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The effect of slope and vessel speed on the performance of a single beam acoustic seabed classification system

Paul G. von Szalay*, Robert A. McConnaughey

Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA, 7600 Sand Point Way NE, Seattle, WA 98115-0070, USA

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Abstract

Although the emergence of an acoustic single beam seabed classification system appears promising as a cost-effective tool to acquire information about bottom types, some limitations of this technology with respect to vessel speed and rough terrain have been identified. To further refine this technology, we examined the *QTC View* system to determine if it would work in an area such as the Gulf of Alaska, which is characterized by deep water, steep slopes, heterogeneous substrate. Studies were undertaken to evaluate the operational limits with respect to vessel speed and bottom slope. Results indicate that speeds between 3 and 12 kn have no significant effect on classification performance, but bottom slopes exceeding approximately 5–8° appear to cause a complete breakdown in classification accuracy. The potential of trawl-mounted sonar systems, currently under evaluation, as a potential solution to expanded range of operation over bottom slopes is discussed.

Keywords: *QTC View*; Acoustic seabed classification; Bottom types; Bottom slope; Vessel speed

1. Introduction

Acoustic single beam seabed classification systems have recently emerged as a cost-effective and promising remote sensing tool that uses acoustics to acquire information about bottom types (Collins et al., 1996; von Szalay, 1998). This technology is based on the principle that an echo return from the bottom contains information about such substrate properties as grain size, porosity, and compactness. Various algorithms are used to extract one or more parameters from the echo return which are then compared to a set of standards from sites with known bottom types. Classification is based on which standard most closely matches the parameters extracted from the incoming signal.

The system used in this study, the *QTC View*,[1] extracts a large number of shape parameters from a digitized echo return. Principal component analysis is then used to reduce these to a set of three uncorrelated factors (known as Q_1, Q_2, and Q_3) that are plotted in three-dimensional Q-space. Seabed classification is based on the principle that acoustically distinct bottom types tend to form separate clusters in Q-space. Incoming signals are classified by comparison with a catalog of known bottom types that are generated during calibration of the system at sites with bottom types representative of the study area (additional details in von Szalay, 1998).

* Corresponding author. Tel.: +1-206-526-4153; fax: +1-206-526-6723.
E-mail address: paul.von.szalay@noaa.gov (P.G. von Szalay).

[1] Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

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Another system, the *RoxAnn*,[1] extracts only two parameters from the echo return. These are known as E1 and E2 and represent roughness and relative hardness, respectively. E1 is the integral of the second part of the amplitude vs. time graph, while E2 is obtained by integrating the entire second echo (Schlageweit, 1993).

A potentially important application of this technology in fisheries research is the identification of essential fish habitat, much of which is found in steep and rocky areas that may present a challenge to seabed classification systems (e.g., Carlson and Straty, 1981; Stein et al., 1992). Some limitations of this technology with respect to ship speed and rough terrain have already been identified. Hamilton et al. (1999) noted that the second echo parameter (E2) used by the *RoxAnn* system was usually inversely related to speed, and Schlageweit (1993) observed that the *RoxAnn* classification system was internally consistent only at constant speed. Hamilton et al. (1999) also reported that the *QTC View* did not exhibit an obvious dependence on speed, but did not present any quantitative methods or results in support of their conclusion. Obvious misclassifications in areas of rocky outcrops on the seafloor have been observed for both the *RoxAnn* and *QTC View* systems (Hamilton et al., 1999).

An acoustic seabed classification system is only useful if it generates accurate data over the full range of operating conditions. Because depth, slope, and vessel speed can be highly variable in different areas and for different applications, it is important to establish the operating limits with respect to these parameters prior to data collection. In addition to vessel speed and rough terrain, steep slopes and great depths are also likely to place limits on where this technology can be used. A sloping bottom results in an increased echo duration (and hence the shape of the return signal), which in turn can lead to echoes appearing as a separate acoustic class if the classification algorithms are sufficiently sensitive to echo length (Preston, J., Quester Tangent Corporation, personal communication, 1999). Also, because each data record of the system that we examined, the *QTC View*, is based on a stacked average of five pings, the effective footprint length (EFL), and hence the spatial resolution becomes a function of vessel speed as well as depth according to

$$\mathrm{EFL} = 2h\tan\left(\frac{\theta}{2}\right) + \frac{4v}{f}$$

where h is the depth (m), θ the beam width, v the vessel speed (m/s), and f the ping rate (Hz). To illustrate the effect at a depth of 100 m, the increase in the EFL is approximately three-fold, going from 12.2 to 36.9 m as the vessel speed increases from 0 to 12 kn. The signal-to-noise ratio is also affected by speed since engine and flow noise increase with speed. However, this potential problem can be overcome by using a high power echosounder and transducer placement (Preston, J., Quester Tangent Corporation, personal communication, 1999).

The objective of this study was to determine the operational limits of the *QTC View* system related to seabed slope and ship speed. In particular, we wanted to determine whether the consistency and certainty of classifications was impacted by the range of speeds that our survey vessels are capable of. We also wanted to determine the maximum bottom slope over which the *QTC View* can be successfully operated.

2. Materials and methods

2.1. Study areas and acoustic equipment

We investigated the slope effect on classification performance during three speed trials on board the NOAA ship *John N. Cobb* in Tenakee Inlet, a protected area off of Chatham Strait in Southeast Alaska (Fig. 1). All fieldwork was conducted in an area near the mouth of the inlet which has an east–west orientation and is approximately 20 km × 3.7 km. The bathymetry is U-shaped with highly variable steepness. Depths in the basin exceed 200 m and the substrate is diverse, characterized by a mosaic of relatively small patches ranging in size from approximately 100 to 200 m (von Szalay, 1998). We conducted a pilot study in 1996 to determine the range of bottom types found in Tenakee Inlet. By deploying a video camera and a Shipek grab sampler at a relatively large number of pseudo-random sites ($n = 42$) throughout the inlet, we determined that the predominant bottom types were: pebble-size gravel embedded in a mud matrix (40%), pure mud (40%), sand and gravel mixture (10%), pure sand (5%), and miscellaneous combinations of mud, sand, pebbles, cobbles, boulders (5%) (unpublished data, 1996). The study area was a parallelogram approximately 6.8 km × 2.2 km, ranged

