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SOME CARBONATE EROSION RATES OF SOUTHEAST ALASKA

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As a way to determine the erosion rate of carbonate bedrock surfaces in Southeastern Alaska, an instrument was designed to directly measure the lowering of rock surfaces relative to fixed stainless steel bolts epoxied into the rock. A total of 582 measuring points were set in 31 measurement sites. Dissolution was found to be the predominant mode of erosion at most stations. Dissolution rate increased with thicker humus soil, but the presence of silty soil limited dissolution, even with deep humus. After deforestation of karst landscapes there was a preliminary dissolution rate increase from 38 mm/ka to 46 mm/ka. Bare rock erosion rates ranged from 31 mm/ka under old growth forests, to 38 mm/ka in alpine settings. Both bare and soil covered site results were similar to measurements elsewhere in the world where precipitation is comparable. However, Alaskan runoff from acidic peat bogs produced dissolution rates up to 1.66 m/ka, which are some of the highest known anywhere.

Southeastern Alaska, also known as the Panhandle, contains one of the few temperate rain forests in the world. Annual precipitation in the areas of this study average 1752 mm on Chichagof Island and over 2540 mm on Prince of Wales Island. The extent of karst development is still unknown, because some regions have been poorly mapped geologically or not at all. Exploration and inventory of the caves and karst topography of the Alaska Panhandle has intensified since 1988.

This study was inspired, in part, by use of the more precise Micro-Erosion Meter (MEM) by High and Hanna (1970) in Ireland, which is similar in technique and challenges to the one described in this paper. Their system consists of a dial indicator mounted on a large triangular plate that is placed on three fixed stainless steel studs in the rock. A measurement of the lowering of the bedrock surface was then possible. In 1993 this author began a monitoring study of the erosion rates of Silurian limestone and marble on Prince of Wales Island and Chichagof Island. In this paper, the term erosion includes the lowering of bedrock surfaces by both corrasion and dissolution. The goals of the study were to more fully understand the rate of karstification in the Alaska Panhandle and to determine how conditions and land use affect the rate. The rate was measured directly at 582 points at 31 sites (Figure 1) over seven to nine years.

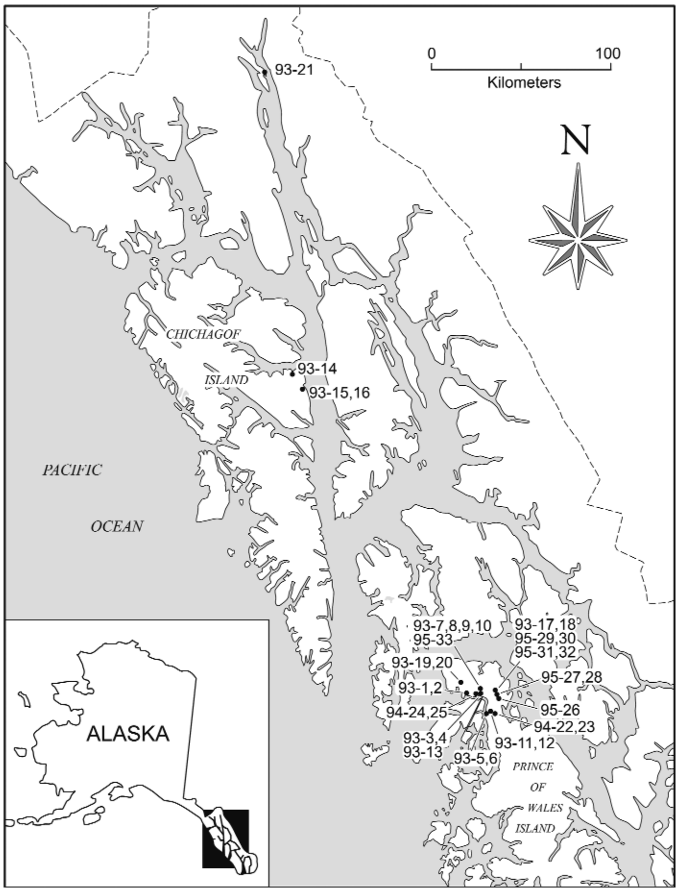

Figure 1. The REM study areas of the Alaskan Panhandle. Numbers represent measurement sites of this study. Drawing by C. Allred based on a United States Forest Service map.

METHODS AND PROVISIONS

The Rock Erosion Meter (REM) was designed by the author to measure the lowering of rock surfaces adjacent to 7.94 mm × 38.10 mm (5/16 inch by 1 1/2 inches) stainless steel bolts that were epoxied into drilled holes in the bedrock (Figure 2). The REM system provides simple and quick installation and measurement at the stations. The measuring tool was built from a Brown and Sharp model 608 one to three inch depth micrometer. It was chosen over metric types because the metric micrometers lacked the carbide-tipped measuring rods needed for durability. The instrument is compact and fits into many constricted and irregular places. A hexagonal socket was precision mounted on the base of the micrometer with copper wire harness and epoxy putty allowing the instrument to be fitted over the fixed stainless bolt heads for taking measurements. The bolt heads had been radially ground so that their top surfaces were slightly concave, and then deburred. Facets

Figure 2. The Rock Erosion Meter at measuring site #95-29. The instrument can be slipped into six different measuring positions for each bolt. By rotating the large knurled handle, the measuring rod moves in and out. Photo by C. Allred.

were ground into the threaded portion for better epoxy adhesion. The REM can be indexed around each fixed bolt to as many as six measuring positions if no rock projections interfere. The positions are designated as 12 O'clock, 2 O'clock, 4 O'clock, and so on. The 12 O'clock position was identified from a prick punch mark on each measuring bolt. Quick-setting epoxy glue was usually used in setting bolts. A small stick or wire was always used to smear the epoxy into the inside surface of each hole for maximum adhesion. After seven to nine years, none of the stations had been heaved by frost action, and the epoxy had taken on a brownish tint, apparently from tannin in the water.

