Journal of Coastal Research | 13 | 1 | 202–208 | Fort Lauderdale, Florida | Winter 1997

The Role of Wave Diffraction in the Formation of St. Ninian's Ayre (Tombolo) in Shetland, Scotland

Derek Flinn

Department of Earth Sciences
University of Liverpool
Liverpool, L69 3BX, U.K.

ABSTRACT

FLINN, D., 1997. The role of wave diffraction in the formation of St. Ninian's Ayre (Tombolo) in Shetland, Scotland. *Journal of Coastal Research,* 13(1), 202–208. Fort Lauderdale (Florida), ISSN 0749-0208.

St. Ninian's Ayre (sand tombolo), on the south-west coast of Shetland, occurs in an environment of deeply plunging hard-rock cliffs which enclose the area containing the tombolo so that the maximum fetch of local wind-driven waves is no more than 2 km. As a result of the presence of the plunging cliffs, there are no adjacent beaches to supply sand to the tombolo by longshore drift. The sea around St. Ninian's Island, at the seaward end of the tombolo, is so deep that wave refraction in the vicinity is restricted. Thus, the various explanations usually offered for the origin of tombolos are precluded or incomplete. Satellite image and airphotos show that wave patterns in the vicinity of the tombolo result from the prevailing ocean swell from the west being diffracted round the island, on either side. As the sea shallows, the diffracted swell is increasingly modified by refraction, before breaking on either side of the tombolo. The shorelines on either side of the tombolo are nearly parallel to the crests of the diffracted and refracted swell-derived waves that these break along the length of the tombolo at the same instant. Local wind driven waves have little effect. The tombolo owes its position and shape directly to the diffraction and refraction of the ocean-swell waves transporting sand from the adjacent sea floor into the area where the waves meet behind the island. Longshore drift acts only within the confines of the tombolo and matches its shape to that the crests of the waves break over it.

ADDITIONAL INDEX WORDS: *Tombolo, wave patterns, wave refraction, wave diffraction, plunging cliffs, Shetland (Scotland) coastline.*

INTRODUCTION

Since JOHNSON (1919), few geomorphology books have addressed the subject of tombolos; of those that do, few discuss their origin. A computer search of geoarchives for titles containing the word "tombolo" found 35 papers of which only 5 discussed origin at any length, and two of these were more than 20 years old. Most papers mentioning tombolos merely record their occurrence, listing them with spits and bars, implying that the origin proposed for spits and bars is also the origin of the tombolos (BIRD, 1984).

However, GUILCHER (1958) explained tombolos as due either to refraction of waves behind an island (if the submarine contours have an appropriate shape) or by their diffraction on each side of the island with the deposition of materials at the meeting point of the two diffracted and weakened sets of waves, but provided no details. ZENKOVICH (1967) in a study of spits and bars included a diagram showing a complex coastline, very like that described below, including a tombolo and a wave pattern resulting from refraction, but omitted the submarine topography. He mentioned that wave diffraction may also play a role. KING (1972) mentions wave refraction and long-shore drift as playing a role but does not specify the role.

Recent journal literature is no better. Thus SUNAMURA and MIZUNO (1987) attribute a tombolo to wave "diffraction and refraction around an island creating a shadow area in which sand accumulates by longshore drift". SCHWARTZ *et al.* (1989) state tombolos are "locally oriented in accordance with the predominant wave and fetch directions"; and BODERE (1973) attributed the formation of a double tombolo in Iceland to wind from two directions, all without specification of the submarine topography or the wave pattern. However, BALLARD (1984) includes an airphoto showing the wave pattern in the neighbourhood of a tombolo.

More attention has been paid to tombolos by coastal engineers; however, they are concerned with the tombolos formed behind breakwaters and thus in very shallow conditions rather than with naturally formed ones. SAUVAGE DE SAINT MARC and VINCENT (1955) state that (in translation) "two phenomena dominate the formation of tombolos: local currents caused, above all, by diffraction which contributes on the one hand to the lateral transport of sand, on the other to the creation of a sedimentation front; and a zone of relative calm in the shadow of the breakwater [island] in which sedimentation is facilitated". These authors' conclusions are based on experiments and observations, but they use the term "diffraction" in an extremely general and nonspecific way, show no interest in wave patterns, and instead concentrate on currents. SHIGEMURA *et al.* (1985) provide another detailed study involving observation, historical records and experiment, but no consideration of the wave behaviour in the neighbourhood of the tombolo. They attribute the tombolo to currents caused by waves in the general area, but do not report the wave patterns. The most important work is that

---

94024 received and accepted in revision 22 February 1994.