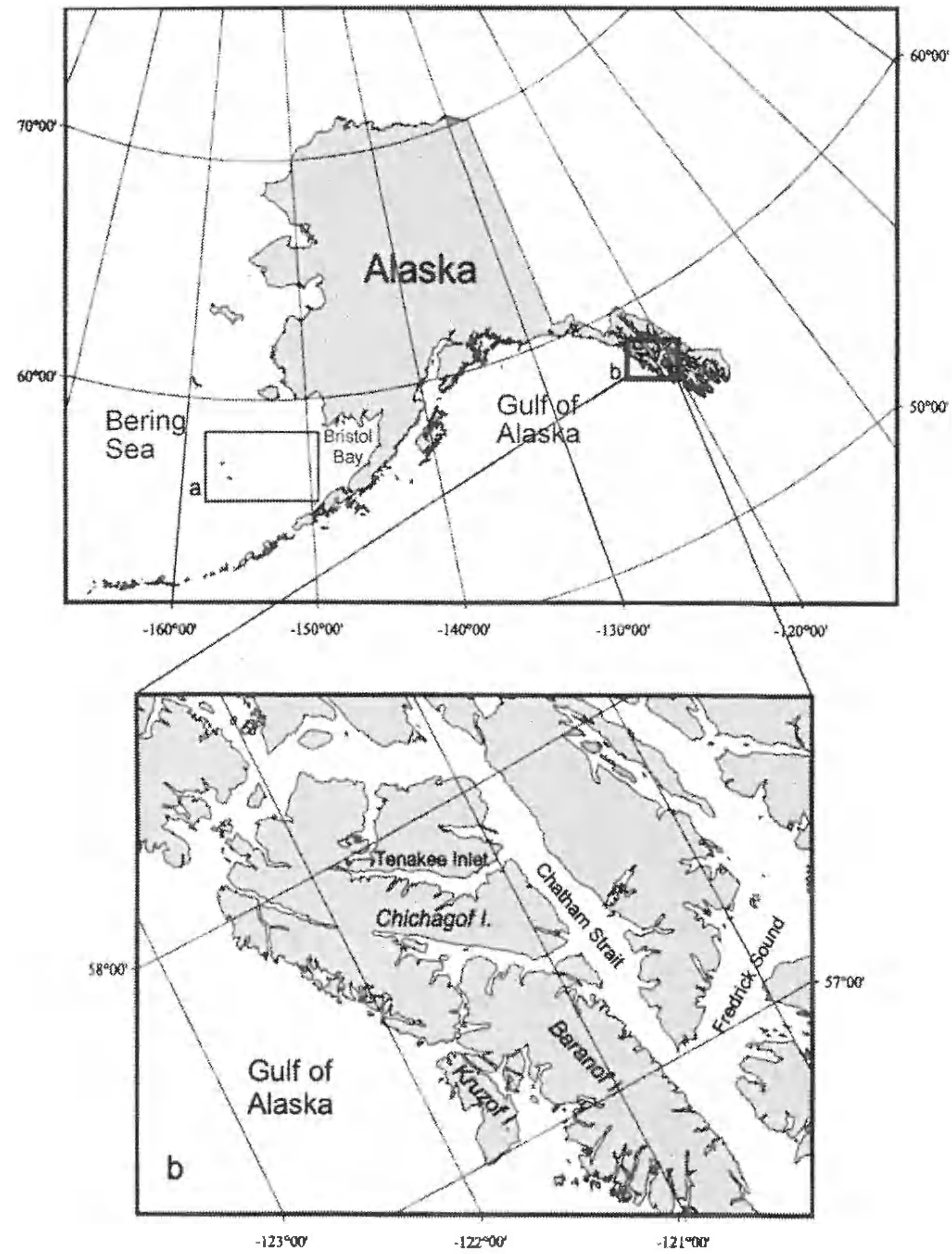

Fig. 1. Study areas (boxes) in the Bering Sea (a) and Tenakee Inlet (b), Alaska.

in depths from 60 to 230 m, and had seabed slopes between 0° and 50°.

We conducted four additional speed trials over the continental shelf (in an area extending from Bristol Bay to the Pribilof Islands) in the Eastern Bering Sea using the NOAA ship *Miller Freeman* (Fig. 1). This was done in order to generalize the findings from Tenakee Inlet on the effect of vessel speed to an area

Table 1
Specifications and settings of acoustic equipment used in the Bering Sea and Tenakee Inlet[a]

	Bering Sea	Tenakee Inlet
Echosounder	EK-500	EQ-50
Manufacturer	Simrad	Simrad
Output power	2000 W (500 W/quadrant)	1000 W
Ping rate	1 Hz	1 Hz
Pulse duration	1 ms	1.25 ms
Transducer	ES 38-B	38-26/22
Manufacturer	Simrad	Simrad
Type	Split-beam	Single beam
Beam width	7° × 7°	9° × 13°
Frequency	38 kHz	38 kHz
QTC View version	Series 3	Series 4
Base gain	0 dB	−7 dB
External attenuation	12 dB	None

[a] The two numbers listed for beam width refer, respectively, to the fore-aft and athwartship angles of the beam (the transducer used in the Bering Sea generates a symmetric footprint, while the transducer in Tenakee Inlet does not).

with different seabed properties. The bathymetry in the Bering Sea study area was relatively flat, ranging in depth from 50 to 100 m. The seabed was considerably less variable at the Bering Sea sites than in Tenakee Inlet and consisted primarily of finer particle bottom types such as mud, medium-sized sand, and combinations of the two (Smith and McConnaughey, 1999).

Specifications and settings of acoustic equipment used in the Bering Sea and Tenakee Inlet are listed in Table 1.

