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Source: Journal of Coastal Research, 36(sp1) : 441-449

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/1551-5036-36.sp1.441

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Journal of Coastal Research	SI 36	441-449	(ICS 2002 Proceedings)	Northern Ireland	ISSN 0749-0208

Wind abrasion (ventifaction) on Donegal and Oregon coasts and implications for the sediment dynamics of coastal systems

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ABSTRACT

Wind-abraded rocks (ventifacts) are common coastal features associated geomorphically with beaches, estuary mouths and sand dunes. This paper compares evidence for ventifaction from similar coastal settings in Donegal (Ireland) and Oregon (USA) and considers their implications for coastal sediment dynamics. Ventifacts on a bedrock platform at Gweebarra Bay, Donegal, show pit and groove ventifact styles and are estimated to have formed over some < 2500 years. Ventifacts on a boulder jetty (built 1892-1901) on the Oregon coast, USA, show similar grooves and pits. Winds above the threshold for sand transport and possible abrasion are present for 28-30% of the time at both locations. Based on depth of rock loss, wind abrasion rates on the Oregon coast are 0.24-0.95 mm yr $^{-1}$, two orders of magnitude greater than in Donegal. Coastal sediment fluxes on these coasts since the late Pleistocene have responded to sea-level fluctuations and changes in onshore sediment supply. Sediment systems are presently less dynamic than in the past, and some coastal geomorphic features may be largely relict.

ADDITIONALINDEXWORDS: *Coastal forcing, ventifacts, sediment systems, sea level change.*

INTRODUCTION

Ventifacts are wind-abraded rocks (individual boulders or bedrock surfaces) found in a range of environments that are characterised by strong winds and the availability of loose sediment or other materials (EVANS, 1911; SHARP, 1949; GREELY and IVERSON, 1985). Coastal environments, where strong onshore winds are common and where sand dunes, beaches and estuaries are a source for loose sand, are an ideal setting for ventifact development (e.g. BISHOPand MILDENHALL, 1994; BRALEY and WILSON, 1997; WILSON *et al*., 2002). However, ventifacts have only been observed occasionally in modern coastal environments, perhaps because of the dynamic nature of coastal geomorphic systems, the possible absence of suitable rocks for ventifaction, and their hitherto unappreciated potential as indicators of past sediment dynamics in the coastal zone (RITTER and DUTCHER, 1990; KNIGHT and BURNINGHAM, 2001; WILSON *et al*., 2002).

Ventifacts, defined qualitatively on the basis of rock surface morphology, are often difficult to identify and catagorise. Additionally, processes of wind abrasion associated with the formation of ventifacts (ventifaction) are difficult to observe and quantify from field or laboratory studies. Field estimates of wind abrasion rates by SHARP (1964) range, according to rock hardness, between 0.09-4.82 mm yr^{-1} (for a 10-year observation period). Wind tunnel experiments derive ventifaction rates of 0.07-1.3 mm yr^{-1} for a variety of rock types (SUZUKI and TAKAHASHI, 1981). SHARP's (1964, 1980) and other studies (e.g. KUENEN, 1960) also show that abrasion rate is critically dependent on wind speed. Due to lithological and windspeed variations therefore, ventifacts can be formed on time-scales from centuries to weeks (KUENEN, 1960; GREELY and IVERSON, 1985).

This paper compares the characteristics, age and abrasion rates of ventifacts from similar modern coastal settings in Donegal, north-west Ireland, and Oregon, western USA. In detail the paper has 3 main aims: (1) to briefly describe the coastal environment and ventifact morphology from these two locations, (2) to evaluate the possible ventifact age and wind abrasion rate at these locations using present-day wind and other data, and (3) to consider changes in coastal sediment dynamics on the time-scale of the last few thousand years and how these may impact on the formation of coastal geomorphic features, including ventifacts.