After four years, a gap between the rock and apron of overflowed epoxy was noticed at a small number of stations. In some cases, the gap appeared to far exceed the average erosion of the station. When the stations were set, there was no concern about cleaning rock dust off or drying any dampness around the entrance of the drilled holes, which resulted in poor adhesion of the overflowed excess epoxy. Close observation of one such station revealed that the apron was detached from the rock and bolt; likely a result of frost wedging. The loss of the aprons in these instances had no effect on the function of the stations.

The REM scale is graduated in 0.025 mm (0.001 inch) but readings were estimated to 0.0025 mm (0.0001 inch). Readings had to be taken with care because the instrument has an inverted scale. In some instances the measuring rod contacted the rock at an angle, making measurements difficult and more inaccurate. On some oblique measurements, inconsistencies up to 0.05 mm occurred, but most measurements were repeatable to within 0.0025 mm.

It was critically important that the instrument be seated firmly against the two facets closest to the measuring point. A very delicate touch was necessary when making measurements. The rod tended to crush the delicate outer most crystals until enough resistance was felt to get a consistent reading. A test was run with two stations in a marble rock to determine erosion caused by the measuring process. Total Erosion was 0.012 mm after measuring nine times. To minimize such erosion from frequent measurements, it was decided to delay re-measurement a minimum of five years and avoid any corrections for measuring rod erosion. This would also allow vegetation and soils above some stations to stabilize and function as naturally as possible. A large number of stations were installed at some sites in order to average in differences in rock purity, drainage, and soils.

There was an initial concern that temperature changes might affect the measurements because of expansion and contraction of the rock, stations, and the REM. After the two stations set in the marble mentioned above were measured at 25° C, the rock and REM were held overnight at –4° C, then measured at the latter temperature. Heated for the same time period, they were checked for measuring rod erosion with none detected. Measurements increased an average of 0.005 mm when cold. Because the normal operating temperature range was only one tenth of the test range, the expected error is far beyond the accuracy of the instrument. Thus no corrections were made for temperature changes.

Five rain gauges were placed in a Western Hemlock and Sitka Spruce old growth forest approximately 400 m from site 93-21 at 60 m elevation. The gauges were moved periodically, monitoring canopy interception of rain and snow as compared to precipitation in an adjacent area of deforestation (clearcut).

REM MEASUREMENT SITES

Five karstified land settings were chosen for measurement sites: caves, sub-alpine, alpine, old growth forest, and clearcuts (deforestation). Stations were set in bare rock, under organic (humus) and silt soils, or just under organic soils (Tables 1 & 2). A station in andesitic basalt, which has negligible solubility, was used as a standard for the instrument and checked twice in a month and then after nine years for possible bolt movement or instrument damage.

DISCUSSION AND RESULTS

Brief descriptions of the site characterizations can be found in this section and in the appendix. All carbonate sites were on Silurian limestone and marble. Monitoring of the rock proved quite complex and challenging because of the large number of environmental variables. For example, one site might happen to be shielded from significant rainfall by the orientation of a single tree bough 30 m above. Subtle irregularity in soil makes acidity and water flow inconsistent. Notwithstanding the hundreds of measuring points of this study, the results should be taken as preliminary. However, the system is still an important tool for measuring epikarstic erosion directly.

Measurements were very inconsistent between points of stations with rock containing abundant veins and bodies of

Table 1. Silurian limestone erosion rates.