2.2. *Calibration of the QTC View*

2.2.1. *Tenakee Inlet*

The base gain was set to the appropriate level for Tenakee Inlet before carrying out the calibration procedure. The base gain (measured in dB) refers to the amount of amplification of the echo prior to being processed by the *QTC View*. If too high, an excess of saturated (clipped) signals may result in poor data quality and loss of information due to flattened signal peaks. If the base gain is too low, however, weak signals are compromised by poor signal to noise ratios. Our goal was to find a level that would yield a 4.5–5.0 V signal over hard bottom types in the shallowest part of the inlet (i.e., depths approximately 50–100 m), while ensuring that the signal exceeded 1.5–2.0 V in the deepest areas with a soft substrate (*QTC View Series* 4 manual). Experimentation with different settings suggested an optimal level of −7 dB for Tenakee Inlet.

We then created calibration files for sites with different bottom types. Sites with known bottom types were targeted first (based on 1996 pilot study). We collected 65 records (corresponding to 325 pings) for each calibration at a ping rate of 1 Hz. A self-contained video camera was deployed during each calibration exercise. The resulting video record was used to verify that all of the records making up a calibration file were collected over the same bottom type. This was necessary because vessel drift can be considerable during the 6 min calibration procedure. We also deployed the Shipek sampler immediately prior to and after each calibration event. The sediment samples were used to quantitatively describe the bottom type by means of a granulometric analysis of particle size.

We generated a preliminary catalog consisting of four calibrations after calibrating all of the known sites. A catalog contains the shape parameter data from the calibrations which were stored as a high-dimensional variance–covariance matrix. This matrix is used to generate the so-called *Q*-values (Q_1, Q_2, and Q_3) from each classification record by means of principal component analysis. The three *Q*-values (defining a point in three-dimensional "*Q*-space") associated with a classification record are compared with the clusters in *Q* space (each cluster consists of 65 points representing the 65 records collected at each calibration site) in order to assign a bottom type class to the new record. The files in our preliminary catalog represented the following bottom types: gravel embedded in a mud matrix, coarse sand with pebble-size gravel, sand, and pure mud.

We tested the completeness of the preliminary catalog by collecting classification data from a zig-zag transect covering the entire survey area. By monitoring classification confidence in real-time and looking at the echosounder's display of the 10 m expansion layer, it was possible to use the preliminary catalog to search for new bottom types. Two additional classes were found this way (barnacle shells and a mixed class containing cobble-size particles with sand and pebbles); thus, a final catalog consisting of six acoustically distinct classes was generated.

2.2.2. Bering Sea

A separate catalog, also consisting of six classes, was generated for the Bering Sea site. The classes contained in this catalog corresponded to the following sediment types: fine gravel, medium sand, fine sand, sandy mud, pure mud, and shell hash. We followed a calibration procedure similar to the one described for Tenakee Inlet with two differences. Each calibration consisted of 100 rather than 65 records, and no camera was used for ground-truthing since a video camera is not effective at distinguishing among the various fine-grained sediment types found over the Eastern Bering Sea shelf.

2.3. Effect of speed

2.3.1. Experimental design

A speed trial in Tenakee Inlet consisted of running a set of eight parallel transect segments at two different speeds: 5 and 9 kn (Fig. 2). These speeds represented the lowest and highest speed that could be consistently maintained by the *John N. Cobb*, and thus the maximum contrast for evaluating speed effects on classification performance. We oriented the segments perpendicular to the depth contours in two of the trials (b and c), and in one (a) they were generally aligned parallel to the contours. Segment lengths ranged from approximately 1100 to 1500 m. Both seabed structure and bathymetry were highly variable in the area where the speed trials were performed.

A speed trial in the Bering Sea consisted of running the same 3.7 km long transect segment at four different speeds: 3, 6, 9, and 12 kn. These speeds span the range that could be consistently maintained by the *Miller Freeman* and allow for an even greater contrast in evaluating speed effects than was possible in Tenakee Inlet. Differential GPS and a plot of the transect in a navigational software was used to ensure that the same ground was traversed when a transect was repeated at a different speed in both the Bering Sea and Tenakee Inlet. We were particularly interested in determining

Table 2
Speed trial results[a]

Trial	χ^2	P	d.f.	Orientation of transects	Depth range (m)
(a) *Classification consistency*					
Bering Sea					
a	9.37	0.154	929		62–64
b	0.53	0.912	977		94–97
c	3.91	0.271	955		67–68
d	5.38	0.496	943		84–85
Tenakee Inlet					
a	1.82	0.402	414	Parallel to contours	28–153
b	6.81	0.235	1884	Normal to contours	22–226
c	0.44	0.979	985	Normal to contours	79–212

Trial	Mean confidence percentage					Orientation of transects	P	d.f.
	3 kn	5 kn	6 kn	9 kn	12 kn			
(b) *Confidence percentages*								
Bering Sea								
a	82.4		85.8	84.9	87.4		0.013	932
b	89.8		89.7	89.3	88.6		0.77	1000
c	86.6		87.1	87.1	86.5		0.034	958
d	79.5		80.7	78.3	81.2		0.41	950
Tenakee Inlet								
a		81.7		82.6		Parallel to contours	0.72	415
b		88.5		89.6		Normal to contours	0.018	1854
c		89.9		90.1		Normal to contours	0.41	986

[a] The χ^2 values in (a) are used to test whether the relative frequency of occurrence of individual bottom type classes is independent of ship speed. P in (b) is the probability that the confidence percentages are statistically identical for all speeds.