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VENTIFACTS ON THE DONEGAL COAST

Physical setting

The western Donegal coast was inundated by ice from Donegal mountain ice centres during the late Devensian (Weichselian) glaciation (~ 25-13 kyr BP) (McCABE *et al*., 1998). Ice margins extended beyond the present coastline to an unknown position on the continental shelf at a time when relative sea-level (RSL) was lowered by perhaps more than 100 m due to a combination of eustatic and glacioisostatic depression (PEACOCK *et al*., 1992). Sediment that was deposited on the continental shelf during ice retreat was generally reworked onshore during postglacial sea-level recovery and marine transgression (SHAW and CARTER, 1994). Sea-level changes in the postglacial period can be reconstructed with some precision from geomorphic, sedimentary and dating evidence onshore (SHAW, 1985; SHAW and CARTER, 1994). Sea-level in western Donegal did not experience a mid-Holocene highstand above present OD, but rose rapidly to less than 1 m below OD at about 4 kyr BP from which it has slowly recovered to present (SHAW and CARTER, 1994). Coastal sand dunes in Donegal developed most likely following this mid-Holocene maximum (CARTER and WILSON, 1993; WILSON and BRALEY, 1997).

Ventifacts are located at Cashelgolan, a small embayment on the south side of the Gweebarra River estuary, western Donegal (Fig. 1). Sand dunes (< 60 m high) are present on both sides of the estuary mouth. A radiocarbon age from a peat bed underlying the dunes suggest they are 2000-3000 years old (SHAW, 1985; SHAW and CARTER, 1994), which is supported by the presence within the dunes of archaeological features from this era (BRUNICARDI, 1914; MacGILL, 1947).

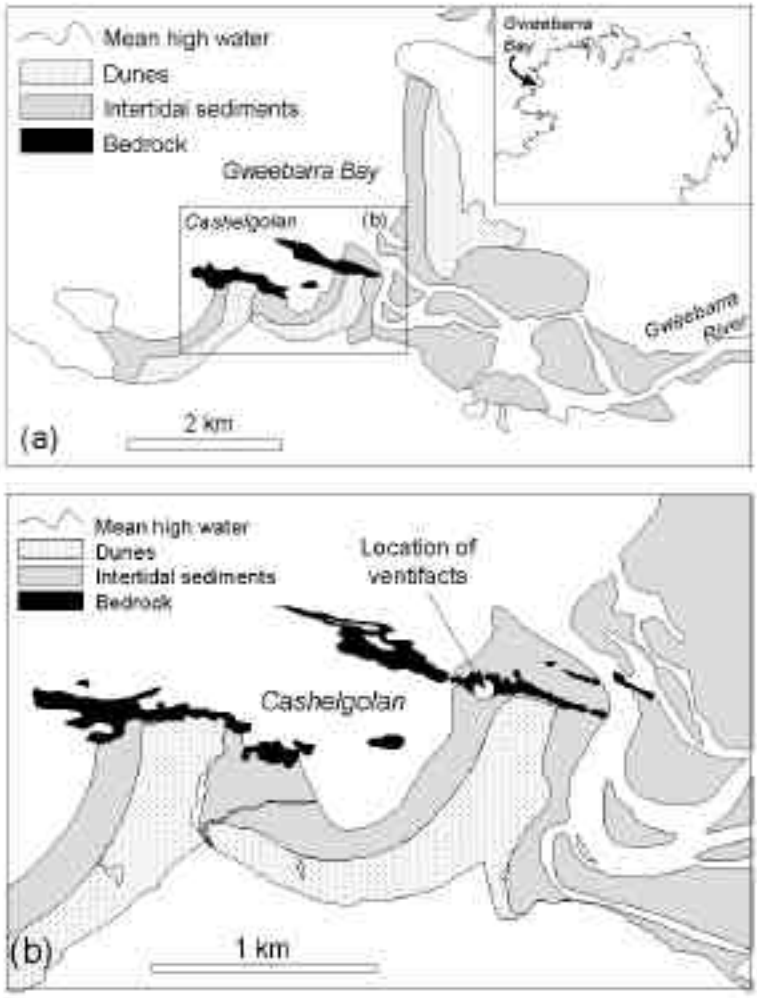


Figure 1. (a) Location and coastal geomorphology of the study area in western Donegal. (b) Location of ventifacts (indicated with white dot) at Cashelgolan (redrawn after KNIGHT and BURNINGHAM, 2001).