Type	Site	Elevation (m)	Number of stations	Number of points	Time lapse (TL) years	Erosion during TL (mm)		Percentage carbonate purity	Erosion rate (mm/1000y)
						Minimum	Maximum		
Muskeg streamlet inflow cave	94-22 Bear's Plunge, 2 cm above low water.	180	1	6	8.77	7.5920	20.9397	- - -	1669.34
Muskeg streamlet inflow cave	94-23 Bear's Plunge, 3 cm above low water.	180	1	6	8.77	7.7038	12.7177	- - -	1078.31
Seasonal cave trickle	93-13 Slate Cave, 45 m inside.	304	1	6	9.00	1.4198	1.8059	- - -	180.62
Resurgence cave	93-5 Cataract Cave, 30 cm above low water.	36	1	6	8.97	1.2446	1.9050	95.30	166.06
Resurgence cave	93-6 Cataract Cave, 35 cm above low water.	36	1	5	8.97	0.9474	1.5697	- - -	137.21
Alpine, bare rock	93-7 El Cap Peak, slope of heel print karren.	670	1	6	8.97	0.2209	0.3276	99.18	30.86
Alpine, bare rock	93-8 El Cap Peak, flat of heel print karren.	670	1	5	8.97	0.2108	0.2844	- - -	26.10
Alpine, bare rock	93-9 El Cap Peak, bottom of meandering karren.	670	1	1	8.97	0.4089	0.4089	- - -	45.57
Alpine,bare rock	93-10 El Cap Peak, rounded knob.	670	1	6	8.97	0.1295	0.4140	- - -	29.72
Alpine, bare rock	95-33 (1,4) El Cap Peak, steep below vegetated mat.	670	2	11	6.92	0.2108	0.9499	- - -	62.51
Alpine, soil covered	95-33 (2,3,5,6,7,8) El Cap Peak, thin, vegetated mat.	670	6	35	6.92	0.0025	0.3251	- - -	23.09
Old growth forest, bare rock	93-4 El Cap, wind throw.	109	1	6	9.00	0.1879	0.5511	- - -	38.95
Old growth forest, bare rock	93-12 River's End, wind throw.	152	1	6	8.99	0.0990	0.3327	- - -	23.71
Old growth forest, soil covered	93-11 River's End, 4cm humus.	152	1	6	8.99	0.1727	0.3098	98.50	27.66
Old growth forest, soil covered	93-17, 93-18 Bridal Veil, 6 cm humus.	243	2	12	8.96	0.0508	0.3937	99.35	25.49
Old growth forest, soil covered	95-26 (1,2,3,4,5,6,7) Cavern Lake, horizontal, 2 cm humus.	91	7	34	6.95	0.0000	0.5308	- - -	29.62
Old growth forest, soil covered	95-26 (8,9,10) Cavern Lake, vertical, 2 cm humus.	91	3	20	6.95	0.0025	0.2514	99.38	11.80
Old growth forest, soil covered	95-31 Bridal Veil, 17cm humus.	274	10	60	6.93	0.1244	0.5511	99.69	52.47
Old growth forest, soil covered	95-32 Bridal Veil, 5cm silt under 10 cm humus.	274	10	58	6.92	0.0457	0.4673	- - -	32.07
Old growth forest, soil covered	93-3 El Cap, 5cm silt under thin humus.	109	1	5	9.00	0.1752	0.2463	96.27	23.14
29-36 year clearcut, soil covered	95-27 Starlight, 5cm silt under 30 cm humus.	167	10	50	6.92	0.0330	0.5232	99.37	35.30
29-36 year clearcut, soil covered	95-28 Starlight, 30 cm humus.	167	10	56	6.93	0.1905	0.8483	- - -	71.60
2-9 year clearcut, soil covered	95-29 Bridal Veil, 2 cm silt under 10 cm humus.	304	10	59	6.93	0.0000	0.4445	98.51	32.81
2-9 year clearcut, soil covered	95-30 Bridal Veil, 10 cm humus.	304	10	59	6.93	0.0787	0.5054	- - -	43.90

impurities. There were no apparent influences from the differences in overall carbonate purity (Tables 1 & 2).

Soil depth and water-flow rates were significant influences on the dissolution rate. By plotting dissolution at measuring points around respective stations on a radar graph, elliptical shapes generally appear displaced to one side, indicating increased runoff along the downward side of bare slopes and those under acidic soils (Figure 3).

A light brown silt layer containing tiny clasts of silt is often found between carbonate rock and under organic humus and moss (Figure 4). This silt occurs throughout the Alaska Panhandle karst and appears to be insoluble residue left from carbonate dissolution. A sample (02-1) taken from a road cut near Bridal Veil (site 95-30) was tested and its insoluble oxides recalculated without the carbonate content. Table 3 compares

Table 2. Andesitic basalt and Silurian marble erosion rates.

Type	Site	Elevation (m)	Number of stations	Number of points	Time lapse (TL) years	Erosion during TL (mm)		Percentage carbonate purity	Erosion rate (mm/1000y)
						Minimum	Maximum		
Cave stream	93-15 Basket Bay, littoral zone.	0.0	1	6	9.16	2.6720	3.2562	99.24	326.85
Sub-alpine, bare overhang	93-19 Blue Marble area.	518.0	1	4	8.96	0.9398	3.1800	- - -	200.50
Sub-alpine, soil covered	93-20 Blue Marble area 5 cm humus.	518.0	1	6	8.96	0.3276	0.4876	- - -	47.00
Old growth forest, soil covered	93-1 Leaning Tree, 5 cm moss.	112.0	1	6	8.99	0.0711	0.3048	- - -	22.59
Open, bare rock	93-2 Leaning Tree, road cut, steep rock.	106.0	1	6	8.99	0.2057	0.3048	99.28	27.68
Old growth forest, soil covered	94-24, 94-25 Annie's, 7 cm silt under 5 cm humus.	274.0	2	12	7.95	0.0609	1.9126	95.55	116.28
Open, bare rock	93-14 Trap Bay, lichen-covered talus.	15.0	1	6	9.25	0.2540	0.5334	- - -	32.38
Littoral, bare rock	93-16 Basket Bay, solution pan.	1.2	1	6	9.16	0.2387	0.4597	- - -	37.98
Andesitic basalt, bare rock	93-21 Haines standard	1.2	1	6	9.06	0.0000	0.0965	- - -	3.40

