastal sands. There are multiple sources having reasonably distinctive mineralogies which supply sands to the nearshore. The rivers contain angular sand grains which are progressively rounded during transport on beaches. It will be seen that combined studies of mineralogy and grain rounding indicate that Oregon beach sands have had a long and complex history. Contrasts in mineralogies and grain rounding between beach and river sands have also permitted detailed examinations of transport paths within Oregon estuaries.

Coastal Morphology and Potential Sand Sources

Much of the Oregon coast consists of a series of large rocky headlands which separate and isolate stretches of beaches. The headlands are composed of highly resistant volcanic rocks, while the beaches exist in areas backed by more easily eroded sedimentary rocks. This segments the coast into a series of pocket beaches where the lengths of the stretches of beach vary from about 5 to 100 km depending on the spacings of the volcanic rocks which form headlands. The northern half of the Oregon coast is shown in Figure 1, which illustrates this interplay of headlands and pocket beaches. The headlands extend well offshore from the beaches, and generally have considerable along-coast lengths. This implies that they prevent or severely limit any bypassing of beach sands. As will be seen, this view is supported by studies

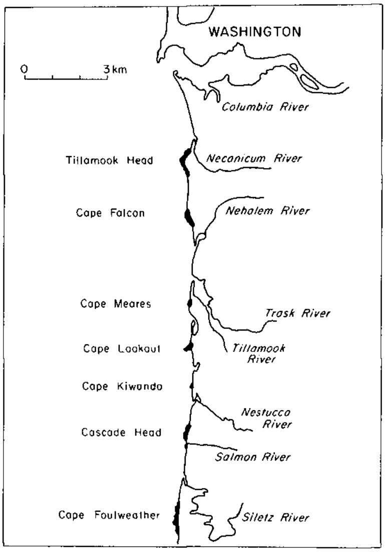

Fig. 1: The northern coast of Oregon, showing the interplay between headlands and beaches.

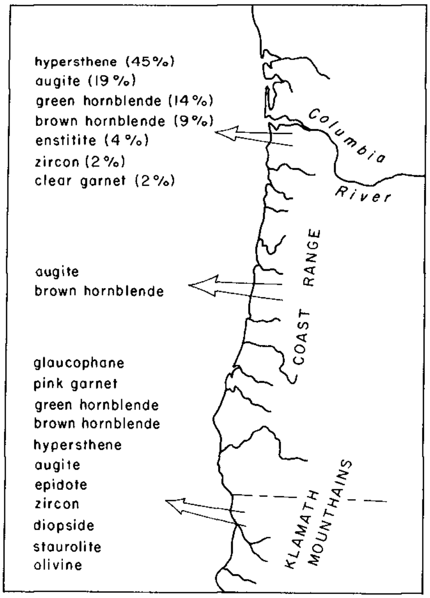

Fig. 2: Schematic of the principal sources of heavy minerals used to trace sand movements on the Oregon coast.

of beach-sand compositions and grain rounding. Therefore, the headlands act to isolate the individual beaches. Portions of the beaches form sand spits behind which are found bays and estuaries of the rivers that drain the Coast Range. Other portions of the beach are backed by sea cliffs eroded into Tertiary mudstones and siltstones, or into Pleistocene sand deposits that are part of uplifted marine terraces. These terrace deposits are raised beach and dune sands, so their erosion can be a significant source of sand to the modern beaches.

The Columbia River is potentially the largest source of sand to the nearshore. Its drainage basin is very large and contains many different types of rocks. A result of this is that sand supplied to the coast by the Columbia contains a wide variety of heavy minerals with hypersthene, augite and hornblende being the most abundant (Fig. 2). It is known that sand derived from the Columbia has resulted in beach accretion on the Oregon coast south to Tillamook Head (Fig. 1). However, at present most of the sand derived from the Columbia is transported northward along the Washington coast.

