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Fractal Analysis of Maine's Glaciated Shoreline Tests Established Coastal Classification Scheme

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ABSTRACT

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Average fractal dimensions (D) are calculated for Maine's four coastal compartments using a GIS approach and digitized U.S. Geological Survey 7.5-minute series topographic quadrangle maps. The D values indicate relatively little complexity for the southwest coastal compartment (avg. $D = 1.11$), higher complexity for the south-central compartment (avg. $D = 1.35$), and intermediate complexity for the north-central compartment (avg. $D = 1.23$). Our analysis suggests that the northeastern compartment should be further divided into two subcompartments (Cobscook Bay and non-Cobscook Bay), which have average D values of 1.37 and 1.18 respectively. Subdivision of the northeast coastal compartment is also supported by the geologic makeup of the region. Statistical tests show that all of the geologically different coastal compartments can be discriminated in terms of D at the 95% confidence level, whereas the geologically similar compartments (south-central compartment and Cobscook Bay subcompartment) cannot be statistically distinguished. Further research along previously glaciated shorelines should be carried out to build upon our results.

ADDITIONAL INDEX WORDS: *Fractal, coastal classification, Maine, GIS.*

INTRODUCTION

Coastline description is a traditional application of fractal analysis after Mandelbrot's (1967) influential paper introduced the concept of fractal dimension (D) to the scientific community. Although coastline shape has historically been difficult to quantify, the introduction of D provides a simple parameter for describing the complexity of shorelines, and D values have been calculated for several coastlines around the world (Table 1). The higher the D value (>1), the greater the coastal complexity. Although fractal techniques were used to characterize the complexity of different coastlines (Mandelbrot, 1967; Pennycuick and Kline, 1986; Xiaohua, Yunlong, and Xiuchun, 2004), relatively little work has been done to associate the resulting D values with geological and geomorphological processes. Data linking fractal dimensions to underlying genetic processes (Gao and Xia, 1996) have, thus far, been sparse and inconclusive. Xiaohua, Yunlong, and Xiuchun (2004) suggest that variations in D values along China's coastline are related to the strike of faults, whereas Jiang and Plotnick (1998) relate D values along the Pacific and Atlantic coastlines of the United States to sea floor complexity, noting that "the more complex (in a 3-D view) the sea floor is, the more complex (in a 2-D view) is its intersection with the ocean surface, the coastline." On the basis of D values, they concluded that the bathymetric complexity of the Atlantic Ocean floor is greater than the bathymetric complexity of the Pacific Ocean floor. Andrle (1996) found two peaks of complexity for the west coast of Britain, and suggested that granite batholiths and parallel grabens are responsible for larger indentations along the coast, whereas glacially incised valleys are responsible for smaller indentations. The objective of this paper is to strengthen existing research by investigating D values along a coastline where there is a well-established and accepted coastal classification system in place.

Although Jackson (1837) was the first to describe and subdivide the Maine coast into four compartments on the basis of bedrock geology, a formal classification scheme was proposed by Kelley (1987) and later expanded to the neighboring New England states and Canadian provinces (Kelley and Kelley, 1995). Kelley (1987) recognized that differentially eroded bedrock outcrop patterns strongly shape the shoreline. Resistant bedrock, such as granite, volcanic rocks, and quartzites, define protruding headlands, islands, and peninsulas. Less resistant phyllites underlie estuaries and embayments. Where the trend of resistant rocks is shore-normal, irregular peninsulas and islands are common. Where rocks strike parallel to the overall trend of the coast, the shoreline is relatively straight.

Glacial deposits, principally till and glacial-marine mud, are arrayed on the bedrock. The retreating ice margin crossed

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Table 1. *Previously published fractal dimension (*D*) values calculated for various coastlines.*

Coastline	*D*	Reference
West Coast, Great Britain	1.25	Mandelbrot (1967)
South Coast, Norway	1.52	Feder (1988)
North Coast, Australia	1.19	Carr and Benzer (1991)
South Coast, Australia	1.13	Carr and Benzer (1991)
West Shore, Puget Sound	1.19	Carr and Benzer (1991)
East Shore, Puget Sound	1.15	Carr and Benzer (1991)
West Shore, Gulf of California	1.03	Carr and Benzer (1991)
East Shore, Gulf of California	1.02	Carr and Benzer (1991)
Delaware Bay, New Jersey	1.46	Phillips (1986)
Adak Island, Alaska	1.20	Pennycuick and Kline (1986)
Amchitka Island, Alaska	1.66	Pennycuick and Kline (1986)
Pacific Coast, United States	1.00–1.27	Jiang and Plotnick (1998)
Atlantic Coast, United States	1.00–1.70	Jiang and Plotnick (1998)
Jiangsu Province, China	1.07	Xiaohua et al. (2004)
China	1.16	Xiaohua et al. (2004)
Taiwan Island	1.04	Xiaohua et al. (2004)