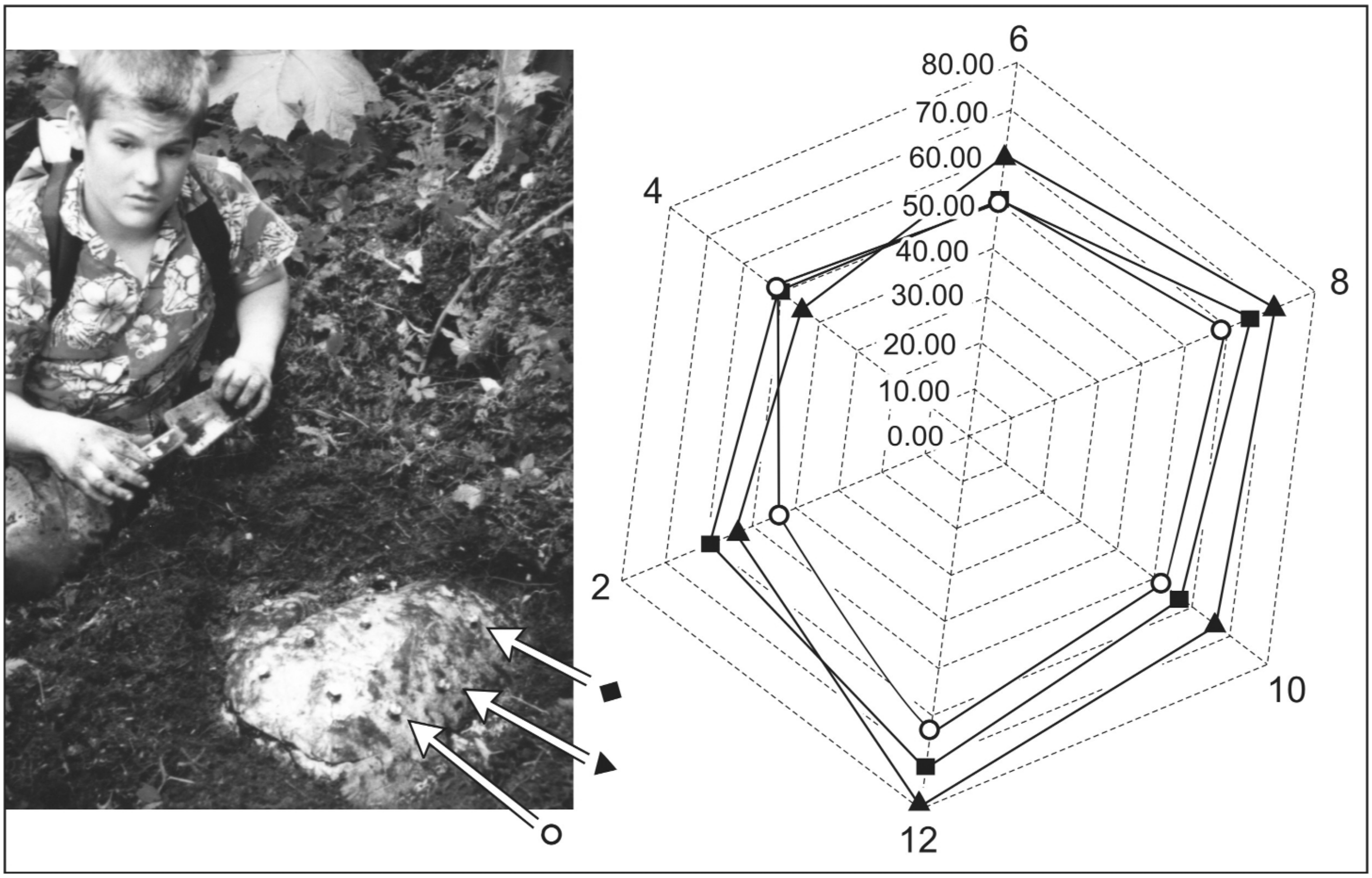

Figure 3. The excavated site #95-31. The measuring points of the three noted stations along the slope of the hump are plotted in mm/ka, showing uneven dissolution rates. The 12 O'clock position of the graph is oriented to the respective stations in the photo. Photo by C. Allred.

the silt to the insolubles of sample 93-3, which had the closest signature of 12 carbonate samples analyzed. Dissolution rates were limited beneath these silty soils regardless of humus depths or water-flow rate (Figure 5). Conversely, deeper organic soils without silt layers showed increased dissolution rates (Figure 6).

Table 3. Whole rock analyses of silty aggregate (sample 02-1) and limestone sample 93-3. Both were recalculated without Ca, MgO, and CO_2. All columns are percentages.

Sample name	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	LOI	Total %
02-1												
Whole rock	29.98	23.19	5.12	1.179	1.07	0.64	1.31	0.85	0.512	0.16	35.79	98.80
Insolubles only	48.9	37.82	8.35	0.292	- - -	- - -	2.13	1.38	0.835	0.26	- - -	99.96
93-3												
Whole rock	2.25	0.69	0.42	0.025	0.78	53.84	0.09	0.19	0.017	0.01	40.85	99.16
Insolubles only	60.94	18.68	11.37	0.677	- - -	- - -	2.43	5.14	0.460	0.27	- - -	99.96

Figure 4. REM site #95-29. Note the silty soil adhering to the center portion of the humus peeled off the rock. The foreground bedrock had been exposed during deforestation.