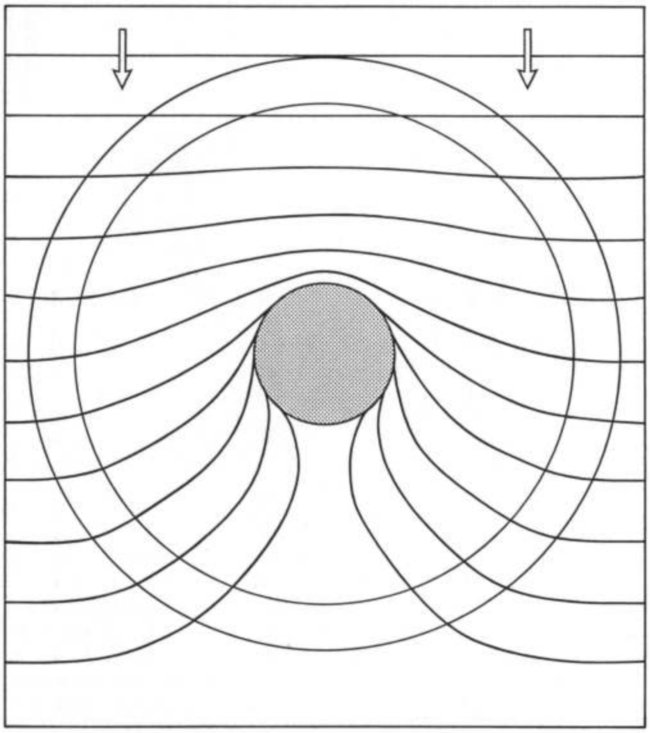

Figure 1. Wave refraction round an island with a shelving shore. Submarine contours at half and quarter wave lengths. Reflection and diffraction effects ignored. After KINSMAN (1965).

of KINSMAN (1965); he quotes even earlier works showing in detail how waves with rectilinear crests can be refracted round an island with shallow shelving shores to meet "head on" behind the island to form an environment conducive to sediment accumulation (Figure 1).

REFRACTION AND DIFFRACTION OF WAVES

Wave diffraction takes place where the advance of waves is interrupted by a shoreline or breakwater, irrespective of the depth of water. Wave refraction occurs where waves advance into waters with a depth of less than half a wave length. The effects of refraction increase with decreasing depth; at depths of one third of a wave length, they equal those of diffraction and exceed them at still shallower depths (SORENSEN, 1978). In waters of less than half a wave length, the waves lose energy and are slowed so that wave length decreases and the wave height increases. If the wave crest or wave front is oblique to the submarine contours, the slowing results in the wave front rotating towards parallelism with the contours. In the case of an island with a smoothly shelving underwater floor, the effect of refraction on the waves is shown schematically (ignoring diffraction and reflection) in Figure 1 (after KINSMAN (1965)). A wave with an originally rectilinear crest or wave front is refracted so that the crest is bent round the island on either side and the wave meets itself head on, on the far side. If there is a nearby shore beyond the island on the far side, any longshore drift on that shore is interrupted by this wave configuration. Seafloor and/or beach sediment is, thereby, swept into and accumulates in the zone where the waves meet.

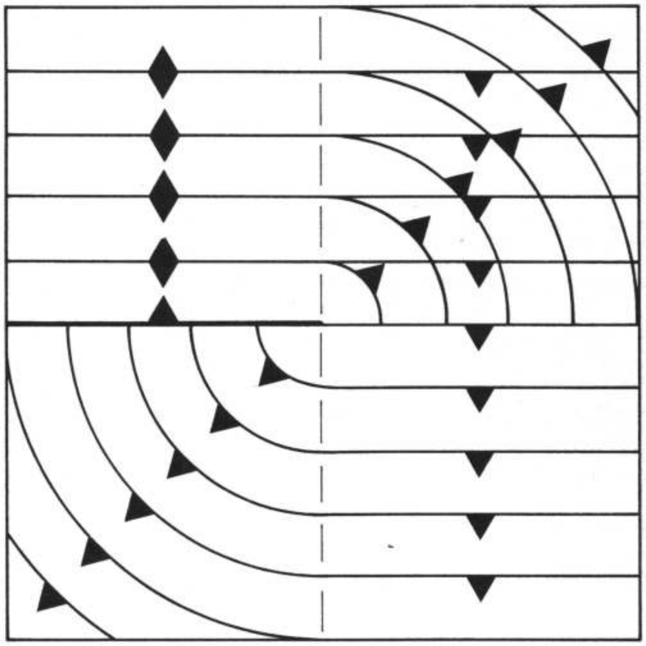

Figure 2. Wave diffraction and reflection by a breakwater in water deeper than one half wave length. Black triangles indicate the direction of advance of the waves.