the Maine coast approximately 14,000 years ago (BORNS *et al.*, 2004) and left moraines perpendicular to rocks that trend in a shore-normal orientation, but blanketed bedrock with a shore-parallel trend. Thus, the trend of the bedrock determines the relative exposure of glacial deposits to prevailing waves, and the erosion of the glacial deposits.

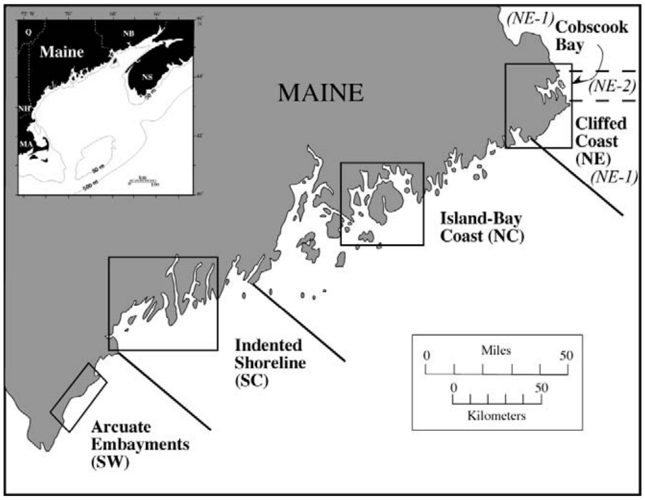

Figure 1. Map of Maine's shoreline showing the four previously established coastal compartments (northeast [NE], north-central [NC], south-central [SC], southwest [SW]). Dashed lines and italics indicate suggested new subcompartment divisions (NE-1 and NE-2). Bedrock geologic maps of areas within boxes are provided in Figure 2.

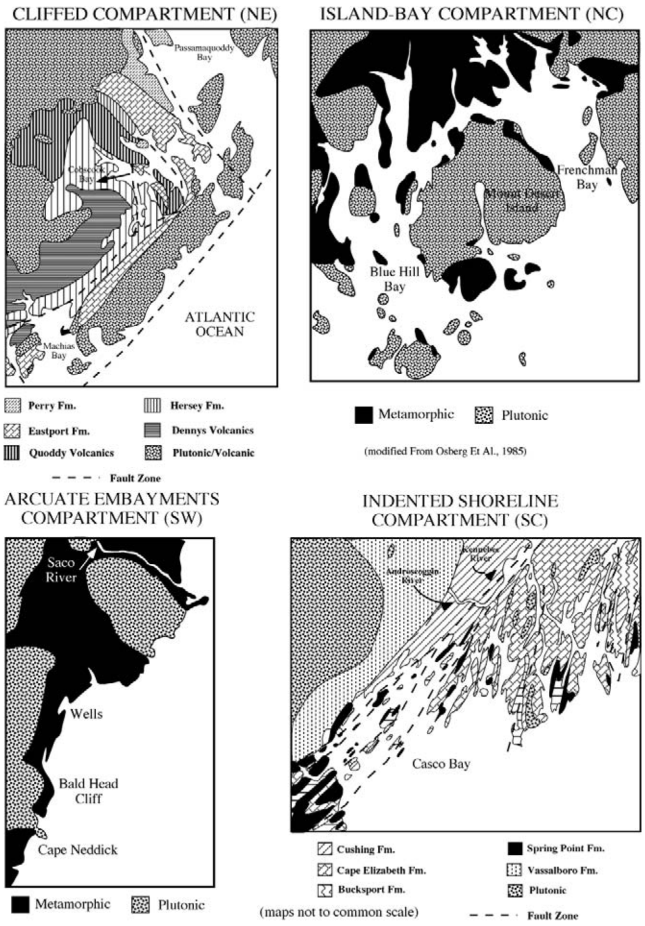

Figure 2. Bedrock geologic map of selected areas illustrated in Figure 1.