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The Cashelgolan embayment comprises a small sandy beach backed by sand dunes and buttressed by outcrops of Falcarragh Limestone which is of Lower Dalradian age (Fig. 1b). Ventifacts are located on a glaciated bedrock platform at about + 2 m above mean high water on the easternmost side of the embayment (Figs. 1b, 2). Wind data from Malin Head (1956-1996), north Donegal coast, show mainly southwesterly winds (36% of all winds recorded) (Fig. 3). Stronger winds (> 22 knots) which are associated with storms and storm surges come mainly from the west (51%). These winds are important geomorphic agents on western Ireland coasts (COOPER and ORFORD, 1998; ORFORD *et al*., 1999).



Figure 2. View of the Cashelgolan embayment looking eastward at the bedrock platform (arrowed) upon which the ventifacts are developed (photo courtesy of Helene Burningham).

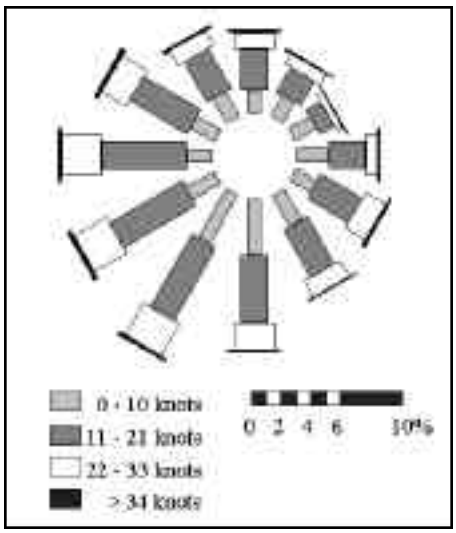


Figure 3. Wind rose from Malin Head (1956-1996) grouped by speed band and direction.

Ventifact morphology

Ventifacts are found exclusively on the west-facing (windward) sides of upstanding bedrock protrusions on the westernmost 20-25 m of the bedrock platform (Fig. 4). Ventifacts decrease in number and change in morphology towards the east, e.g. with distance from the beach sand source. Grooves (wind-parallel ridges and troughs) are found on gently inclined bedrock faces. Grooves are generally aligned parallel to one another, have sharp crests, are up to 40 cm long and have a local relative relief of up to 5 mm. Pits (few mm deep and wide) are found mainly on steep windward faces. Polished rock surfaces are found in all locations. The depth of rock surface loss by wind abrasion is difficult to evaluate but is on the order of 0.5-1.5 cm based on total relief of the ventifacted faces.





Figure 4. Ventifact morphologies at Cashelgolan. (a) Steep windward face showing pits and polish. Note the sharp crest (arrowed) and the unabraded, lichen-covered upper surface. (b) Ventifact with a finely polished surface and sharp wind-parallel crest (arrowed). Trowel for scale is 28 cm long.

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VENTIFACTS ON THE OREGON COAST

Physical setting

During the late Wisconsinan (Weichselian) glaciation northwestern North America was covered by the Cordilleran ice sheet which extended as far south as the Puget lowlands at 15-14 kyr BP (EASTERBROOK, 1992). The tectonically-active coast of Oregon therefore lay outside the glacial limit but was affected by glacioisostatic depression and proglacial sediment deposition (KOMAR, 1997). At the present time the Oregon coast is characterised mainly by long, dissipative beaches and sand dunes which are associated geomorphically with estuaries and river mouths and separated by bedrock headlands (COOPER, 1958) (Fig. 5). Bedrock comprises mainly Tertiary igneous rocks. The sand dunes reflect sediment reworking during Holocene sea-level rise (CLEMENS and KOMAR, 1988; KOMAR, 1997). The area of the Oregon Dunes National Recreation Area, between Coos Bay and Florence, contains 85% of Oregon's active coastal dunes (USDA, 1975) (Fig. 5b). Sediment dynamics in this region are controlled by seasonal wind and wave regimes (FOX and DAVIS, 1978; HUNTER *et al*., 1983). Data from Cape Arago (1992-2000) show that winter winds are generally (55%) from the south whereas summer winds are from the north (56%) (Fig. 6). These winds reflect seasonal synoptic-scale shifts in the location of high and low-pressure cells over the northeastern Pacific (MASS and BOND, 1996).