If the island has cliffs plunging to depths greater than half a wave length, only diffraction takes place and the effects are entirely dependent on the shape of the shoreline. Figure 2 shows the diffraction effect produced by a breakwater on waves in water of that depth (SORENSEN, 1978). As it passes the breakwater, the wave is truncated, and spreads sideways beyond the truncation point in the form of a wave; its amplitude (and energy) decreases away from the truncation point and a crest line forms an arc of a circle centered on the end of the breakwater. In the case that the breakwater is an island surrounded by deep water, the effect on the waves is somewhat similar to that shown for refraction in Figure 1; the waves sweep around the island to intersect on the far side, but the pattern differs in detail (Figure 3). In coastal waters of less than half a wave-length depth, both diffraction and refraction take place; the effects of refraction become increasingly noticeable as the water depth decreases below one third of a wave length. Refraction shortens the wave length of the waves, thus postponing to some extent its rotational effect on the wave crest. In the figure published by KINSMAN (1965), only the effect of refraction is shown. If the diagram displayed diffraction only, it would be very similar in appearance.

Neither Figure 1 nor Figure 3 take account of wave reflection which in both cases may occur, depending on the steepness of the shore where the waves strike. Figure 2 shows how the waves striking a steep-sided breakwater are reflected and

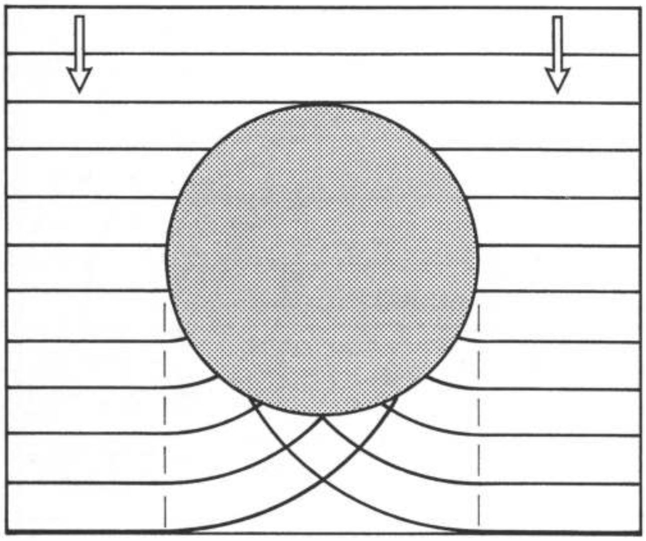

Figure 3. Wave diffraction around an island with cliffs plunging to depths of more than half a wave length. Reflection effects omitted. Open arrows—direction of advance of waves.

diffracted in a manner symmetrically related to the diffraction of the transmitted waves (centre of symmetry at the end of the breakwater).

THE SHETLAND COASTLINE

The Shetland Archipelago (Figure 4) is a partially drowned monadnock-like feature rising from the surrounding floor of the continental shelf between the north of Scotland and Norway (FLINN, 1969, 1973). The outer parts of the coastline, forming the boundary of the monadnock, are dominated by cliffs of fresh crystalline rock plunging directly to the surrounding sea floor at depths varying up to about 100 m. However, the gradual drowning of the monadnock by rising sea level, following the last (Late Devensian) glaciation, has also created an "inner coastline" of drowned valleys. These valleys are sheltered from the open ocean, with shallower, more gently shelving sea floor than occurs on the outer coastline facing the open ocean. This inner coastline, in common with other recently drowned coastlines (JOHNSON, 1919:Figure 50), is characterised by the occurrence of spits, bars and barriers as well as some 50 tombolos (FLINN, 1974). However, on the outer coast, there are only three tombolos, formed behind islands facing the open ocean. One of these, St. Ninian's Ayre, is the subject of this paper; it is the largest and most spectacularly developed of all the Shetland tombolos (Figure 4). It occurs in an environment of hardrock, plunging cliffs facing westward to the Atlantic Ocean, with no adjacent beaches to supply sand by longshore drift. The shape of the adjacent coastline limits the maximum fetch of local wind driven waves to no more than two kilometres. The depth of water is too great for the effects of refraction to be greater than those of diffraction, except close to the shoreline. Thus, previously proposed mechanisms of tombolo formation are precluded or their effectiveness minimised, and diffraction acting on the ocean swell approaching from westward is left to play the major role.