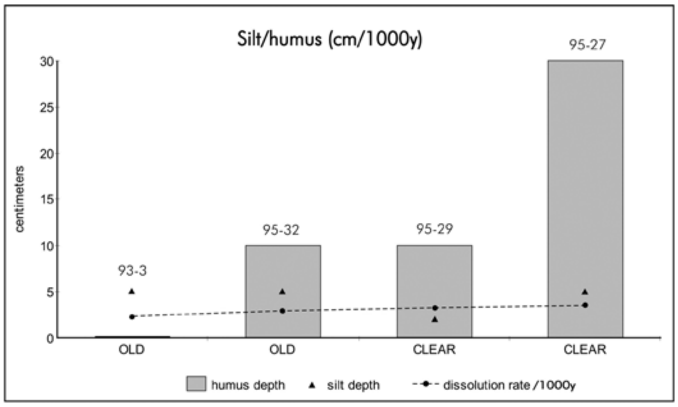

Figure 5. Silt and humus depths plotted with dissolution rates in old growth forests and clearcuts. Silt severely limits dissolution, even with greater humus depths. A total of 172 measuring points were used for this graph.

It is speculated that thick silt accumulation would result in a decrease in exposed rock surfaces and sinkhole depths in the long term because silt limits dissolution rates. Some epikarst terranes may have escaped glaciation for long periods and evolved into less rugged topography. These karstlands are typically mantled with deep silty soils, yet continue to drain to the subsurface. Soil piping may play an important role.

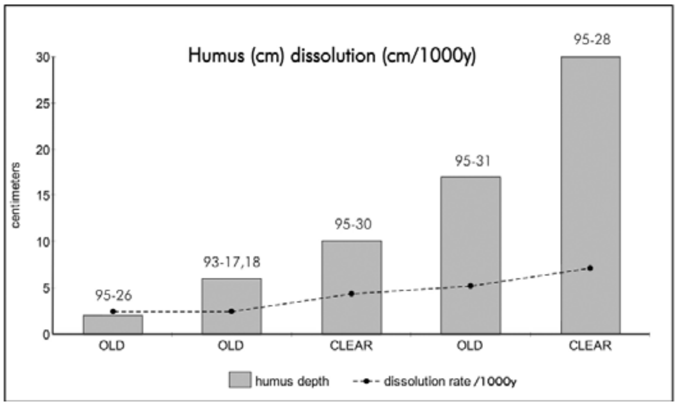

Figure 6. Humus depths plotted with dissolution rates in old growth forests and clearcuts. The dissolution rate shows a slight increase after deforestation. A total of 241 measuring points were used for this graph.

Eight REM sites were on marble (Table 2). The averaged erosion rate was 32 mm/ka at bare rock sites. Some marble on Prince of Wales Island had higher erosion rates than those of limestone. This was due to the tendency of surfaces of this area to break down into sand, perhaps by frost action. In other instances, erosion rates were less than limestone averages, suggesting that dissolution was the prime factor in erosion. In contrast, none of the limestone sites had discernible corrasion.

OLD GROWTH AND CLEARCUT SETTINGS

Two clearcuts of different ages were chosen to compare dissolution rates with nearby old growth forests. The silty stations were unsuitable for this comparison because dissolution was so limited. The old growth forests had three proximate sites with 126 points, with an average dissolution rate equaling 34 mm/ka. These were sites 93-17/18, 95-26, and 95-31. The two- to nine-year-old clearcut (site 95-30) had 59 points with an average dissolution rate equaling 43 mm/ka dissolution. This clearcut had not yet been overgrown by brush or second growth conifers. The 29-36-year-old clearcut (site 95-28) had 56 points with an average dissolution rate of 71 mm/ka. Brush and moss had been killed at the site by the shade of second growth conifers. The stand had been thinned about 20 years after clearcutting. Clearcuts with humus soil experienced an 11% dissolution rate increase over old growth sites with humus