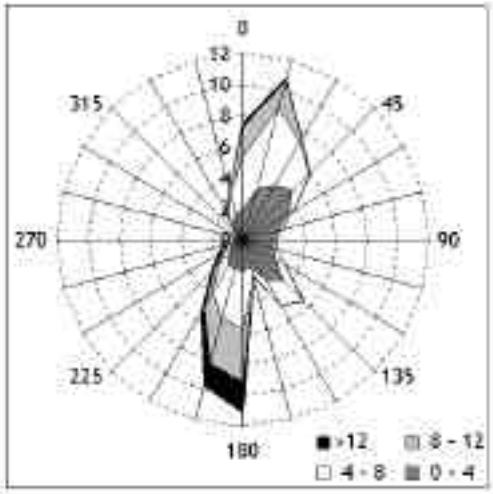


Figure 6. Wind rose for Cape Arago, Oregon coast (1992-2000) grouped into speed bands (m s^{-1}) and direction.

Ventifacts are found at the northernmost end of the Oregon Dunes National Recreation Area which is bounded by the Siuslaw River near the city of Florence (KNIGHT and BURNINGHAM, submitted) (Fig. 5c). Jetties at the mouth of the river were constructed of diabase and sandstone boulders by the US Army Corp of Engineers between 1892-1901. Map evidence suggests that the jetty surface and position of the shoreline on adjacent beaches have been stable since about 1930 (KOMAR *et al*., 1976).

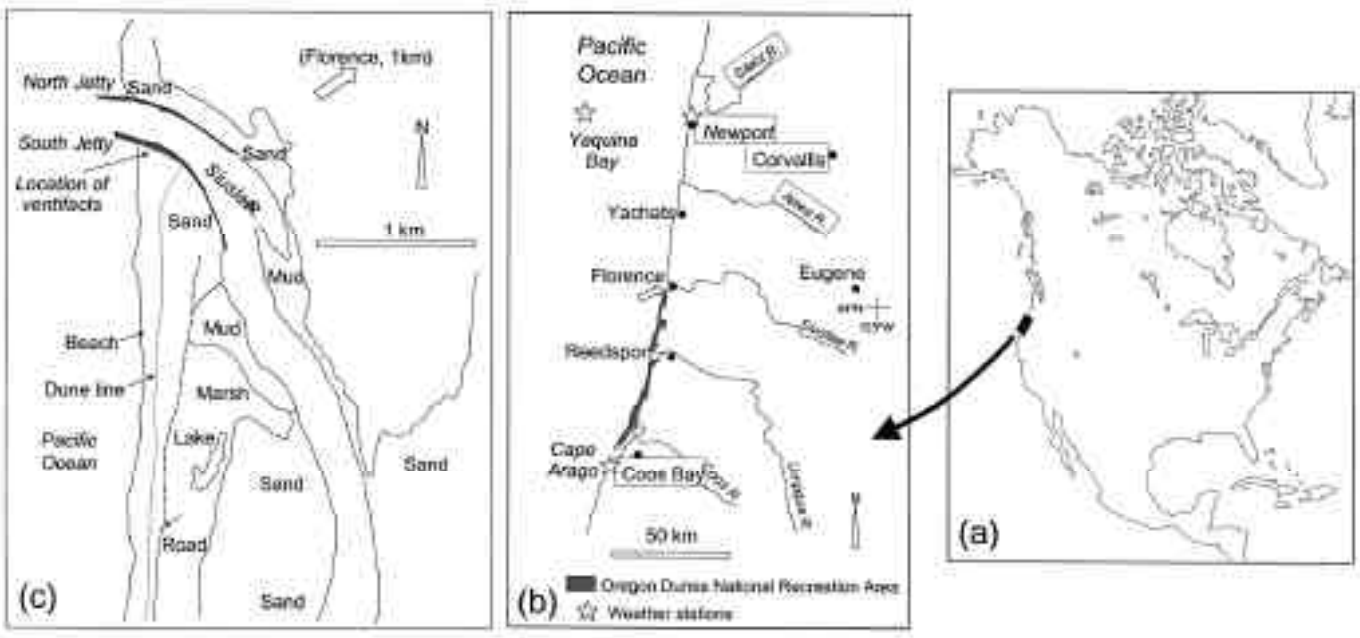


Figure 5. (a) Location of the Oregon coast in western USA, (b) location of the study area (arrowed) near Florence, (c) simplified substrate types and coastal geomorphology at the mouth of the Siuslaw River (after KNIGHT and BURNINGHAM, submitted).