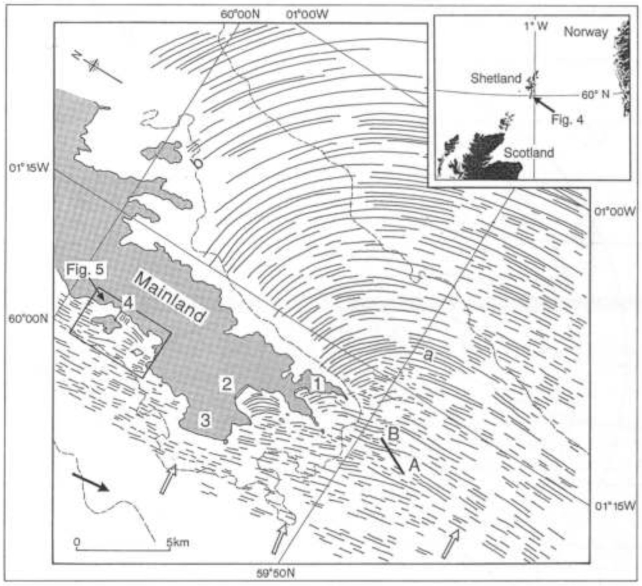

Figure 4. Tracing from a satellite radar image of the south end of Shetland. Only the more prominent and well formed waves are shown. A & B = the geometric centres of waves a & b respectively. Dashed lines are submarine contours at one quarter (−55 m) and one third (−73 m) wavelength depth, from Flinn (1973). Solid arrow—wind direction. Open arrows—direction of advance of waves. Wind 350°, 18 kts (9.3 m·sec^{-1}; force 5) gusting to 27 kts (13.9 m·sec^{-1}; force 6), courtesy Meteorological Office, Edinburgh. (1) Sumburgh Head; (2) Quendale Bay; (3) Fitful Head; (4) St. Ninian's Ayre. Esa/Earthnet Seasat 1 SAR image. Orbit 1149, received UKO 15 Sept. 1978, GMT image centre 8 hr 23 min 24 sec, approximate scale of photographic representation of the image 1:175,000. Digitally processed at RAE, U.K. 3rd Dec. 1983. Courtesy National Remote Sensing Centre Ltd, Farnborough.

The great depth of water around Shetland gives rise to a good example of wave diffraction, shown in Figure 4 and based on an SLR satellite image of the south end of Shetland. The figure includes a tracing of the waves visible on the satellite image, with the local weather conditions specified in the caption. The swell from the open ocean is seen to be approaching from the west-south-west and to be diffracted into relatively sheltered waters to the east of Shetland. The diffracted waves form arcs of circles and have a wave length of about 220 m (average of a train of 100 waves). The one-quarter wave length submarine contour (−55 m) lies well inshore. Outside this contour, refraction effects are not detectable on the image since the diffracted wave crests maintain their circular form and their wave length. Diffraction is the dominant process in this area.

The geometric centres of the diffracted circular wave fronts in Figure 4 are displaced progressively from south-west to north-east as the waves advance to the north and north-east (Figure 4, points A & B). This displacement of the waves to the north-east is considered to be due to the fact that from two hours before the satellite image was taken (and to two