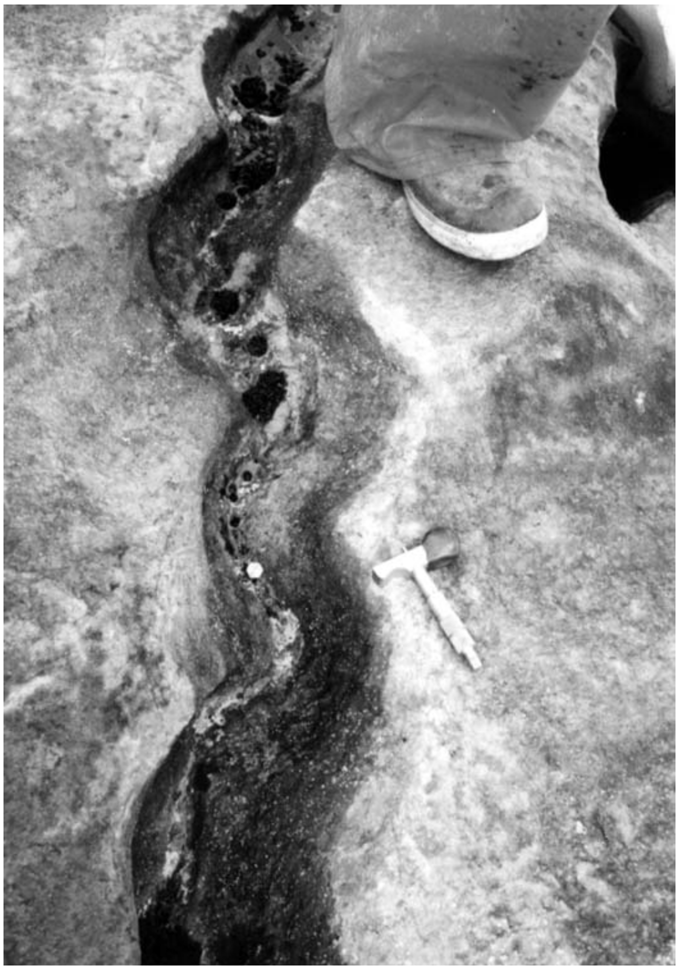

Figure 7. REM site #93-9 in the bottom of an alpine meandering karren. Photo by C. Allred.

Figure 8. REM sites #93-7 and #93-8 on an alpine heelprint karren. Photo by C. Allred.

soil (Figure 6). This is based on the linear interpolation of humus sites and suggests a tentative conclusion. The overall average dissolution rates for all of the old growth and clearcut sites were 38 mm/ka and 46 mm/ka, respectively.

The increased dissolution rate in deforested areas may be due, in part, to decreased canopy interception, reduced transpiration of precipitation, or change in the pH of the water. Old growth foliage interception is less than 35% in wetter, overcast weather according to Wilm (1949). This study showed an average interception of 17% during a mostly rainy period from September 21 to December 31, 2002. The interception ranged from extremes of 100% to –8%, depending on the exact spot of interception, foliage drainage, and amount of rainfall and wind. Of the sites, 14% of the total clearcut precipitation occurred in cases where rain gauges were situated under closed canopy. The remainder of the old growth testing was done under very open canopy. Transpiration values remain an unknown. An attempt was made to determine if canopy drainage was significantly more acidic than direct rain water. One single sample of Western Hemlock canopy drainage was tested and found to have a pH of 6.3 compared to a nearby clearcut with a pH of 6.4.

Toppled old growth trees often peel away the thin soils from bedrock, making bare rock measurements possible. Sites 93-4 and 93-12 were of this type, and had an average erosion rate of 31 mm/ka.

ALPINE AND SUB-ALPINE SETTINGS

On the alpine karst, the average bare rock dissolution rate was 38 mm/ka. At site 95-33, six stations were set under a thin organic mat on a sub-horizontal surface with two additional stations on steeper bare rock adjacent to and below the six stations. Surprisingly, the bare rock stations yielded 2.5 times greater dissolution than the covered stations. It is speculated that the mat of heather and other small alpine vegetation absorbed much of the precipitation, but other influences not yet recognized or understood may also be important. The other bare limestone measurements (Table 1) were 19.5% higher than the forested bare rock measurements and may have been influenced by increased precipitation, turbulence, concentrated flows, or persistent snow (Figures 7,8,9). Both of the subalpine sites were in marble subject to significant corrasion and had an average erosion rate of 124 mm/ka.

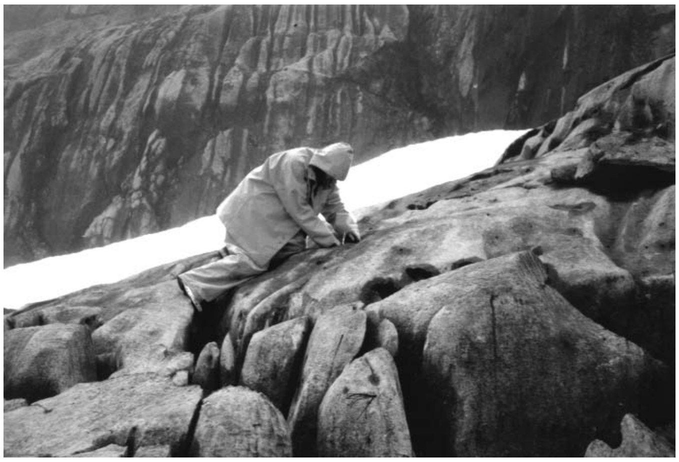

Figure 9. Abundant precipitation coupled with an absence of soils results in classic alpine karren forms. REM sites #93-7 and #93-8 only just recently became free of snow when measured on July 4, 2002. Photo by C. Allred.

Figure 10. The author at REM sites #94-22 and #94-23. The muskeg runoff first makes contact with the limestone in front of author's left boot, flows past the measuring sites, and then into the 42.6 m pit. Photo by C. Allred.

Figure 11. Soon to fall out, station 94-23 is increasingly exposed by highly acidic muskeg drainage over the limestone. The apron of overflowed epoxy is at the former level of the rock surface.

Figure 12. Re-measuring stations #93-5 and 93-6 in Cataract Cave during low water flow. Photo by C. Allred.