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Ventifact morphology

Ventifacts are found on south-facing boulder sides (facing the direction of winter winds) along a 30 m stretch of the south jetty (Fig. 7). Features most commonly recorded are pits and grooves (Fig. 8). Pits vary in size and shape according to the alignment of the boulder face into the windstream. Faces that are aligned at right angles to the wind have small but deep, vertical pits (few mm dimensions); faces that are aligned obliquely to the wind have shallower asymmetric pits that resemble grooves (Fig. 8). Wind-parallel grooves are also developed on some boulder faces. The grooves have a relative relief of 2.0-2.5 cm and are spaced 6-30 cm apart.



Figure 7. Photo of the south jetty, Siuslaw River, Oregon, showing the location of ventifacts (arrowed) (KNIGHT and BURNINGHAM, submitted)





Figure 8. Photos of (a) pit and (b) groove ventifact styles, Oregon coast (KNIGHT and BURNINGHAM, submitted)

Table 1. Comparison of wind and ventifaction parameters from Donegal and Oregon coasts

Parameter	Donegal	Oregon
Meteorological station	Malin Head (1956-1996)	Cape Arago (1992-2000)
Prevailing wind	Southwesterly (38% annually)	Southerly (42% annually)
Threshold for sand transport	2.7 m s^{-1}	2.8 m s^{-1}
Period of time threshold is exceeded	86% annually	68% annually
Potential ventifaction period	25-28% annually	28% annually
Ventifact age	No direct evidence, Perhaps 2500 years	Likely 70 years
Abrasion rate	Possibly ~ 0.01 mm yr^{-1}	0.24-0.95 mm yr^{-1}

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CALCULATING THE THRESHOLD VELOCITY FOR SAND TRANSPORT

The grain size distribution of surficial sand samples taken from the adjacent beaches at each location was analysed using the sieve method. Mean grain size was 0.115 mm in Donegal and 0.203 mm in Oregon. The wind speed required to move sand grains of these sizes, and thus the wind threshold for potential abrasion, was calculated according to the equation of CLARK and ELSON (1961) after BAGNOLD (1941). Results are shown in Table 1.

Calculating the age of ventifacts and wind abrasion rates

The age of the ventifacts can be calculated on the basis of the exposure age of the rocks upon which the ventifacts are developed. In the case of Oregon this period of exposure is likely to date from around 1930 when the south jetty was finally stabilised (KOMAR *et al*., 1976), giving a ventifact age of approximately 70 years (KNIGHT and BURNINGHAM, submitted) (Table 1). In the case of Donegal the exposure date is more uncertain since that could be any length of time since the last deglaciation. Sand-blow activity and the formation of sand dunes in the region since about 2000-3000 BP (CARTER and WILSON, 1993) suggests that this is a likely maximum age for active ventifaction (KNIGHT and BURNINGHAM, 2001). Additionally, there is evidence for reinvigorated coastal sediment systems and sand dune building events during the Little Ice Age (~ 1350-1850 AD) in western Ireland (e.g. WILSON and BRALEY, 1997; WINTLE *et al*., 1998). Ventifacts may have developed, or been actively trimmed, during the Little Ice Age (KNIGHT and BURNINGHAM, 2001).

Calculation of wind abrasion rates also requires information on the depth of loss from rock surfaces. This can be estimated from the relative relief of ventifact features with respect to adjacent unabraded rock surfaces, and is around 2.0-2.5 cm at both locations. Wind abrasion rates are calculated from total rock surface loss divided by total time period of rock exposure. Results are shown in Table 1. Results from Donegal are potentially variable given the uncertain age of the ventifacts. However, here the calculated wind abrasion rate is of the same order of magnitude as found commonly in the literature (e.g. GREELY and IVERSON, 1985). Abrasion rates in Oregon are calculated with some confidence and are comparable to some other field studies (e.g. SHARP, 1964, 1980).