A number of rivers of various sizes reach the Oregon coast from the nearby Coast Range (Fig. 1), and these are another potential source of beach sands. This range of low mountains (450-m average elevation) contains volcanic rocks which yield augite, the mineral that together with a small amount of brown hornblende dominate river-sand compositions (Fig. 2). South of Cape Blanco the Coast Range gives way to the older but higher Klamath Mountains. The Klamaths contain complexly folded metamorphic rocks and intrusions of serpentinized ultrabasic and granitic rocks; these yield a wide spectrum of heavy minerals (Fig. 2), with glaucophane, pink garnet and other metamorphic minerals being tracers unique to this source.

Compositional Variations of Oregon Beach Sands

There have been a number of studies of the mineralogies of Oregon beach sands, largely induced by the economic potential of concentrated deposits of the opaque minerals (Kulm et al., 1968; Scheidegger et al., 1971; Komar and Wang, 1984). These studies demonstrated that Oregon beach sands have had multiple sources. Of particular interest is that metamorphic minerals such as pink garnet, which clearly originated in the Klamath Mountains, are traceable northward along nearly the full length of the Oregon coast. The southward dispersal of sand derived from the Columbia River was less apparent in the results of those studies, and it was uncertain how much sand has been derived from rivers that drain the Coast Range. There appeared to be along-coast variations in the relative mixtures of sands derived from these potential sources, but this had not been clearly delineated by the early investigations. In addition, an important question involved whether the rocky headlands are effective in blocking along-coast sand movements. Does the finding of Klamath Mountain sands in the beaches along nearly the entire Oregon coast imply that there is bypassing in spite of the large sizes of most of the headlands?

In order to answer such questions, we undertook a detailed study of the mineralogy and grain rounding of Oregon beach sands (Clemens, 1987; Clemens and Komar, 1988). Sand samples were collected from 26 beaches extending from immediately south of the Columbia River to Cape Blanco on the south-Oregon coast. Sand samples were also obtained from rivers and sea cliffs that are potential sources of beach sand. In total 18 different minerals were identified in microscopic analyses of the samples, but the major constituents are augite, hornblende, hypersthene and garnet. The percentages of those four major heavy minerals are plotted in Figure 3, revealing how they vary with along-coast distance south of the Columbia River. The most noticeable variation is in the percent of augite, which dominates beach-sand compositions between Tillamook Head, the first headland south of the Columbia River, and Cape Foulweather midway through the study area. These augite-rich beach sands appear to reflect contributions by the Coast Range volcanics directly landward from this stretch of coast. North of Tillamook Head the percentage of augite abruptly drops as the beach is richer in hornblende and hypersthene, minerals that are clearly derived from the Columbia River. The content of garnet in the beach sands systematically increases toward the south (Fig. 3), an expected distribution in view of its source in the Klamath Mountains of southern Oregon. Of interest is that garnet is found in beach sands all the way north to Tillamook Head, some 500 km north of its source.

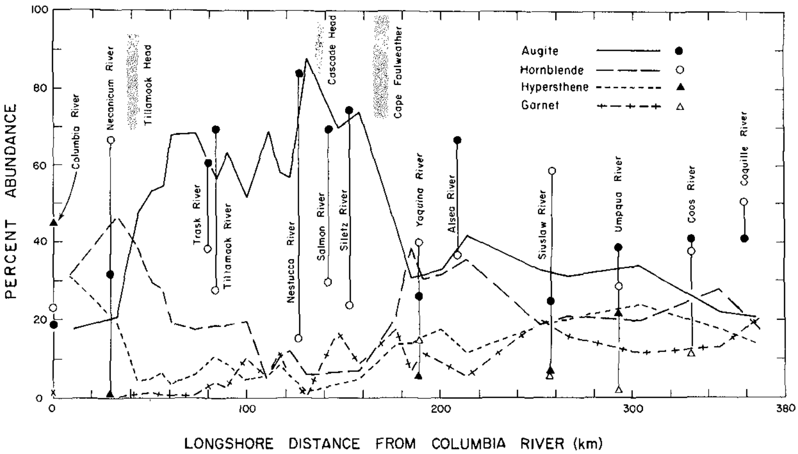

Fig. 3: Along-coast variations in abundances of the principal heavy minerals found in Oregon beach and river sands. [*from* Clemens and Komar (1988)]

The along-coast distributions of individual minerals, Figure 3, has already permitted tentative interpretations of sources and dispersal routes of beach sands on the Oregon coast. We have identified minerals that are suggestive of various sources and have qualitatively assessed their relative contributions along the length of the coast. The abrupt compositional changes at Tillamook Head and Cape Foulweather indicate that at least those headlands are effective in blocking longshore sand movements on the beaches.