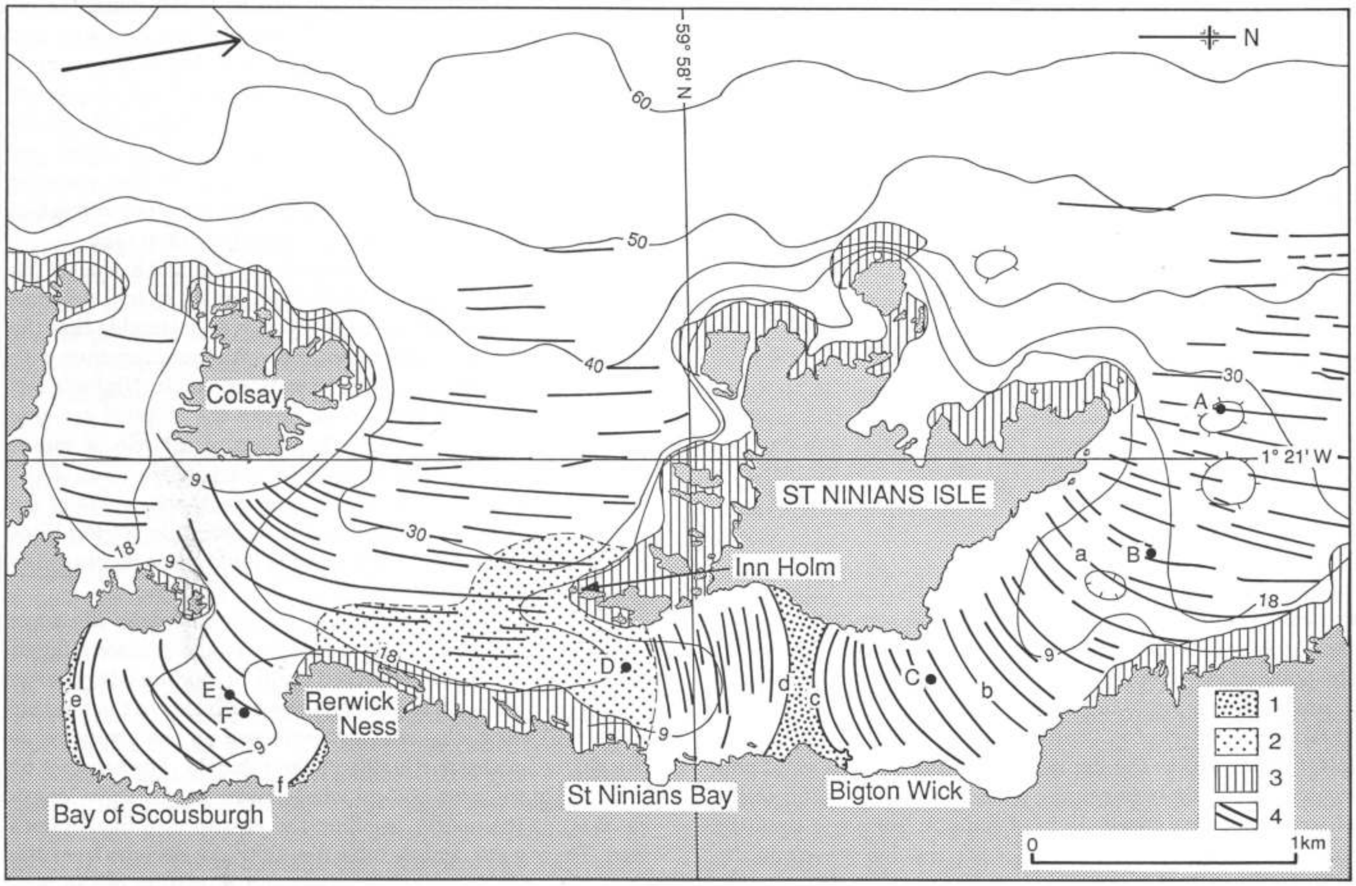

Figure 5. Tracing from airphotos of St. Ninian's Isle—only the more prominent and well formed waves are shown. Submarine contours in metres from Hydrographic Department fair charts used in Flinn (1973). A to F are the geometric centres of waves a to f respectively. Solid arrow—wind direction. Wind at 1200 GMT 170°, 11–16 kts (5.7–8.2 m·sec^{-1}; force 4), courtesy Meteorological Office, Edinburgh. (1) sand tombolo and sand beaches. (2) areas of 9 m wave length wind-driven waves. (3) areas of broken water. (4) wave crests traced from airphotos. RAF airphotos 60006, 60007 & 60008, 106G/DYCE 19 Sept. 1944, from 28,200 feet, approximate scale of the airphoto 1:25,000. Time unknown. Copyright Ministry of Defence, see acknowledgements.

hours after), the tidal flow past the south tip of Shetland was to the east and north-east (according to tidal predictions (Whitaker, 1977) and tidal flow charts for Shetland (Anon, 1986)). However, the centers of diffraction lie in deep water, several kilometres to the south-south-west of Sumburgh Head and not on the breakwater-like tip of Sumburgh Head. The explanation for this apparent departure from theory may be that diffraction takes place at a prominent boundary in the tidal stream, which is very strong in this region.

St. Ninian's Ayre (Tombolo)

St. Ninian's Ayre is a spectacular and well-developed sand tombolo joining St. Ninian's Isle to Mainland, Shetland (Figure 5). The tombolo is half a kilometre in length and formed of sand with a median grain size averaging 0.22 mm and a range of 0.3 to 0.2 mm. The carbonate content averages ca. 50% by volume and the heavy mineral content 0.1% by volume. No systematic variation in these properties was found to occur between nine sampling stations along the tombolo. Probings with a hydraulic lance, in the center of the tombolo, found rock (probably pebbles) at a depth of two metres over a wide area, but a pit dug in the east end of the tombolo to exploit the sand commercially disclosed no pebbles or rock to a depth of 10 m or so below the tombolo surface.

The earliest map of Shetland showing the tombolo is one made by a local landowner, John Bruce of Whalsay, about 1700 and published in 1745 (Ottens and Ottens, 1745). The earliest accurately surveyed map of the area (Thomas, 1830) and the three editions of the Ordnance Survey Maps of the area (1880, 1900 and 1973) all show the tombolo in the same place with very similarly shaped high-tide shorelines. For three hundred years, despite being commonly submerged by waves during storms and recently supplying large amounts of sand to local industry, the shape and position of the tombolo has not significantly changed.

The swell-derived wave pattern in the neighbourhood of St. Ninian's Isle on 19th September 1944 is shown by a series of airphotos that are reasonably clear with a scale of about 1:25,000. Figure 5 is a tracing of the wave crests and the shoreline and shows the submarine contours, while the caption