KELLEY (1987) quantified differences in Maine's four coastal compartments using principle components analysis (HAYDEN and DOLAN, 1979) of a matrix of 13 variables (dealing with topographic relief and exposure of the coast and intertidal environments). Three of the components accounted for 83% of the total variance (ledge factor, marsh factor, and mudflat factor). KELLEY (1987) related these factors to: (1) along-coast variations in bedrock composition and structure; (2) spatially varying deposits of till and glacial-marine sediment; and (3) modern processes acting on the irregular shoreline.

Kelley's scheme is widely accepted and is often cited in literature dealing with Maine coastal classification. A visual inspection of a map of coastal Maine reveals that there are differences in shoreline complexity between the four coastal compartments: northeastern (NE), north-central (NC), south-central (SC), and the southwestern compartment (SW; Figure 1).

The NE coastal compartment is characterized by relatively resistant northeast-striking metavolcanic rocks with less resistant, glacially scoured metasedimentary rocks comprising Cobscook Bay (Figure 2). The resulting shoreline is typified by high cliffs along the outer, Atlantic coast. The less resistant rocks of Cobscook Bay, though protected in a sheltered estuary, have eroded to expose the highly irregular limbs of a plunging anticline (KELLEY and KELLEY, 2004). This compartment is, thus, composed of highly exposed bedrock and gravel beaches (Atlantic coast) and sheltered and extensive tidal flats (Cobscook Bay).

Maine's NC coastal compartment is characterized by abundant granitic plutons and deeply embayed areas underlain by less resistant metamorphic rocks (Figure 2). The relative resistance of the plutonic bodies to erosion has resulted in a coastline that contains broad estuaries with numerous granitic islands. Coarse-grained glacial deposits cross most embayments and form gravel beaches and coarse-grained tidal flats.

The SC coastal compartment is characterized by north-striking metasedimentary rocks with deep glacially scoured valleys (Figure 2). This combination of bedrock and structure results in a series of northwest-oriented peninsulas with intervening deep, narrow estuaries. Eroding bluffs of glacial-marine mud yield sediment in these very sheltered embayments to form extensive mud flats and salt marshes.

Maine's SW coastal compartment is characterized by northeast-striking metasedimentary rocks that are intruded by several Paleozoic and Mesozoic plutonic bodies (Figure 2). Extensive glacial sand and mud deposits blanket this section of the coast, leaving an environment that is typified by plutonic capes and intervening sand beaches that front the region's largest salt marshes.

The detailed classification of Maine's coast makes its shoreline an ideal location to compare fractal dimensions with geological processes responsible for producing the shoreline. The purpose of this study is to calculate fractal dimensions for Maine's four coastal compartments and to determine if these compartments can be statistically discriminated using this parameter.

METHODS

The shoreline maps used in this study were digitized by the Maine Geological Survey and are freely available online from the Maine Office of GIS (http://apollo.ogis.state.me.us). The coastline data are in vector format and are derived from 1 : 24,000 scale, 7.5-minute series U.S Geological Survey topographic quadrangles. We selected a random sample of 10 quadrangles each from the SC (of 25 possible) and NC (of 52 possible) compartments. We analyzed all 10 of the digital maps covering the NW compartment and all 9 of the digital maps that cover the SE compartment.

We calculated the fractal dimension of the coastline for each of the sampled topographic quadrangles using the box-counting method (KLINKENBERG and GOODCHILD, 1992). The box-counting method is based on the following equation:

$$N_r = Cr^{-D} \tag{1}$$

where N_r is the number of boxes that cover the boundary in question, r is the side length of the individual square boxes making up the grid, D is the fractal dimension, and C is a constant. The log–log form of Equation (1) follows:

$$\log[N_r] = -D\log(r) + \log(C) \tag{2}$$

D values calculated using this equation are obtained by counting N_r for different box lengths (r). The value of D is then estimated from the slope of an xy plot of log (N_r) *vs.* log (r) using least-squares linear regression (Figure 3). We used box sizes (r) of 30 m, 100 m, 250 m, 500 m, 1000 m, 1500 m, and 3000 m, thus establishing the fractal character of Maine's coastline for two orders of magnitude (see AVNIR *et al.*, 1998). The analysis was performed using ESRI ArcView GIS version 3.2.