Factor analysis is in general a more powerful approach to interpreting mineral assemblages than relying on individual minerals. Factor analysis examines natural groupings of minerals found within the assemblages contained in the series of individual samples (Imbrie and van Andel, 1964). The technique searches for end-member vectors or factors which can be summed in varying proportions to yield the mineralogies of the samples. Such an analysis (Q-mode factor analysis) was undertaken on the heavy-mineral percentages found in the Oregon beach-sand samples (Clemens and Komar, 1988). Three dominant factors were derived which account for 89% of the compositional variations in the samples. The mineral compositions of these end-member factors are given in Figure 4, and their

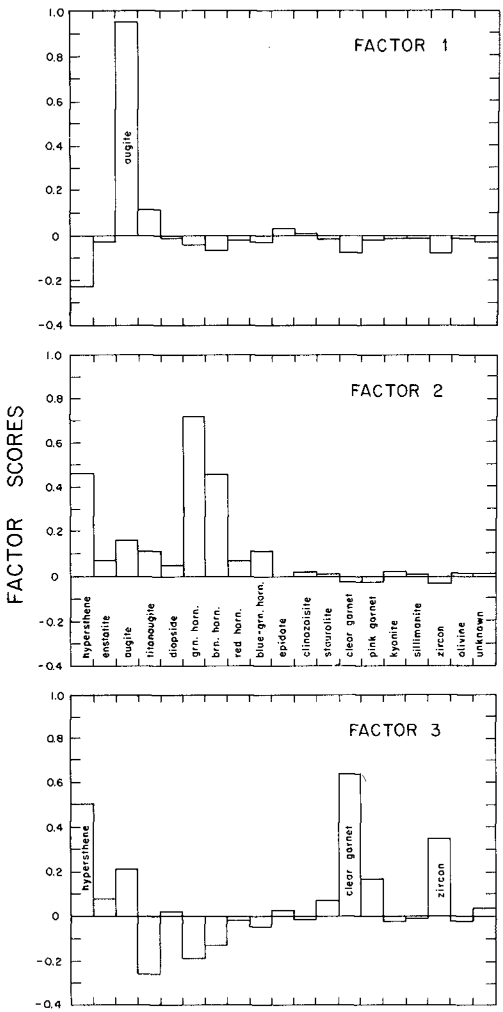

Fig. 4: Compositions of the factors obtained in factor analyses of the heavy mineral compositions of Oregon beach-sand samples. [*from* Clemens and Komar (1988)]

along-coast variations are graphed in Figure 5. Factor 1 consists almost entirely of augite, and it is seen that this factor dominates the beach-sand compositions between Tillamook Head and Cape Foulweather. In this case, since there is a source consisting of essentially one mineral, the results from the factor analysis correspond closely with our analysis based on individual minerals (Fig. 3). Factor 2 is rich in hypersthene and green and brown hornblende (Fig. 4). This factor has a bimodal distribution along the coast (Fig. 5). Its main loading, approaching 1, occurs on the beach north of Tillamook Head and is clearly associated with the Columbia River which is rich in those minerals. The more southerly increase in Factor 2, extending from 190 km south of the Columbia to the end of our sample range at 365 km south, is most likely contributed by the Umpqua River. Sand derived from that river has a high content of both hypersthene and hornblende, as well as augite, and with its large drainage basin the Umpqua could have been a major source of beach sand (more so than the other rivers draining the Coast Range). Therefore, Factor 2 appears to be associated with two major sources that are similar in compositions, the Columbia and Umpqua Rivers. This interpretation is verified if the river-sand samples are included in the factor analysis together with the beach samples. The Columbia River is then identified as 100% Factor 2, and the Umpqua River sand is found to consist of nearly equal portions of Factors 1 and 2.