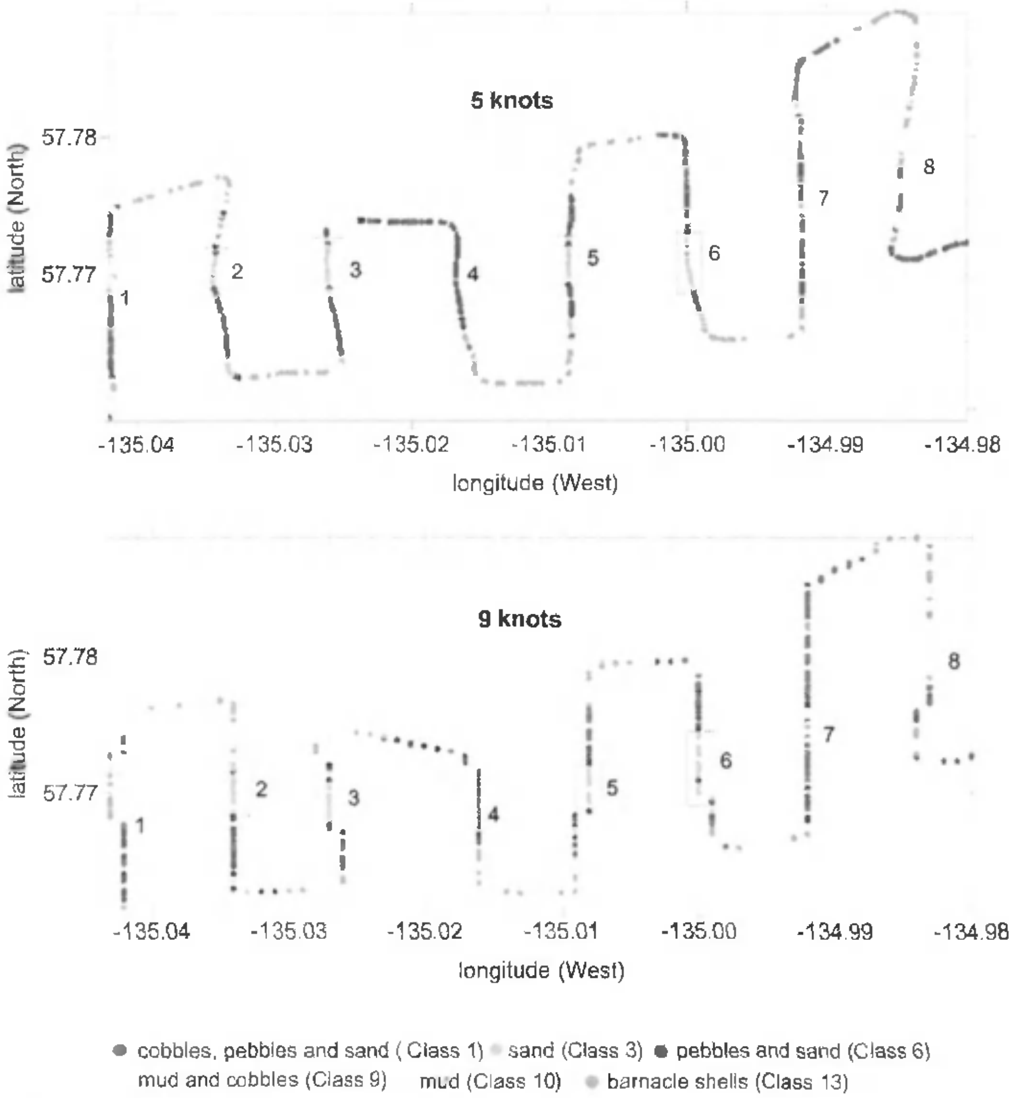

Fig. 2. Speed Trial c in Tenakee Inlet. The upper panel illustrates a transect color coded by bottom type with data collected at 5 kn. The lower map shows a transect over the same area with data collected at 9 kn. The numbers to the right of the segments indicate transect segment numbers and the boxes illustrate classification repeatability of sand (class 3) at two different speeds.

the quality of the *QTC View* data under normal operating conditions of an acoustic survey (12 kn). The depth ranges covered by the four speed trials are listed in Table 2 for both Tenakee Inlet and the Bering Sea.

2.3.2. *Analysis of speed trial data*

We considered two factors in the assessment of speed effects on bottom type classification: repeatability and degree of certainty of classifications. Repeatability was evaluated with a contingency table analysis. Classification was considered repeatable if the relative frequency of the various bottom type classes did not differ significantly ($\alpha = 0.05$) between vessel speeds. Bering Sea speed trials were based on approximately 450–550 data points for runs at 3 kn, approximately 100–130 data points at 12 kn, and intermediate numbers at 6 and 9 kn. The corresponding figures for the Tenakee Inlet trials were

250–1300 data points at 5 kn and 160–600 data points at 9 kn. Since the validity of a contingency table analysis is jeopardized when a table has more than 20% of its cells with an observed frequency less than 5 (Zar, 1984), it was often necessary to exclude certain rare classes from consideration in calculating the chi-square statistic.

The degree of certainty of classifications is measured by confidence percentages which are a measure of the relative position of an incoming signal in three-dimensional *Q*-space (Collins et al., 1996) and the center of mass of the two nearest clusters contained in the calibration catalog. The closer an incoming point is to the center of mass of either cluster, the higher the percentage. This quality control measure is useful because the *QTC View* always assigns a class to each echo return. A high percentage indicates a great deal of similarity between the true bottom type and the class assigned by the *QTC View*.

Since the assumption of normality of the confidence level data was not met, even after transforming them according to the techniques recommended by Zar (1984), we evaluated the effect of speed on the degree of certainty of classifications using non-parametric analysis of variance. The Kruskall–Wallis test was applied to the Bering Sea data where the independent variable (speed) had four levels, and the Mann–Whitney test was used for the speed trials in Tenakee Inlet with only two speeds.

2.4. Effect of slope

2.4.1. Granulometric and statistical analyses of sediment samples

We examined the impact of slope on classification performance by looking for patterns in misclassifications. Classification accuracy, in turn, was assessed through quantitative comparison of sediment samples collected with the Shipek sampler at both calibration ($n = 5$) and validation ($n = 18$) sites. We performed granulometric analysis on dry sediments (von Szalay, 1998) using a stack of nine sieves ranging in mesh size from 0.063 to 16 mm. The mesh size of each sieve was twice that of the next smaller one, hence, the mesh sizes were 0.063, 0.125, 0.25, 0.50 1.0 mm and onward. Particles larger than 16 mm were separated from the subsamples and measured individually with calipers. Particles smaller than 0.063 mm, on the other hand, were lumped together with those trapped in the sieve with the smallest mesh size, forming a combined "mud" category. We generated a total of 12 size categories, ranging from mud (less than or equal to 0.063 mm) to cobbles up to 180 mm in diameter. A graphical representation of the particle size composition (i.e., cumulative particle size distribution function, or CDF) of individual grab samples was generated by plotting the cumulative weight (expressed as a percentage of the total sample weight) against the mesh sizes of the different sieves (Fig. 3).