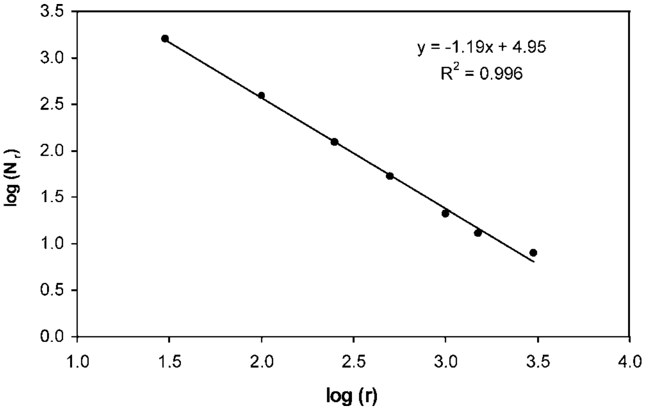

Figure 3. Typical log(N_r) vs. log(r) plot showing the regression equation, which gives a value of $D = 1.19$. This log–log plot is for the Kittery quadrangle, the first quadrangle on the Maine coast moving from west to east.

Two additional details are considered regarding the fractal dimensions calculated for the different shoreline segments:

(1) The boundaries between rivers and the ocean were visually determined by inspecting river mouths. Narrow river channels were not counted and do not influence the values of D obtained.

(2) Islands are included in the analyses since they comprise an important part of the Maine coast ($n > 1500$) and are of primary importance in the NC coastal compartment. The box-counting method is well suited to counting the shoreline compartments of the islands, as well as the adjacent mainland sections (FEDER, 1988).

For most of the maps, the grids covered an area of 9 km × 12 km, a multiple of the largest box size (3 km). Several of the maps (<10%) required using a smaller overall grid coverage as a result of an unavoidable intersection of certain linear features (*i.e.,* the Canada/Maine border) with the coastline. The software could not distinguish between these linear features and the coastline, and thus inclusion of these features would have influenced the resulting D values.

RESULTS AND DISCUSSION

High R^2 values (>0.99) for all linear regression analyses support the argument that the Maine coast is fractal throughout the range of scales tested. Average fractal dimensions for the four coastal compartments are presented in Table 2. The average D value for the SW compartment (9 quadrangles) is 1.11, the lowest average value for D in this study. The average D value for the SC compartment (sample of 10 quadrangles) is 1.35, the highest average value obtained for any of the four compartments. The NC (sample of 10 quadrangles) and NE (10 quadrangles) compartments had average D values of 1.23 and 1.26 respectively, intermediate between the other two compartments.

Protected (analysis of variance [ANOVA]) t tests showed

Table 2. *Mean values and standard deviations (SD) calculated for the different coastal compartments and subcompartments discussed in this study.*

	D Values					t tests[b]	
Compartment	n[a]	Low	High	Mean	SD	NE	NE-subdivided
SW	9	1.02	1.21	1.11	0.06	A	A
SC	10	1.25	1.43	1.35	0.06	B	B
NC	10	1.19	1.27	1.23	0.04	C	C
NE	10	1.13	1.45	1.26	0.11	C	—
NE-1	6	1.13	1.25	1.18	0.05	—	D
NE-2	4	1.28	1.45	1.37	0.07	—	B

[a] Total number of U.S. Geological Survey topographic quadrangle maps sampled for each compartment.
[b] Probability at the 95% confidence level that the mean fractal dimension for each coastal compartment was drawn from a different population. Compartments that share the same letter cannot be statistically discriminated from one another at the 95% confidence level. Analysis of variance was run separately for each group of data (NE and NE-subdivided).
SW = southwest, SC = south-central, NC = north-central, NE = northeast.

that mean values calculated for the fractal dimension parameter were significantly different (ANOVA, $p < 0.05$) among three of the four compartments (Table 2). Mean *D* values for the NC and NE coastal compartments were statistically indistinguishable. Close inspection of the data for the NE compartment shows that there is a high standard deviation for the *D* values and a large range between the lowest (1.13) and highest (1.45) fractal dimensions (Table 2). Recall that the Cobscook Bay region of the NE coastal compartment is geologically different from the rest of the NE compartment. Whereas much of the NE compartment is composed of resistant metavolcanic rocks, glacially scoured metasedimentary rocks underlie Cobscook Bay. In addition, Cobscook Bay's trend is perpendicular to that of the outer coast (remainder of NE compartment). Therefore the outer coast parallels the structural grain, whereas Cobscook Bay cuts across. KELLEY and KELLEY (2004) provide a thorough description of the geology of Cobscook Bay.