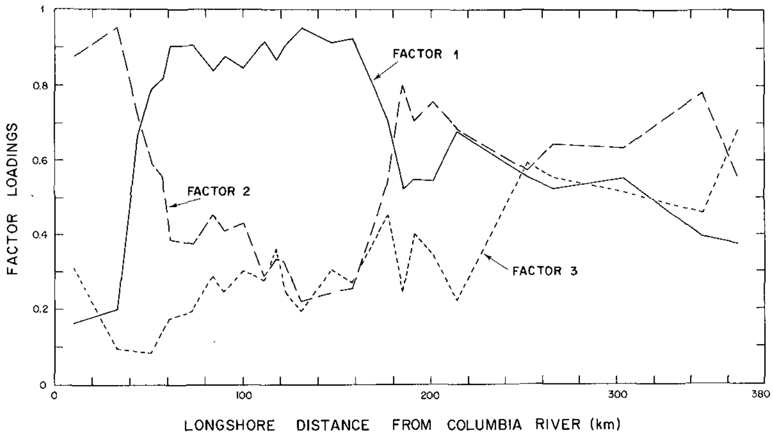

Fig. 5: Along-coast loadings of the three factors (fig. 4) obtained in the analyses of the beach-sand compositions. [*from* Clemens and Komar (1988)]

Factor 3 is rich in garnet and zircon (Fig. 4), and also includes the metamorphic minerals staurolite and epidote. This composition, together with its northward, along-coast decrease (Fig. 5), clearly points to a source in the Klamath Mountains. This interpretation is the same as in Figure 3 which was based on garnet alone, but is more firmly established here by a complete assemblage of metamorphic minerals.

It is apparent that more information about sand sources and dispersal paths can be obtained from factor analyses than from distributions of individual minerals. Considerable interpretation is still required, but the end-member factors can generally be traced back to specific sources. These sources may not necessarily be individual rivers, but instead could be rock terrains. This is the case on the Oregon coast where it is better to think in terms of the sources being the metamorphic rocks of the Klamaths, the augite-rich volcanics of the Coast Range, and the hypersthene and hornblende-rich rocks of the Cascade Mountains. We have seen that the Umpqua River combines two of these terrain sources.

The switch from Factor 1 (Columbia River sand) to Factor 2 (Coast Range) is seen in Figure 5 to be abrupt at Tillamook Head, more so than the change in augite alone (Fig. 3). This further substantiates the ability of Tillamook Head to block longshore movements of beach sands. While determining the heavy-mineral compositions of the samples, differences in grain rounding were also noted in the sands on opposite sides of Tillamook Head. North of this headland the heavy-mineral grains are highly angular and many delicate crystals are present, while to the south they are noticeably more rounded. This change was further established by using the photo-comparison roundness scale of Shepard and Young (1961). Roundness was evaluated for about 50 grains of each mineral in a sample, yielding a distribution of roundness values for a mineral. Such analyses were primarily performed on augite, but some evaluations were also made for hypersthene, hornblende and quartz. The results are shown in Figure 6 for samples from the Columbia River, and from the beaches to the south of the Columbia but on opposite sides of Tillamook Head. A significant change in rounding is seen to occur at Tillamook Head, the beach sands to its north being more angular than to the south. Augite in the beach north of Tillamook Head appears to retain the same degree of high angularity as sand in the Columbia River. This, together with the fragile nature of some of the mineral crystals in the beach sands, indicate active contributions from the Columbia. The rounder grains on the beaches south of Tillamook Head suggest a much longer residence time for those sands in the nearshore.