We classified bottom grab samples from validation sites to categories established at the calibration sites using the following procedure. In the calibration phase, an acoustic sample was linked to a calibration sediment sample. In the validation phase, the category of a validation grab sample was established by determining which calibration sediment sample was most similar in terms of particle size composition. Comparisons were based on a sum of squares analysis between all possible pairs of CDFs, where a pair consisted of a sediment sample from a calibration and a classified validation site. A classification was considered successful if the validation sample was most similar to the calibration sample for the assigned *QTC View* class. Thus, a validation grab sample was compared with the reference calibration samples, and a similarity index, or square root of sum of square (SQRSS) differences, was computed for all such pairs. We generated an SQRSS value by taking the differences for all integer values of phi (ϕ) between two cumulative distribution curves (von Szalay, 1998), where ϕ is defined as

$$\phi = -\log_2 E,$$

and E is the diameter, in millimeters, of a particle. The lower the SQRSS value the greater the similarity in particle size distribution between the validation and calibration sites. We did not perform an SQRSS analysis on one of the Tenakee Inlet calibration sites which consisted exclusively of large barnacle shells, a bottom type which cannot be analyzed for particle size composition by means of granulometric analysis. Instead, we examined the validation samples visually to determine whether barnacles were present or absent.

2.4.2. Analysis of slope

To assess the impact of slope on classification performance, it is necessary to determine whether

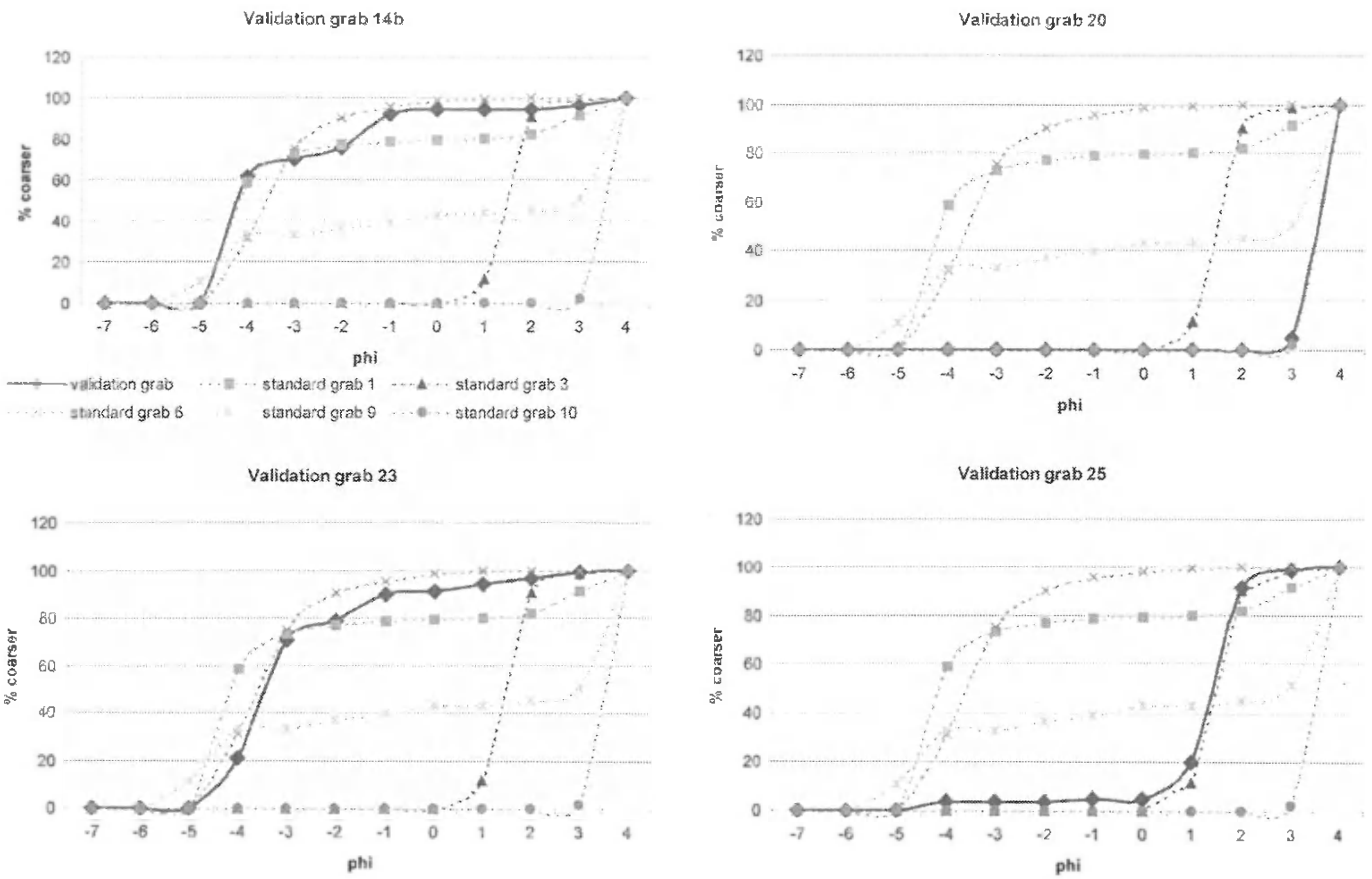

Fig. 3. Comparison of particle size CDFs between validation and standard grab samples. Each graph contains the same five standard CDFs as well as a CDF from a representative validation site.

the slope at incorrectly classified sites is significantly greater than slopes at correctly classified sites. Slope was calculated as the absolute value of the change in depth divided by the distance traveled between two classification records. We performed a standard two-sample *t*-test to test for differences in mean slopes at correctly and incorrectly classified sites. In addition, to determine whether steep bottom slopes affect the echo return to the point where they effectively constitute an acoustic seabed class, we calculated the mean slope associated with each class' classification records for data collected at two different speeds in two nearby areas during four of the Tenakee Inlet surveys (specifically using transects that were oriented perpendicular to the depth contours). The data were pooled and tested for differences in mean slope among the classes, using a two-way analysis of variance (slope was treated as the response variable, speed and *QTC View* class as the two factors, and area as a blocking factor). We then applied Tukey's multiple comparison test to test for differences ($\alpha = 0.05$) in the mean slopes.