DISCUSSION

Comparison of Donegal and Oregon coasts

The geomorphic setting of the two studied coasts is very similar (Table 2). Of most relevance to the generation of sand-sized coastal sediment, and its movement within the coastal zone, is the igneous bedrock geology and changes in RSL. Due to glacial abrasion from land-based ice, igneous rocks break down readily into quartz sand that is stored in the nearshore and on the continental shelf. Sediment has been largely reworked onshore by changes in RSL due to glacial unloading (Donegal) and active tectonics of the Cascadia forearc (Oregon). Morphologically, the ventifacts observed on these coasts are also very similar and reflect the combination of an abundant sand source and strong prevailing onshore winds.

Table 2. Characteristics of Donegal and Oregon coasts.

Characteristic	Donegal	Oregon
Energy level	High	High
Tidal range	Marginally macrotidal	Marginally macrotidal
Fetch length	‘000s km	‘000s km
Synoptic climate	Onshore cyclones	Onshore cyclones
Coastal features	Sand dunes, sandy beaches, estuaries buttressed by bedrock headlands	Sand dunes, sandy beaches, estuaries buttressed by bedrock headlands
Bedrock types	Igneous	Igneous
Sea-level controls	Glacial unloading	Active tectonics

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Ventifacts and coastal sediment dynamics

Ventifacts provide physical evidence for the effectiveness of abrasion by windblown sand in the coastal zone. Coastal sand dunes can be considered the terrestrial depositional signature of windblow activity, and are linked morphodynamically to beaches and the offshore zone by tidal and wave processes, and to river mouths/estuaries by fluvial and tidal pumping effects (Fig. 9). Sediment dynamics in the coastal zone therefore describe the degree to which sediment is moving between onshore and offshore sinks during periods of environmental change that may be forced by changes in RSL, storminess etc. As a 'signature' of one of these sediment transport processes, ventifacts can reveal the direction and sometimes the age of windblow activity (BISHOPand MILDENHALL, 1994). Recent work has also focused on the role of sand dunes and dune sediments in recording such changes in coastal environments over time (e.g. ORFORD *et al*., 1999).

Sediment dynamics of coastal Donegal

The development of coastal sand dunes in western Donegal reflects net onshore sediment transport and storage over the time-scale of the past few thousand years (SHAW and CARTER, 1994). Because this development has taken place against a background of little or no RSL change it suggests that there are other first-order controls on sediment dynamics along this coast. Mesoscale studies in Gweebarra Bay (BURNINGHAM and COOPER, 1998; BURNINGHAM, 2000) suggest that little new sediment is entering the beach/dunes part of the sediment system from offshore. At the present time, sediment is recirculating seasonally between between beach/dune and estuary storage (BURNINGHAM, 2000). Superimposed upon these closed sediment cells are the effects of episodic storm and storm-surge events which are known to cause imbalances in coastal sediment systems in western Ireland (e.g. COOPER and ORFORD, 1998; ORFORD *et al*., 1999). Storms have the effect of transporting sediment onshore, both from the nearshore zone and from beaches into the dunes through barrier breaching and overwashing (ORFORD *et al*., 1999). The enclosed embayment at Cashelgolan is sheltered from these effects (KNIGHT and BURNINGHAM, 2001) but the presence of ventifacts, which are largely relict features, record previously more intense periods of sand mobility and wind abrasion.

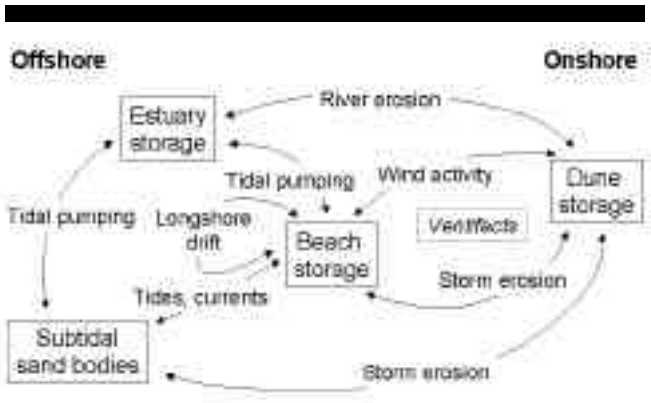


Figure 9. Processes of sediment movement (arrowed) and storage areas (boxed) in the coastal zone. Note the position of ventifacts (dashed box) between the beach and dune sinks