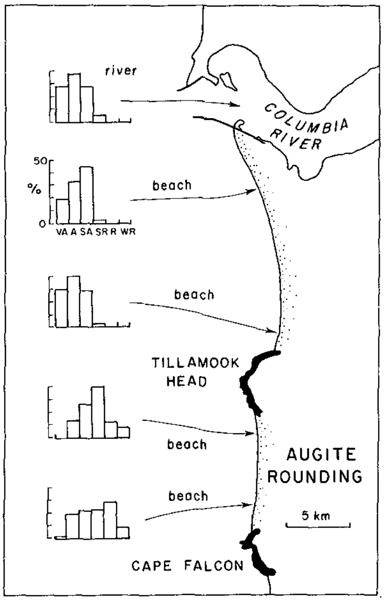

Fig. 6: Histograms of grain rounding for augite in river and beach sands: VA - very angular; A - angular; SA - subangular; SR - subrounded; R - rounded; WR - well rounded.

The only other headland which demonstrates a marked compositional change in beach-sand mineralogies on its north and south sides is Cape Foulweather (Figs. 3 and 5). This change can be attributed to differences in materials derived primarily from sea-cliff erosion. North of Cape Foulweather most of the cliff erosion has been in alluvium derived from the Coast Range and therefore is rich in augite (like the rivers draining the Coast Range). Pleistocene marine terraces are more important south of Cape Foulweather, and these terraces contain uplifted beach and dune sands. These old deposits contain a full spectrum of minerals from the various sources including the Columbia River and the Klamath Mountain metamorphics.

It might mistakenly be concluded from our results that Tillamook Head and Cape Foulweather are the only headlands that are effective in blocking movements of sand on the modern beaches. However, blockage by those headlands is made apparent by differences in sand sources on their opposite sides. If the sand sources to the north and south are much the same and the long-term history of the sands do not differ, then there will be no compositional or textural differences. Tillamook Head and Cape Foulweather are not unusually large, nor do they extend to deeper water than most of the other headlands. Therefore, it is probable that the other headlands are also effective barriers to longshore sand movements, even though this could not be established directly by our analyses of beach sands.

The results of our investigations of Oregon beach-sand mineralogies and grain rounding have confirmed that the compositions are derived from the mixing of sands from multiple sources. All beaches, excepting those south of the Columbia River to Tillamook Head, contain significant quantities of metamorphic minerals derived from the Klamath Mountains of southern Oregon and northern California. This indicates a northward transport of sand along the coast, but this transport cannot occur now due to the presence of headlands. Instead, it must have taken place during Pleistocene lower stands of sea level when headlands did not interrupt such sand movements. With a rise in sea level at the end of the ice ages and accompanying migrations of the beaches, the formerly continuous beach became segmented and isolated between headlands. Therefore, much of the along-coast variation in beach-sand mineralogies on the Oregon coast is relict, preserving the longshore patterns established thousands of years ago when sea levels were lower. The beach-sand compositions have been altered somewhat during the last few thousand years following their isolation between headlands. Most noteworthy has been the growth of the beach north of Tillamook Head due to large sand contributions by the Columbia River. However, elsewhere the additions must have been comparatively small since the volumes have not been sufficiently large to obscure the relict pattern established thousands of years ago. This implies that modern-day inputs of sand to most Oregon beaches from sea cliff erosion and from rivers draining the Coast Range are relatively small.

Exchanges of Sand Between Beaches and Estuaries

A primary reason for the small contributions of sands to beaches from rivers draining the Coast Range is that most of these rivers are separated from the ocean by estuaries. To varying degrees, these estuaries trap the river sands. This has been established by Kulm and Byrne (1966) and Byrne and Kulm (1967) in Yaquina Bay, by Scheidegger and Phipps (1976) in Grays Harbor, Washington, and by Peterson et al. (1982, 1984) in several other Oregon-coast estuaries.