Separation of Cobscook Bay (denoted by NE-2, 4 quadrangles) from the rest of the NE section (now NE-1, 6 quadrangles) lowered the standard deviations for both subcompartments (Table 2, Figure 1). No *D* values for quadrangles from the two subcompartments overlapped. The NE-2 subcompartment has a much higher mean fractal dimension (1.37) than the NE-1 subcompartment (1.18), indicating a more complex shoreline. Protected t tests (Table 2) including the two subcompartments show that NE-2 and NE-1 are significantly different (ANOVA, $p < 0.05$). The only coastal compartments that are not significantly different (ignoring the now subdivided NE compartment) are the NE-2 subcompartment and the SC compartment (ANOVA, $p > 0.05$). This is not surprising since the underlying geology of these two compartments is generally similar. Both are composed of metasedimentary rocks that have been deeply scoured by glacial processes, and subject to similar Holocene sea level history (GEHRELS, BELKNAP, and KELLEY, 1996). However, Cobscook Bay is macrotidal, whereas the SC compartment is mesotidal. This difference in tidal range affects the relative abundance of different types of intertidal environments (HAYES, 1979). The higher rate of sea level rise in the NE compartment and the associated coastal submergence has led to a paucity of salt marshes along this section of the coast.

Overall, our results indicate that the complexity of Maine's four coastal compartments is consistent with statistically significant differences in average *D* values.

NE Compartment—Our analysis suggests that this compartment should be further divided into two subcompartments. This conclusion is supported by the underlying geology of the NE coastal region, with coast-parallel-striking metavolcanic rocks on the exposed Atlantic coast and highly irregular sedimentary and volcanic rocks in Cobscook Bay.

NE-1 Subcompartment—The average fractal dimension of 1.18 reflects a relatively uncomplicated shoreline that is distinct from the other segments included in this study. The NE-1 subcompartment is composed of relatively straight cliffs of resistant metavolcanic rocks.

NE-2 Subcompartment—The average fractal dimension of 1.37 is suggestive of a relatively high level of complexity and cannot be statistically distinguished from the average *D* value for the SC compartment. The NE-2 subcompartment is in many respects geologically similar to the SC compartment.

NC Compartment—The average fractal dimension of 1.23 suggests an intermediate level of complexity, reflected by the compartment's broad estuaries and numerous granitic islands, with abundant coarse-grained glacial deposits exposed to erosion by waves.

SC Compartment—The relatively high average fractal dimension (1.35) is indicative of a tortuous shoreline, a result supported by visual inspection of a map of coastal Maine. High *D* values are likely a reflection of the many erosion-resistant, northwest-oriented peninsulas with intervening deep, narrow estuaries of weaker bedrock.

SW Compartment—The low average fractal dimension (1.11) reflects a relatively uniform shoreline, in this case composed of plutonic capes and intervening arcuate sand beaches. Though simple in its planform view, like the NE-1 subcompartment, it is distinguished by its sand beaches instead of high cliffs.

JIANG and PLOTNICK (1998) calculated fractal dimensions for 1° latitudinal increments covering the eastern United States coast. They obtained a fractal dimension of 1.11 for the 45° to 44° segment, and a *D* value of 1.13 for the 44° to 43° segment (covering the Maine coast) using the divider method. Our results support the conclusion of XIUOHUA, YUNLONG, and XIUCHUN (2004) that *D* values calculated for an entire coastline are different from average *D* values for various segments of the same coastline. They are also in agreement with the conclusion of ANDRLE (1996) that complexity varies with position along the coastline. Results from the present study suggest that shoreline D values derived from $1:24{,}000$ quadrangles are useful for comparing complexity at scales used in statewide coastal classification schemes.

CONCLUSIONS

Relatively little research has been undertaken to associate coastal fractal dimensions to geologic processes. Our study indicates that Maine's coastal geologic compartments can be statistically discriminated using fractal analysis, with the caveat that the NE compartment should be divided into two distinct subcompartments. This further subdivision is supported by the underlying geology of the NE compartment. The Cobscook Bay segment of the NE compartment (NE-2) is geologically similar to the SC coastal compartment, and D values for the NE-2 and SC compartments are statistically indistinguishable. Although our analysis indicates that D values can distinguish geologically dissimilar segments of the Maine coast, additional research is needed to determine if D values obtained for coastal segments can be further linked to a general set of underlying geological processes. Linking fractal dimensions to coastal geological processes will require an extensive database of shoreline D values. In this regard, it may be worthwhile to apply our approach to similar coastal environments (*i.e.,* glaciated shorelines) in other parts of the world.

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