Sediment dynamics of coastal Oregon

Some previous work has outlined changes in shelf sediment dynamics along the Oregon coast using naturally-dispersed heavy minerals as tracers (e.g. SCHEIDEGGER *et al*., 1971; CLEMENS and KOMAR, 1988). These studies found that, broadly, both onshore, offshore and alongshore sediment movements were most active during long-term changes in RSL (late Pleistocene regression, Holocene transgression). Additional shelf sediment was inputted from adjacent rivers especially during lowstands. Shelf sand supply has reduced over the past 3000 years (SCHEIDEGGER *et al*., 1971), likely due to estuary infilling and the growth of sand dunes, the presence of bedrock headlands which impede longshore drift, and Holocene RSLrise. Together these factors have the effect of forcing sediment systems onshore. Superimposed upon these long term trends, however, are sedimentary sequences preserved in estuaries and back-barrier lagoons which record tectonically-induced changes in RSL (LONG and SHENNAN, 1998; SHENNAN *et al*., 1998). Land deformation associated with the Cascadia subduction zone, located offshore northwestern USA, results in coastal uplift of 1-4 mm yr^{-1} in Washington and Oregon (LONG and SHENNAN, 1998). Here, sediment sequences show episodic stages of estuary and lagoonal infilling associated with periods of tectonic activity. In this model, coseismic submergence of the coastal zone (by < 0.5 m during seismic events; SHENNAN *et al*., 1998) likely provides accommodation space for onshore sediment storage. Land uplift and RSL regression during interseismic (quiescent) periods may be associated with an offshore shifting of these sediment systems and infilling of some lagoons. The intense ventifaction observed at the present time could be regarded as a short-term response to jetty construction and resulting changes in local nearshore sediment dynamics (KOMAR *et al*., 1976). Alternatively, the presence of ventifacts could be regarded as simply the morphological signature of the sedimentary processes that have enabled other beach/dune components elsewhere along the coastline to be maintained in relative stability over historical time-scales (KOMAR, 1997).

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Controls on sediment dynamics on different coasts

Despite their similar geological, glacial and coastal settings (Table 2), the coasts of Donegal and Oregon show very different controls on sediment dynamics over the time-scale of the last few thousand years. On the Donegal coast, storms and storm surges are the dominant agent of coastal forcing rather than RSL changes (BURNINGHAM and COOPER, 1998). On the Oregon coast the major forcing factor is tectonically-induced RSL changes (LONG and SHENNAN, 1998). Present sediment dynamics along both coasts are relatively small compared to the size of the onshore and offshore sinks. An important additional factor controlling the reworking of this sediment between these onshore and offshore sinks (Fig. 9) is the geometry of the coastline itself. The intricate and compartmented Donegal coast gives rise to closed sediment cells (KING, 1965) which are likely to respond in different and discrete ways to coastal forcing. The open Oregon coast is likely to show enhanced sediment transport between sinks throughout this coastline (KOMAR, 1997), and is likely to respond uniformly to coastal forcing. The largely-relict ventifacts found in Donegal, and presently-forming ventifacts found in Oregon, may be a useful signature of the present sediment dynamics of these coasts.

Recent work from coastal environments elsewhere (e.g. BOURMAN *et al*., 2000; van der MOLEN and van DIJCK, 2000) confirms that sediment fluxes were highest during late Pleistocene and Holocene changes in RSL, and have decreased to the present day. Some coastal sediment systems (Fig. 9) are therefore largely relict and some coastal geomorphic features (such as sand dunes, estuaries, ventifacts) may have been emplaced much earlier than previously thought.

CONCLUSIONS

Based on field evidence, ventifacts have formed on time-scales from millennia to decades along Donegal and Oregon coasts respectively. Ventifacts, as signatures of part of the coastal sediment system, likely record periods of time in which sediment fluxes were enhanced under certain environmental conditions such as changed RSL and/or climate. This study shows that ventifacts may be sensitive proxy indicators of coastal zone changes on sand-dominated, tectonically-active or formerly-glaciated coasts. Considered with other coastal geomorphic features, ventifacts may be used to help evaluate changes in sediment dynamics (movement between onshore and offshore sediment sinks) over time-scales of a few thousand years.

ACKNOWLEDGEMENTS

Helene Burningham drew some of the figures.

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