In their investigations of Yaquina Bay, the estuary of the Yaquina River, Kulm and Byrne (1966) were able to establish the three realms of deposition diagramed in

Figure 7; a marine realm which extends approximately 2.5 km into the bay from the ocean inlet, a fluviatile realm in the upper reaches of the bay, and a broad "mixed" realm which is a zone where the two sand sources mix in varying proportions. These were delineated on the basis of sediment grain sizes, compositions, and particle rounding. The compositional distinctions included not only differences in heavy minerals found in the marine versus fluviatile sands, but also in the mineralogy of the feldspars and the distribution of "yellow grains". Yellow grains are diagnostic of marine sands where they constitute about 10% of the light-mineral fraction; they consist primarily of weathered feldspars and chert, and are derived from erosion of terrace sands in the sea cliffs. Because they are distinctive and easily recognized, yellow grains can serve as a simple tracer of marine-sand movements into Yaquina Bay (Fig. 8). Heavy minerals such as staurolite and kyanite, found in the beach sands but not in the Yaquina River, were also used by Kulm and Byrne as tracers of marine-sand movement into Yaquina Bay.

Peterson et al. (1982) has demonstrated a similar pattern of mixing of marine and fluviatile sands in Alsea Bay. However, the use of factor analysis of heavy-mineral assemblages, together with quantitative measurements of grain rounding, permitted a more detailed mapping of the transport paths of sands in this estuary. Based on the abundances of 15 non-opaque heavy-mineral varieties in surface sand samples, two factors were obtained in a factor analysis which account for 95% of the sample variance. One factor consisted almost exclusively of augite, and this end member represents contributions by the Alsea River. In contrast, the marine-related factor was composed of a number of minerals including hyperthene, hornblende and garnet. The weightings assigned to these two factors for each sand sample in Alsea Bay represented the respective contributions by the river versus the marine beach. Peterson et al. also noted that the augite and hornblende grains of fluvial origin are angular, while those of marine origin are rounded. This provided another means to evaluate sources and trace sand movements in Alsea Bay. The delineation of sand mixing in Alsea Bay by the two methods, factor analysis of heavy-mineral compositions and grain rounding, yielded essentially the same results. The general patterns are similar to those found by Kulm and Byrne (1966) in Yaquina Bay (Fig. 7), with marine sand dominating near the mouth, a broad zone of marine-fluviatile mixing, and pure riverine sands occurring only in the upper reaches of the estuary. However, more details of the mixing patterns were established in Alsea Bay, the tidal channels clearly serving as conduits of sand transport throughout the central estuary with an interfingering of sands from the two sources. Repeated sampling in different seasons revealed that down-channel transport of fluviatile sands occurs during winter periods of high river discharge, while beach-sand intrusions under tidal currents occur during the summer months of low river discharges.

Similar analyses have been conducted in other Northwest estuaries: Grays Harbor, Washington (Scheidegger and Phipps, 1976), the Sixes River estuary, Oregon (Boggs and Jones, 1976), Tillamook Bay, Siletz Bay, and the estuaries of the Siluslaw and Salmon Rivers (Peterson et al., 1984). Although these investigations demonstrated that most Northwest estuaries act as traps for both fluviatile and marine sands, it is more difficult to establish whether some river sand is able to pass through an estuary to become a source of beach sand. Small rivers such as the Sixes River studied by Boggs and Jones (1976), have essentially no estuary, and during winter floods the riverine sands are flushed out onto the neighboring beaches. However, since the rivers are small, the volumes of sand contributed to the beach are small. More uncertain is whether the larger rivers, such as the Yaquina and Alsea,

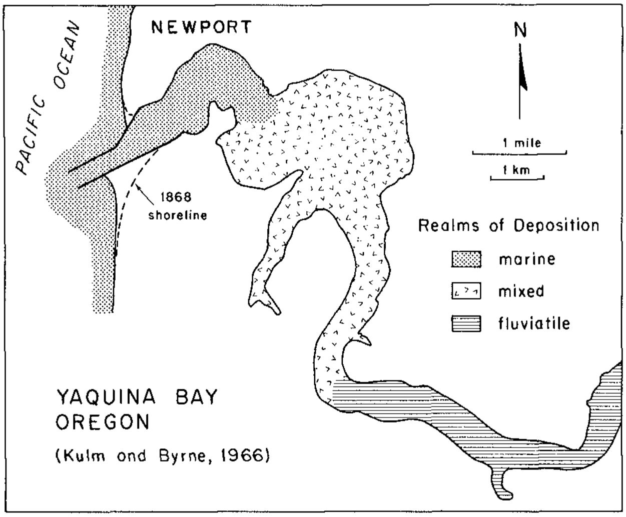

Fig. 7: Realms of sand deposition in Yaquina Bay. [*after* Kulm and Byrne (1966)]