3. Results

3.1. Effect of speed

The repeatability of seabed classification is independent of speed, as indicated by non-significant differences in the relative frequency of class assignments at speeds between 3 and 12 kn (Table 2a). The spatial distribution of substrate patches was also relatively similar at different speeds (Fig. 2). Although some differences, attributable to the increase in footprint size (i.e., decrease in resolution) at higher speeds, are noticeable (Fig. 2), the similarities are considerably more pronounced.

Mean confidence percentages were similar among trials as well as among the different speed levels within trials. There were no statistically significant differences in the mean confidence percentages in four out of seven speed trials ($P > 0.05$, Table 2b). The smallest percentages were recorded during Trial d in the Bering Sea where the mean ranged between 78.3% (9 kn) and 81.2% (12 kn). The highest confidence

Table 3
Results of SQRSS analysis of validation grab samples[a]

Validation grab	SQRSS standard grab					SQRSS classification	*QTC View* classification
	1 (c,p,s)	3 (s)	6 (p,s)	9 (m,p)	10 (m)		
6	2100	37565	*161*	17502	58764	6	6
9	23753	10428	34508	*2515*	4440	9	9
14	*22066*	74685	22693	43798	96357	1	1
14b	*814*	38743	1244	16467	58622	1	1
15	7111	22468	*5916*	12221	43770	6	6
16	*1159*	27436	1626	10894	46644	1	13
17	*1347*	27788	1451	11633	47867	1	13
18	*10387*	49529	12995	24061	67198	1	1
19	6789	12398	12146	*2057*	23198	9	13
20	47868	17108	62546	13026	*7*	10	10
21	10506	10051	18104	*810*	16492	9	13
22	44807	15988	59112	11459	*73*	10	10
23	2188	34960	*383*	15992	55692	6	6
23b	2684	40264	*98*	19299	61815	6	6
24	2296	37724	*194*	17819	59204	6	6
25	27953	*165*	36671	10563	18200	3	3
26	2083	29317	*1224*	13411	50782	6	6
27	*2781*	23092	3314	10081	43677	1	1

[a] SQRSS values associated with the CDF comparison between the respective validation and calibration grab samples. Minimum SQRSS value for each validation grab is italic indicating the true seabed class. An SQRSS value could not be generated for category 13 since barnacle shells cannot be processed by granulometric analysis (c: cobbles, m: mud, p: pebbles, s: sand, b: barnacles).

values were obtained in Tenakee Inlet during Trial c (89.9–90.1%) and in the Bering Sea during Trial b (88.6–89.8%). For all other trials, the means were near 80% with variations no greater than one or two percentage points. Although the null hypothesis stating that confidence percentages are invariable with speed was rejected (Table 2b) in three out of seven trials, there was no apparent trend, increasing or decreasing in the confidence percentage with speed.

3.2. *Effect of slope*

The *QTC View* correctly classified 14 out of 18 validation sites (Table 3). The mean slope of the misclassified sites (13.4°) was significantly higher

Table 4
Catalog summaries and description of calibration and validation sites[a]

Standard grab (class number)	Heterogeneity	Depth (m)	Slope (°)	Description
(a) *Catalog summaries and description of calibration sites*				
Tenakee Inlet				
1	Low	200	0.27	Cobble, pebbles, sand
3	Low	200	0.46	Sand
6	Low	221	0.98	Pebbles, sand
9	Low	132	15.94	Mud, pebbles
10	Low	162	4.71	Mud
13	Low	133	34.20	Barnacle shells (100%)
Bering Sea				
1	Low	71	<0.5	Sandy mud
2	Low	66	<0.5	Med. Sand
3	Low	78	<0.5	Mud
4	Low	47	<0.5	Fine gravel
5	Low	56	<0.5	Med. Gravel
6	Low	119	<0.5	Fine sand

Validation grab	Heterogeneity	Depth (m)	Slope (°)	SQRSS classification	*QTC View* classification
(b) *Description of validation sites at Tenakee Inlet*					
6	Medium	228	1.36	6	6
9	Low	121	2.02	10	10
14	Medium	196	0.49	1	1
14b	Medium	196	0.49	1	1
15	High	195	1.72	6	6
16[b]	Low	107	12.24	1	13
17[b]	Low	136	16.05	1	13
18	Low	181	1.74	1	1
19[b]	Low	173	17.18	9	13
20	Low	169	5.01	10	10
21[b]	Low	160	8.13	9	13
22	Medium	201	1.14	10	10
23	High	220	0.60	6	6
23b	High	219	0.72	6	6
24	Medium	206	0.66	6	6
25	Low	209	0.78	3	3
26	Low	210	0.68	6	6
27	Low	192	1.42	1	1

[a] Each calibration file from Tenakee Inlet was based on 65 records (100 records for the Bering Sea files) and the reference depth, which standardizes calibration files generated at different depths, was 175 m for the Tenakee Inlet catalog (120 m for the Bering Sea catalog). The numbers in the rightmost column of (b) refers to the Tenakee classes listed in (a).

[b] Misclassified sites.

($P < 0.01$) than that of the correctly classified sites (1.3°). In particular, all of the misclassified sites had slopes greater than 8° while the slope of the correctly classified sites never exceeded 5° (Table 4), indicating that slopes exceeding approximately 5–8° have a significant effect on *QTC View's* classification performance.

The misclassified sites were all classified as class 13 by the *QTC View* but none of the validation samples from these sites, or any other validation site, contained even a trace of barnacle shells. Yet, the standard grab defining class 13 consisted exclusively of barnacle shells according to a visual inspection of the grab sample contents obtained from calibration site 13. This finding was also supported by video footage taken of the bottom at this site.

The slope at the calibration site defining class 13 (approximately 34°) was substantially greater than the other calibration sites whose slopes ranged between 0.27° and 4.71° (Table 4). The only calibration site with a comparable slope was the one defining class 9 (approximately 16°), but since none of the validation sites were assigned to class 9, there is no way of determining whether a class 9 validation site would have been correctly classified or not.