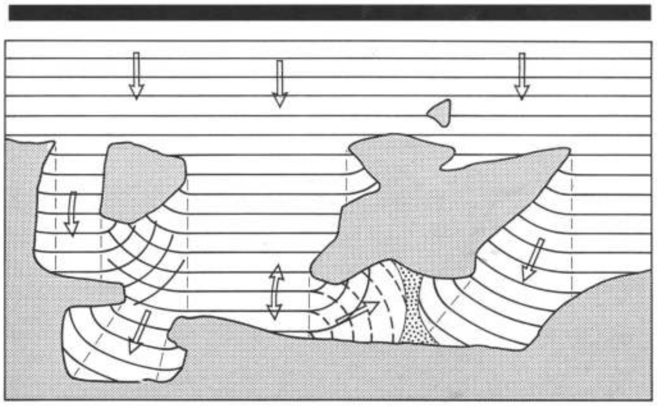

Figure 6. Schematic diagram of wave diffraction effects around St. Ninian's Isle omitting refraction. Reflection effects also omitted, except in the area south-east of St. Ninian's Isle, where dashed lines mark the position of diffracted waves which have not been observed—see text. Open arrows—direction of advance of waves.

specifies the local weather conditions at the time. Gaps in the traced wave pattern are due to a lack of discernible waves on the airphotos. Waves fail to appear on the airphotos where the angle of reflection of the light from the sea to the camera is unfavourable for recording them and where the amplitude of the waves is very low compared with the wave length. The latter effect makes the delineation of the incident swell particularly difficult because amplitude varies along the crests of waves forming swell. It is obvious in Figure 4 that the incident swell is not formed of such regular waves as the diffracted swell. The wave pattern close to the shore is also made difficult to decipher by broken water and by the superposition of short wave length, local wind-driven waves. The areas of both of these are marked on Figure 5.

When the airphotos were taken, the ocean swell was approaching from the west-south-west (similarly at the time the satellite image, used in Figure 4, was made); but the dominant wave length of the swell was 165 m in the area of deep water to the west, as measured on several airphotos belonging to the same run. The swell became subject to refraction on crossing the 82 m submarine contour 1 to 2 km west of the west coast of St. Ninian's Isle (west of Figure 5). The observed wave length of the swell between St. Ninian's Isle and Colsay has decreased to about 100 m. However, the true wave length of incident waves in this region may be greater than this; the number of visible waves may have been increased by waves reflected from the cliffs to the east, which here plunge to a depth of about 20 m and are capable of reflecting waves.

Both diffraction and refraction operate within the area covered by Figure 5; the importance of refraction increases relative to diffraction as the sea floor shallows. However, shallowing is restricted as the sea floor meets the foot of the cliffs at a depth of between about 20 and 30 m until far inshore. Figure 6 provides a diagrammatic representation of the wave pattern due to diffraction, to be expected if the coastline plunged everywhere to a depth of greater than half wave length. This diagram ignores the effects of reflection, except south of St. Ninian's Bay (see below). While this diffraction pattern depends entirely on the outline of the coast, the refraction pattern depends on the shape of the sea floor and the changing wave length of the waves. The bathymetry is not known in sufficient detail to enable a refraction pattern to be predicted, especially near the base of the cliffs where the water shallows rapidly and the refraction effects are strongest. However, the difference between the observed wave pattern shown in Figure 5 and the expected diffraction pattern shown in Figure 6 is the result of refraction.

The swell entering the channel on the north side of St. Ninian's Isle is subject to diffraction on entry and becomes increasingly refracted as it advances. It is noticeable that the combined effects of diffraction and refraction, together with further diffraction by a minor headland on St. Ninian's Isle at the entrance to Bigton Wick, make the channel act as a wave guide. The wave front is an arc of a circle of radius between half and three-quarters of a kilometre most of the way up the channel; the center remains in the centre of the channel even though the channel is curved. In Bigton Wick at the end of the channel, the wave length has decreased to 60 m as a result of refraction.

However on the south side of St. Ninian's Isle, the wave pattern immediately south-east of the island is more difficult to explain. The waves observed to fill St. Ninian's Bay (wave length ca. 30 m) and to break on the south side of the tombolo (Figure 5) are not as sharply developed on the airphotos as the waves on the north side of the tombolo. They cannot be detected in the area of local wind-driven waves (wave length ca. 9 m) to the south, masking the entrance to St. Ninian's Bay. Their wave length indicates they are derived from the swell, but whether by diffraction and refraction of the incident swell (solid lines on Figure 6) by Inn Holm or by diffraction and refraction of the swell reflected by the cliffs south of St. Ninian's Bay (dotted lines on Figure 6) or both is not clear.

Airphotos of the area taken for the Ordnance Survey on the 17th July 1965 in calmer conditions show a wave pattern very similar to that presented in Figure 5; however, wave lengths are very much shorter, and no waves can be discerned within St. Ninian's Bay on the photo.