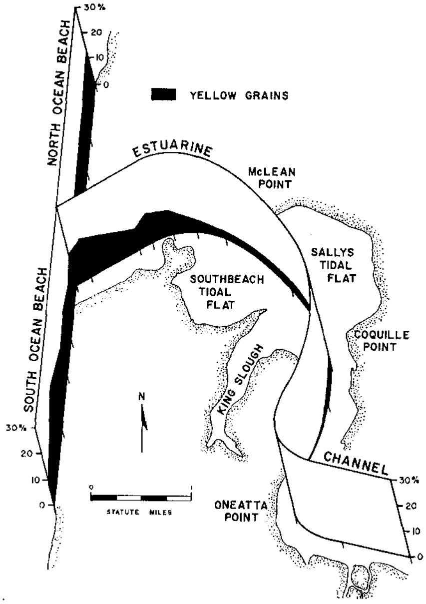

Fig. 8: Distribution of "yellow grains" in Yaquina Bay, used as a tracer of marine-sand movements into the estuary. [*from* Kulm and Byrne (1966)]

supply sands to Oregon beaches. Heavy minerals transported by these rivers are abundant on the adjacent beaches, and this correspondence might suggest that some river sands do pass through the estuaries. However, it is possible that most of the beach sand derived from rivers draining the Coast Range is relict, and reached the beaches during lower stands of sea levels when drowned-river estuaries were not present. It is likely that the degree of grain rounding will be the key to determining whether the Coast Range sands found on the modern beaches are relict or represent recent additions. Clemens and Komar (1988) analyzed the rounding of augite in beach samples from Neskowin near the Nestucca River, again using the photographic chart of Shepard and Young (1961). We found something of a bimodal distribution in the sand angularity, and suggested that the more angular mode might represent recent contributions by the Nestucca River while the mode of higher grain rounding represents relict augite in the beach sand. The Nestucca River has a reasonably small estuary so it could be expected that some riverine sand does reach the ocean beach. The results from this one location suggest that a comprehensive study of grain rounding of Oregon beach sands would help answer questions concerning which rivers are presently supplying sands to the nearshore. However, it is also apparent that using the photo roundness scale of Shepard and Young would be inadequate in this application, and that the more quantitative approach of using Fourier shape analyses would be required.

SUMMARY OF CONCLUSIONS

Studies of the mineralogies and grain rounding of sands on the Oregon coast have helped answer many questions relevant to the preservation of beaches and have led to an increased understanding of estuarine sedimentation. Differences in beach-sand mineralogies and grain rounding on opposite sides of headlands confirm that they are effective in blocking longshore sand movements and therefore isolate the beaches. The mineralogy studies have further established that most beaches contain relict sands, transported alongshore from various sources during lowered sea levels when headlands did not exist, and then onshore with the rising sea at the end of the last glacial period. This origin explains the observed patterns of along-coast variations in beach-sand mineralogies. Our research has established that sea-cliff erosion is a source of sands to some beaches, although the quantities generally are not so large as to have completely diluted and masked the relict sands on the beaches. Studies of estuarine sedimentation show that the river-drowned estuaries are sinks of both river and beach sands; additional research is required to establish whether measureable quantities of riverine sands are able to bypass these estuaries to reach the ocean beaches.

These Oregon-coast studies have been used in this review to illustrate the types of applications and questions that can be addressed using techniques of mineral compositions and textures to trace sand movements. Such studies could be used by engineers working in other coastal areas to assist in the proper design of structures and to help in the preservation of our coastlines.

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REFERENCES

BOGGS, S., and JONES, C.A. (1976) Seasonal reversal of flood-tide dominated sediment transport in a small Oregon estuary: Geol. Soc. Amer. Bull., v. 87, p. 419-426.