The SQRSS analysis of the samples from the misclassified sites and the ground-truthing exercises conducted at the class 13 calibration site linked class 13 to at least three different bottom types: cobbles, pebbles and sand (c,p,s) at validation sites 16 and 17, mud and pebbles (m,p) at validation sites 19 and 21, and barnacles (b) at calibration site 13. The c,p,s class is an acoustically distinct bottom type under flat-bottom conditions, but in steep areas such as sites 16 and 17, it lost its "acoustic identity" and was lumped together with two other bottom types (mud

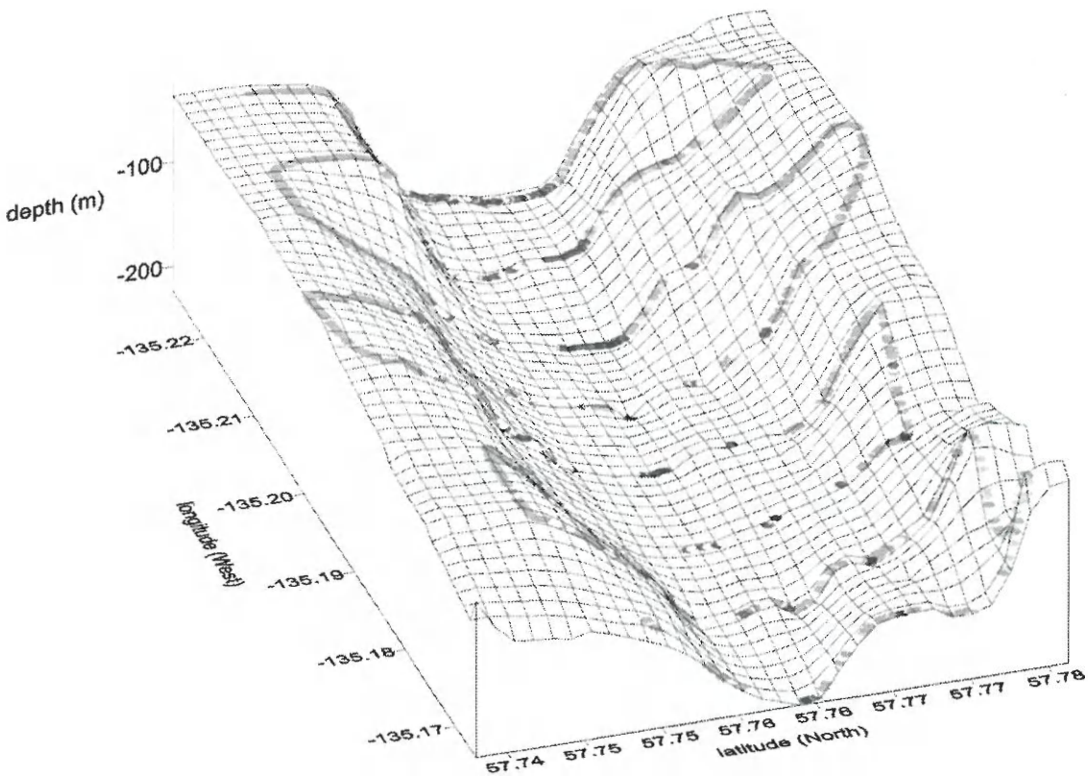

Fig. 4. Representative transects with bathymetry from Tenakee Inlet illustrating the existence of an apparent slope class (class 13 = turquoise) which shows up in steep areas, irrespective of the transit direction relative to the depth contours. The gray dots represent the only other class defined by a steep calibration site (class 9). 3D bathymetry generated by kriging based on depth data collected along transect lines.

and pebbles and barnacle shells) into an apparent "slope" class. All of the other classes were associated with only one bottom type each (Table 3).

The mean slopes associated with the Tenakee Inlet classification records of the various classes were significantly different ($P < 0.01$). Classes 1, 3, and 6 all had slopes of approximately 1–2°, which is considered flat. The mean slopes of classes 9, 10, and 13, however, were different from each of the first three classes. The mean of class 10 was 4.2° and the means of classes 13 and 9 were 9.7° and 13.9°, respectively. The relatively steep slope associated with the class 13 records along with the steep slope at the misclassified sites (all of which were classified as class 13) and the steep calibration site defining class 13 (Table 4), strongly suggest that class 13 constitutes a "slope class" rather than an actual bottom type (i.e., barnacle shell), regardless of whether the transects are oriented parallel or perpendicular to the depth contours (Fig. 4). Speed proved to be a non-significant ($P = 0.09$) factor and was dropped from a subsequent one-way ANOVA (with class as the only factor, and area as a blocking factor) which the above results are based on.

4. Discussion

4.1. Effect of speed

Seabed classification with the *QTC View* is not affected by vessel speeds between 3 and 12 kn. Although not tested directly, *QTC View*'s performance probably would not be affected by vessel speeds substantially greater than 12 kn based on the modest fractional changes in the effective footprint size for speeds several knots greater than 12 kn. This result corroborates the findings of Hamilton et al. (1999), with data from two other vessels. As expected, spatial resolution of seabed class was noticeably lower at higher speeds, as evidenced by wider spacing of returns at 9 kn compared with 5 kn. As such, the smallest patches would be undetected at the higher speeds in areas where the bottom type changed over a very small spatial scale. The significance of this, however, depends on the survey objective. In an area such as the Gulf of Alaska, e.g., the spacing between transects is considerably more limiting to both resolution and the precision in estimates of habitat quantity (von Szalay, 1998).

Even though there was some statistical evidence for significant differences in the confidence levels with speed, the results are counter-intuitive. The speed trial with the highest level of significance (Trial a in the Bering Sea), e.g., indicated an increase in the mean confidence percentage with speed, rather than a decrease as one might expect because of the larger effective footprint size at higher speeds. Furthermore, in practice, the observed differences are too small to be important, and the statistically significant outcome of Trials a and c in the Bering Sea and Trial b in Tenakee Inlet are most likely a reflection of large sample sizes (i.e., Type I error) and inevitable navigation errors when attempting to duplicate a track line.