CAVE SETTINGS

Many caves in the Alaska Panhandle form where highly acidic waters flow onto carbonates from peat lands, locally called muskegs. Water with a pH as low as 2.4 has been measured (Aley *et al.* 1993). The four cave sites had an average erosion rate of 507 mm/ka.

Bear's Plunge is a 42.6 m deep pit receiving a small streamlet from a muskeg. Two stations were placed just above the low water level at the brink of the drop, and less than 0.3 m from glacial till, which seals the limestone bedrock from the muskeg (Figure 10). One station (94-22) was slightly lower, and both are estimated to be in the streamlet less than 75% of the time. The lower station showed an average dissolution rate of over 1.66 m/ka and the other at over 1.07 m/ka. After nearly nine years, aggressive dissolution had created a large space between the rock and overflowed epoxy aprons (Figure 11). The bolts are expected to fall out in approximately eight years. To date, these dissolution rates are some of the highest documented anywhere (High & Hanna 1970; Spate *et al.* 1985; Cucchi *et al.* 1987).

A station (93-13) was set about 45 m into the inflow at the entrance of Slate Cave. The site is subject to seasonal trickling estimated at about 75% of the year. Water flowing into the cave might have become less acidic than the Bear's Plunge because of filtering through the limestone breakdown of the entrance portion. The average dissolution rate was 180 mm/ka. Corrasion at the station (93-13) was unlikely because the station was protected by a large boulder.

Cataract Cave has a large perennial resurgence flowing through a spacious passage. Two stations (93-5 and 93-6) were set in a vertical wall about 0.3 m above the low water level, and 30 m inside the cave (Figure 12). After nearly nine years these bolts were found coated with a black film (manganese oxide?) similar to that deposited on non-carbonate surfaces in cave streams. Vigorous rubbing only partially removed this film. Dissolution rates averaged 153 mm/ka. Estimated time under water was 50% based on weather observation and comparison to other streams in the area. All the dissolution is believed to be from the stream rather than condensation corrosion, because there are speleothems showing no dissolution approximately three meters above the stations.

A station was set in the sloping side of a marble stream bed of a short cave located downstream from a series of longer river caves and karst windows (93-15). The site is littoral, but brackish water probably does not reach the site much of the time because of stream out-flow. Estimated time under water was 75% based on the time of year visited and local weather conditions. The average dissolution rate was 326 mm/ka.

Very little is known of glacial advances in southeastern Alaska. Further REM monitoring may help clarify some glacial prehistory. Original polished or striated carbonate surfaces have been found perfectly preserved after thousands of years sealed under deposits of glacial clay. Without the clay, dissolution plays a large part in quickly transforming the land. Supposing that the most recent glaciation in the area was 15,000 years BP (Baichtal *et al.* 1997) and the climate has remained consistent, some cave floors could have been lowered over 25 m from even seasonal acidic muskeg runoff. However, many caves have evidence of much greater stability. Chambers containing fossil animal bones dating over 40,000 years BP (Heaton *et al.* 1996) appear to have undergone little recent modification.

Comparisons with erosion rates elsewhere

Jennings (1985) summarizes studies of pedestals under glacial erratics, estimating erosion of between 10 to 42 mm/ka. No pedestals have been reported so far from the Panhandle, but the alpine karst REM stations averaged 33 mm/ka. In Ireland, High and Hanna (1970) reported stream erosion of 50mm to 500mm/ka that was thought to be partly due to corrasion. The Bear's Plunge dissolution rates are approximately three times the Irish maximum erosion rate. The Slate Cave trickle site was similar to their cave stream measurements. Spate *et al.* (1985) reported MEM based erosion data from cave stream sites in New South Wales, Australia yielding a combination of dissolution and corrasion many orders of magnitude less than our REM results. Their average 6mm/ka measurements on bare limestone from New South Wales, Australia compare to 29 mm/ka for this study. Precipitation in New Wales averages 950 mm/y (Ford and Williams 1989). The average Australian erosion rate under 25 cm of soil was 21 mm/ka compared to 52 mm/ka and 71 mm/ka under similar depths in the Alaska Panhandle (Table 1). Kraufmann and Braun (2001) comment that Italian erosion rates of 20 mm/ka with 1442 mm/yr precipitation were higher at 30 mm/ka with 2800 mm/yr precipitation. However, Cucchi *et al.* (1987) found no short term relationship between Italian precipitation rates and biyearly dissolution rate measurements. The reason for this is unclear. Bogli (1980) determined erosion rates of 81 mm/ka from soil-covered Silvan Switzerland karst with a precipitation of 2200 mm/yr. Many REM erosion measurements were similar to those elsewhere in the world if precipitation differences are taken into account. However, the Alaska Panhandle rates were much higher when subject to runoff from acidic muskegs.

Conclusions

Considerable precipitation coupled with very acidic drainage from muskegs contribute to some of the highest dissolution rates yet documented. Dissolution rates varied considerably in limestone and marble containing veins and clasts of impurities even from adjacent measurement points. Other contributing factors to erosion rates were corrasion, soil cover type, and soil depth. Preliminary comparison indicates dissolution rates are greater in clearcuts than old growth forests. Additional sites would improve the average data for both in future work.