BYRNE, J. V., and KULM, L. D. (1967) Natural indicators of estuarine sediment movement: *Jour. Waterways and Harbors Div., Proc. Amer. Soc. Civil Engrs.*, v. 93, no. WW2, p. 181-194.

CALLAHAN, J. (1987) A nontoxic heavy liquid and cheaper filters for separation of mineral grains: *Jour. Sedimentary Petrology*, v. 57, p. 765-766.

CLEMENS, K. E. (1987) Along-coast variations of Oregon beach-sand compositions produced by the mixing of sediments from multiple sources under a transgressing sea: Unpubl. Master's Thesis, Oregon State Univ., Corvallis, 75 p.

CLEMENS, K. E., and KOMAR, P. D. (1988) Oregon beach-sand compositions produced by the mixing of sediments under a transgressing sea: *Jour. Sedimentary Petrology*, v. 58, p. 519-529.

EHRLICH, R., and WEINBERG, B. (1970) An exact method for characterization of grain shape: *Jour. Sedimentary Petrology*, v. 40, p. 205-212.

IMBRIE, J., and VAN ANDEL, TJ. H. (1964) Vector analysis of heavy mineral data: *Geol. Soc. America Bull.*, v. 75, p. 1131-1156.

KOMAR, P. D., and WANG, C. (1984) Processes of selective grain transport and the formation of placers on beaches: *Jour. of Geology*, v. 92, p. 637-655.

KUENEN, Ph. H. (1959) Experimental abrasion 3. Fluvial action on sand: *Amer. Jour. Science*, v. 172-190.

KULM, L. D., and BYRNE, J. V. (1966) Sedimentary response to hydrography in an Oregon estuary: *Marine Geology*, v. 4, p. 85-118.

KULM, L. D., SCHEIDEGGER, K. F., BYRNE, J. V., and SPIGAI, J. J. (1968) A preliminary investigation of the heavy mineral suites of the coast rivers and beaches of Oregon and northern California: *The Ore Bin*, v. 30, p. 165-180.

MAZZULLO, J., EHRLICH, R., and HEMMING, M.A. (1984) Provenance and areal distribution of Late Pleistocene and Holocene quartz sand on the southern New England continental shelf: *Jour. Sedimentary Petrology*, v. 54, p. 1335-1348.

PETERSON, C., SCHEIDEGGER, K. F., and KOMAR, P. D. (1982) Sand-dispersal patterns in an active-margin estuary of the northwestern United States as indicated by sand composition, texture and bedforms: *Marine Geology*, v. 50, p. 77-96.

PETERSON, C., SCHEIDEGGER, K. F., KOMAR, P. D., and NIEM, W. (1984) Sediment composition and hydrography in six high-gradient estuaries of the northwestern United States: *Jour. Sedimentary Petrology*, v. 54, p. 86-97.

POWERS, M.C. (1953) A new roundness scale for sedimentary particles: *Jour. Sedimentary Petrology*, v. 23, p. 117-119.

SCHEIDEGGER, K. F., KULM, L. D., and RUNGE, E. J. (1971) Sediment sources and dispersal patterns on Oregon continental shelf sands: *Jour. Sedimentary Petrology*, v. 41, p. 1112-1120.

SCHEIDEGGER, K. F., and PHIPPS, J. P. (1976) Dispersal patterns of sand in Grays Harbour estuary, Washington: *Jour. Sedimentary Petrology*, v. 46, p. 163-166.

SCHWARTZ, H.P., and SHANE, K.C. (1969) Measurements of particle shape by Fourier analysis: *Sedimentology*, v. 13, p. 179-212.

SHEPARD, F.P., and YOUNG, R. (1961) Distinguishing between beach and dune sands: *Jour. Sedimentary Petrology*, v. 31, p. 196-214.

TRASK, P. D. (1952) Sources of beach sand at Santa Barbara, California, as indicated by mineral grain studies: *Beach Erosion Board Tech. Memo. No. 28*, U.S. Army Corps of Engrs., 24 p.