DISCUSSION AND CONCLUSIONS

The local climate is dominated by depressions which throughout the year cross the area from south-west to north-east. They generate winds which over the years blow rather equably from all the points of the compass, though changing direction rapidly with time. As measured in Shetland over 40 years up to 1960, the winds blew from the south, south-west and west 52% of the time (expected uniform % = 37.5), and from each of the other five points of the compass between 6 and 13% of the time (expected uniform % = 12.5), though the form of the monthly average wind-rose varied significantly from month to month (ANON, 1960). Similar results were obtained from a wave-measuring buoy (DB3) sited 87 km to the WNW of St. Ninian's Isle in waters with a depth of 184 m during the years 1985–1988 (MAREX, 1992). Averaged over this period, the wind blew from the south-westerly quadrant

45% of the time instead of the expected uniform value of 37.5% and from each of the other five points between 7 and 12% of the time.

The swell-rose for the period 1985–1988 at DB3 shows swell advancing from the north, north-west and west 75% of the time (expected uniform % = 37.5), including 35% of the time from the west (expected uniform % = 12.5). There is very little difference in the all-wave-rose (both swell and wind-sea, *i.e.*, wind-driven waves) to the swell-rose; this indicates that at DB3 the wind-sea has had little influence on the swell-rose, despite the difference between the wind-rose and the swell-rose. The chief difference caused by the inclusion of the wind-sea data is a slight but significant increase in recorded wave height. A period of 5 sec (wave length of 38 m) was arbitrarily selected as separating swell from wind-sea.

For the whole period 1985–1988 waves, both swell and wind-sea, approached the west coast of St. Ninian's Isle from the south-west, west and north-west 53% of the time, as indicated by measurements at DB3 (from the west 30%). Waves which approached Shetland from the north for 20% of the time were diffracted by the west coast of Shetland so as to approach St. Ninian's Isle from the north-west, though weakened. All these waves were diffracted and refracted around St. Ninian's Isle so as to break on the tombolo. Over the measured period, the waves at DB3 tended to vary between a wave height of 1 m with a period of 5 sec (wave length of 38 m) and a height of 5 m with a period of 9 sec (wave length of 124 m), anything outside this range being less common.

Thus, the wind-sea is relatively unimportant relative to the swell at DB3, partly because the wind directions are much less persistent than swell directions. Immediately offshore of St. Ninian's Isle, the wind-sea is of even less importance due to the limited fetch for all directions from north through east to south. Winds from the north and the south have the maximum available fetch of no more than 2 km. Measurement on airphotos associated with Figure 5 indicate a maximum wave length of 9 m for such wind-driven waves in the neighbourhood of the tombolo. Because of their shorter wave length, the wind-driven waves are less influenced by refraction and therefore approach the tombolo with more rectalinear crests than swell-derived diffracted waves with the same wave normal. While the swell derived diffracted waves approaching the tombolo always present the same pattern of approach, the wind-driven waves approach from a variety of directions according to the current wind direction. If the wind-driven waves other than those approaching from the west and reinforcing the swell have an effect on the tombolo, it must be to create a different water-line shape to that produced by the swell-derived waves. Furthermore, it is possible to show by means of the relationship Energy $\propto$ amplitude × wave length that the energy exerted by the swell derived waves on the beach is r^2 times that exerted by the smaller wind driven waves, where r is the ratio of the longer wave length to the shorter wave length and assuming the ratio of the amplitude to wave length is the same in both cases. This gives from 10 to 40 times more energy from the swell-derived waves in Figure 5.

The strength and direction of the wind, at the time that the airphotos used for Figure 5 were taken, is not known; but at the middle of the same day, it was blowing force 4 (5 to 8 $m \cdot sec^{-1}$) from the southward and long strings of foam reaching down wind in this direction from the cliffs indicates that the wind had been blowing like this, or more strongly, for some time. The only waves that result from this wind have a wave length of 9 m and appear to be of very minor importance on the airphoto, compared with the waves derived by diffraction from the swell coming from the west. Similarly, the force 5 to 6 wind (9 to 14 $m \cdot sec^{-1}$) blowing from the north at the time the satellite image was made, has produced waves, if any, too small to be recorded on the image.

The long term constancy of the form of the tombolo is revealed by the similarity of the maps and airphotos of different dates quoted above. The airphotos show that the shorelines of the tombolo are parallel to the crests of the swell-derived waves breaking on it. Visits to the tombolo over many years have shown these waves to break simultaneously the length of the tombolo, in equilibrium with it. Therefore, local wind-driven waves have no long term effect on the tombolo. It is apparent that the tombolo is dependent on wave energy supplied from the westward by the swell and is independent of locally-created wind-driven waves.

The notation on the charts of the area shows that the sea floor is covered by sand on both sides of the tombolo as far west as the deep sea floor. The sand from the sea floor has been swept into St. Ninian's Bay and Bigton Wick, by the diffracted and refracted swell, to form the tombolo where the two sets of waves meet. This tombolo is the direct result of wave action on the sea-floor sand and not of currents partly controlled by wave action, as commonly cited for other tombolos. Longshore drift, a commonly cited agent in the formation of tombolos, acts only within this tombolo to maintain the shoreline parallel to the crest of the breaking wave. There is no macroscopically visible variation in the properties of the sand forming the tombolo and no consistently directed longshore drift.