4.2. Effect of slope

Our assessment of *QTC View* accuracy, and hence, the determination of the effect of slope on classification performance, assumes that acoustic classes are largely based on grain size. Although potentially significant contributors to the acoustic response (Collins et al., 1996), factors related to condition of state such as degree of compactness and porosity, were not considered in this study. Given this caveat, we conclude that even relatively modest slopes significantly effect *QTC View's* classification performance. This finding supports at least two theoretical arguments for an adverse impact on classification performance in sloping areas. First, bottom slope lengthens the echo duration, and hence the shape of the return signal (Preston, J., personal communication, 1999). Moreover, returns from the side lobes of the acoustic beam become more prominent with steeper bottom slope, resulting in echoes with altered physical characteristics for a given bottom type (Traynor, J., Alaska Fisheries Science Center, Seattle, WA, personal communication, 1997). It also corroborates the findings of Greenstreet et al. (1997) who suggested that systematic differences in the E1 and E2 values recorded by the *RoxAnn* system was most likely caused by variations in the attitude of the transducer. The theoretical basis of *RoxAnn* (Chivers et al., 1990) assumes that the transducer is horizontal.

In addition to slope, we considered depth and substrate patchiness, referred to as heterogeneity, as alternative explanations for the misclassifications. We ruled out substrate patchiness (defined in terms of

QTC View's classification consistency while the vessel is allowed to drift in the vicinity of the site) as a potential candidate because the heterogeneity at all of the misclassified sites was relatively low. Depth was also ruled out despite a somewhat significant difference in mean depth between correctly and incorrectly classified sites. The reason was that the mean depth at the correctly classified sites was higher than that of the misclassified sites and the distributions of depths at the two types of sites partially overlapped. If depth were a cause of the misclassifications one would expect the mean depth to be higher at the misclassified sites, indicating that the maximum depth limit of the system had been exceeded.

The approach used to evaluate the impact of slope on classification accuracy was based on two premises. First, if a sloping bottom affects *QTC View's* performance to the point that slope itself, regardless of substrate, constitutes an acoustically distinct "class", then the classification records of a class defined by a steep calibration site should have a higher mean slope than those of a "flat-bottom class". This premise by itself is not sufficient to conclude that slope affects classification accuracy since slope and bottom type could be highly correlated. A second premise is therefore necessary, and it states that bottom types that are acoustically distinct in areas of low relief lose their identity when classified over a slope exceeding some critical angle, resulting in different bottom types being lumped together into a "slope class". The validity of both premises was strongly supported by the data.

The first premise was supported by the fact that the slope at the calibration site for class 13 was considerably steeper than that of the other calibration sites, combined with the much steeper slopes associated with class 13 classification records than all other classes (except for class 9 which appears to be a separate slope class). The second premise was substantiated by our demonstration that class 13 does not refer to a unique substrate type since the SQRSS analysis and ground-truthing conducted at the class 13 calibration site linked this class to at least three different bottom types. This is in contrast to the other classes which are defined by relatively flat calibration sites (except for class 9) and were only associated with one bottom type. Based on the objective SQRSS analysis, validation sites 16 and 17 should have been assigned to class 1, while validation sites 19 and 21 should have been assigned to class 9 (Table 3). Instead, all of these sites were assigned to class 13. In addition, none of these four sites (i.e., sites 16, 17, 19 and 21) contained any barnacle shells (and neither did any other validation site) which is what extensive ground-truthing at calibration site 13 revealed.

An additional indication that class 13 may represent slope rather than a bottom type comes from the fact that with one or two possible exceptions (Fig. 4), the *QTC View* never indicated the presence of class 1 on the slope. Yet, two out of the four grab samples taken from the slope (validation sites 16 and 17) suggest that class 1 may be quite common there. We acknowledge that the amount of data supporting the second premise is limited albeit consistent. Further research similar to that conducted in this study is necessary to confirm the validity of a slope class at steep calibration sites as well as to more precisely determine the threshold angle at which the *QTC View* fails to classify the bottom accurately.

4.3. Assessing fish habitat with the QTC View over the continental slope?

The assessment and mapping of essential fish habitat is a potentially important application of acoustic bottom typing. Research in this area is already underway with the majority of studies focused on benthic marine habitat (e.g., Greenstreet et al., 1997; Collins and McConnaughey, 1998). Because many commercially important species such as sablefish (*Anoplopoma fimbria*) and Pacific ocean perch (*Sebastes alutus*) in the North Pacific are found almost exclusively over the continental slope as adults, it is crucial to address the limitations of seabed classification systems with respect to slope before proceeding with habitat mapping.

Slope-related classification error could perhaps be reduced by using separate catalogs for steep and flat-bottom areas. The idea is that sand, e.g., on a sloping surface constitutes a class that is acoustically distinct from the same type of sand over a flat bottom. By using the appropriate catalog for a particular area (i.e., the "slope" or "flat bottom" catalog), it would be possible to classify the bottom correctly in all areas.

There are great obstacles to this approach, however. First, it is unlikely that all slopes have the same impact on the echo since the effect of side lobe returns gradually increases with slope. Consequently, it would be necessary to create several "slope catalogs" for different slope ranges. Of even greater concern is the fact that variability in slope in the Gulf of Alaska is so great that it would be logistically unfeasible to switch back and forth between different catalogs on such small scales.

Perhaps a more realistic solution would be to mount the transducer on an adjustable frame that automatically orients the transducer face parallel to the bottom. This configuration would eliminate the effect of slope, provided it is able to respond sufficiently fast to changes in the bathymetry. An echosounder with a split beam transducer could be used as a slope sensor since the phase differences between the four quadrants are directly related to the bottom slope.

Alternatively, one could mount the transducer on a relatively stable platform that "traces" the bottom profile during data collection (e.g., the headrope of a bottom trawl), thus eliminating the effect of slope entirely. A prototype net-mounted and self-contained underwater echosounder system is currently being tested (Acker et al., 1999). Preliminary findings suggest that the attitude of the transducer relative to the bottom can be successfully kept within the 5–8° limit reported here.

In summary, there is an obvious need for research addressing the negative impact of slope on the performance of single beam seabed classification systems. At present it is not clear if this problem should be addressed mechanically (such as the approaches suggested here), or whether a modeling approach that incorporates the effect of slope in the classification algorithms is better. It may also be beneficial to try shorter transmit pulses than those used in this study.

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