Additional data should be gathered by setting more REM stations in a number of varied places, both in and out of Panhandle caves. Many other carbonate types could also be measured. As yet, diffuse dissolution rates are unknown from Alaskan cave walls. A more accurate REM could incorporate a dial indicator which might also result in less crushing of the rock surface during measuring than the present system. Given the large dissolution rates, this would allow for more frequent measurements. Correlated work on water chemistry would be useful.

Appendix

Additional REM site descriptions (Silurian limestone)

94-22, 23 The Bear's Plunge lip was originally covered with non-carbonate cobbles and was not subject to increased flooding from deforestation. The lip was cleaned off for safety during the first exploration of the pit. A few large cobbles were placed around the stations and left in place during the measuring period. These stations were measured once more using a longer measuring rod six months later because the REM was no longer able to reach the radically lowered rock in a few places.

93-13 The trickle water source was estimated to be about 40 gpm in the month of May, 1990. The stream comes from a muskeg atop slate above the entrance. The limestone is somewhat impure and the streamlet subject to increased flooding from deforestation.

93-5,6 Cataract Cave is subject to increased flooding from partial deforestation of the recharge area above the cave. The stations were located off the bedrock floor of the stream bed, and therefore not subject to corrasion. The average stream flow is 630 gpm (Winfield Wright, personal communication). The limestone is brecciated with moderate amounts of impurities.

93-7,8 The flats of heelprint karren were of a darker color due to thicker lichen growth. This coating was sparser on the slopes where the dissolution rate increases.

93-10 was not subject to flow from adjacent surfaces and was lichen-coated.

93-33 The vegetated mat was peeled back in one piece in order to expose the rock, then pressed back into place after measuring. No lichen growth had occurred under the mat and the limestone was clean.

93-4 was located on an outcropping exposed from an uprooted tree and under an old growth canopy without an understory.

93-12 was located on rounded brecciated limestone exposed by a large uprooted tree. The station was partially protected by the root wad of the tree and understory growth.

93-11 The station was located at the edge of the same bare area as 93-12. It was covered by an open old growth canopy. The limestone is brecciated.

93-17,18 These stations were located on the lip of a swallet receiving inflow near Bridal Veil Cave. They were covered by an old growth canopy with some understory growth.

95-26 was protected under an old growth canopy with some understory growth. The forest is a band only about 30 m wide bounded by deforestation, and may be more subject to periodic drying. One station (number 1) was situated so that it was nearly exposed under a thin moss covering. Dissolution rates of 36.13 mm/ka. were measured. The stations averaged 2 cm of humus covering.

95-31 was under an old growth canopy. Blueberry bushes were re-planted. It was located on a rounded hump submerged under 15-20 cm of dark brown humus above a thin layer of black humus.

95-32 was in limestone breccia on a mossy slope protected by an old growth canopy. The soil was 5 cm silt aggregate containing minor amounts of clay, covered by 10 cm of dark brown humus, then moss. A blueberry bush was re-planted on top.

93-3 was located on a small ledge in a bare outcropping. The rock was exposed by the roots of a fallen tree. Since exposed, only small amounts of humus had accumulated on the surface.

95-27,28 were located on rounded humps. Some adjacent areas in this clearcut still contained brush. Nearby soil depths were undetermined. The humus soil was laced with roots, limbs, and bole fragments.

95-29 was located on a flat, sub-horizontal, concave area adjacent to a grike. The brecciated limestone contains visible siltstone clasts and bands. Adjacent to this site were tree stumps and grikes partially covered in bushes.

95-30 was oriented on the top of a slightly rounded hump of brecciated limestone with minor visible impurities. The site was under an open spot used by bedding deer, and surrounded by tree stumps and bushes. The stations were covered in reddish rotten wood over a thin layer of black humus.

ADDITIONAL REM SITE DESCRIPTIONS (SILURIAN MARBLE)

93-15 was located on scalloped marble several feet above the clastic-covered stream bed. It was re-measured under 0.3 m water at low tide, with a strong downstream fresh water current.

93-19 was on the crumbling grainy surface of an overhang, and was subject to minor water seepage from above. Two of the measuring points were on an exfoliation which had been frost-heaved outwards and had a hollow sound when tapped. These points were not used. The exposed cliffs in the general area are rounded from decomposition and have large recent accumulations of sand and larger debris at their bases.

93-20 was only 5 m from 93-19 on a ledge of marble. Even though humus-covered, it was subject to frost action, judging from the granular, crumbly appearance of the rock and the aggressive erosion.

93-1 was set in the southern moss-covered lip of the upper main entrance of Leaning Tree Cave. The site was subject to periodic drying, because it is adjacent to a road. It was protected by an old growth canopy with no understory.

93-2 was on bare rock, yet overhung by thick bushes next to a logging road. The site could receive flow from the rock above.

94-24,25 were at the edge of a ledge above a solution gully. They were partially covered by a rotten root. The rock surface had a granular texture and adjacent exposures were crumbly.

93-14 was set into the top of a large marble boulder. The lichen covering was a “leaf” variety rather than a fine, dark coating. The lichen was scraped from one measuring point with a fingernail during the re-measurement. The measurement did not change after scraping.

93-16 was the bottom of a 30 cm diameter solution pan about 10 cm deep. The smooth flat floor was covered in algae.

93-21 was located on top of a large boulder above high tide where there were no lichens.

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