Figures 4 and 5 show that the diffracted and refracted swell from the west controls the shape and orientation of the other sandy beaches in the area as closely as it controls the tombolo. This control extends to the major sand beaches at Sumburgh and Quendale (Figure 4) where the sea is so deep that refraction becomes significant only in the immediate neighbourhood of the beach. All these beaches, including the tombolo have shorelines forming arcs of circles.

Comparison with other tombolos is difficult, because wave patterns and underwater topography are never reported, yet it is the waves which create the tombolo. It is obvious that longshore drift is an important factor in those tombolos extending out from long shelving beaches; however, it is probable that many tombolos attributed to local winds blowing from either side are instead the result of an onshore swell being refracted and/or diffracted around an island, with or without the assistance of longshore drift.

ACKNOWLEDGEMENTS

Iain Farquhar of the Meteorological Office, Edinburgh, kindly provided the wind speed and direction data for specified dates. The airphotos reproduced here as a tracing are © British Crown copyright/MOD and reproduced with the permission of the Controller of Her Britannic Majesty's Stationery Office. The satellite image was reproduced here as a tracing by permission of the National Remote Sensing Centre Ltd., Farnborough. Mr. T.S. Hedges, Dept. of Civil Engineering, University of Liverpool, very kindly gave advice concerning wave diffraction and Dr. D.A. Neave of the British Oceanographic Centre supplied wave-climate data. The United Kingdom Offshore Operators Association kindly allowed access to and citation of confidential wave data obtained from the DB3 buoy.

LITERATURE CITED

ANON., 1960. *North Sea Pilot*. Vol. 1. London: Hydrographic Department, 384p.

ANON., 1986. *Tidal Stream Atlas—NP 209—Orkney and Shetland Islands*. Taunton: Hydrographic Department, 4th edition, 43p.

BALLARD, P., 1984. An ephemeral tombolo at Gabo Island. Victoria. Occasional Paper No. 35, Dept. of Geography, Royal Military College, Duntroon, A.C.T.

BIRD, E.C.F., 1984. *Coasts*. Oxford: Blackwell.

BODERE, J-C., 1973. Le tombolo double de Thordarhoefdi (Islande septentrionale). *Norois*, 20, 213–235.

FLINN, D., 1969. The development of coastal profiles in the north of Scotland, Orkney and Shetland. *Scottish Journal of Geology*, 5, 393–399.

FLINN, D., 1973. The topography of the sea floor around Orkney and Shetland and in the northern North Sea. *Journal of the Geological Society of London*, 129, 39–59.

FLINN, D., 1974. The coastline of Shetland. *In:* GOODIER, R. (ed.). *The Natural Environment of Shetland*. Edinburgh: The Nature Conservancy Council, 13–23.

GUILCHER, A., 1958. *Coastal and Submarine Geomorphology*. London: Methuen, 274p.

JOHNSON, D.W., 1919. *Shore Processes and Shoreline Development*. New York: Wiley, 584p.

KING, C.A.M., 1972. *Beaches and Coasts*. London: Arnold, 403p.

KINSMAN, B., 1965. *Wind Waves*. New Jersey: Prentice-Hall, 676p.

MAREX, 1992. *Environmental Conditions at DB3*. Marex Technology Ltd. Unpublished, United Kingdom Offshore Operators Association. Vol. 1.

OTTENS, R. and OTTENS, J., 1745. Atlas van Zeevaert en Koophandel. Amsterdam.

SAUVAGE DE SAINT MARC, M.G. and VINCENT, M.G., 1955. Transport littoral formation de fleches et de tombolos. *Proceedings of the Fifth Conference on Coastal Engineering*. Engineering Foundation. Chapter 22.

SCHWARTZ, M.L.; GRANO, O., and PYOKARI, M., 1989. Spits and tombolos in the southwest archipelago of Finland. *Journal of Coastal Research*, 5, 443–451.

SHIGEMURA, T.; TAKASUGI, J., and KOMIYA, Y., 1985. Formation of a tombolo at the west coast of Iwo-Jima. *Proceedings of the 19th Coastal Engineering Conference*, ASCE, New York, Chapter 96.

SORENSEN, R.M., 1978. *Basic Coastal Engineering*. New York: Wiley, 267p.

SUNAMURA, T. and MIZUNO, O., 1987. A study on depositional shoreline forms behind an island. *Annual Report of the Institute of Geoscience*, University of Tsukuba, No. 13, 71–73.

THOMAS, G., 1830. MSS Chart. Unpublished. Hydrographic Department, Taunton.

WHITAKER, J., 1977. *Almanack for 1978*. London, 1220p.

ZENKOVICH, V.P., 1967. *Processes of Coastal Development*. Edinburgh: Oliver and Boyd, 738p.