Supplement of Earth Surf. Dynam., 9, 1505–1529, 2021
https://doi.org/10.5194/esurf-9-1505-2021-supplement

Earth Surface Dynamics
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EGU

Supplement of

Multi-objective optimisation of a rock coast evolution model with cosmogenic ^{10}Be analysis for the quantification of long-term cliff retreat rates

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Supplementary Materials

Table S1. Model input corrected ^{10}Be concentration data for Bideford study site

Sample ID	Distance from cliff (m)	^{10}Be concentration (atoms g^{-1})	^{10}Be concentration error (± atoms g^{-1})
CB02	28.2	4482	584
CB03	46.0	4520	633
CB04	66.1	6591	635
CB05	82.9	9242	658
CB10b	91.3	8112	802
CB10a	92.6	9129	693
CB06	102.0	10063	706
CB07	116.4	11880	669
CB08	134.5	12802	702
CB09	144.6	11058	763
CB11	146.4	12843	690
CB24	154.4	9728	1291
CB23	161.2	14550	1610
CB22	170.3	13304	1070
CB21	180.7	14818	1150
CB28	196.5	9266	846
CB27b	203.1	7766	755
CB27a	203.5	10026	918
CB26	211.5	10383	1341
CB25	219.3	7269	1219

Table S2. Model input corrected ^{10}Be concentration data Scalby study site

Sample ID	Distance from cliff (m)	^{10}Be concentration (atoms g^{-1})	^{10}Be concentration error (± atoms g^{-1})
SY05	22.3	583	376
SY06	34.8	1509	419
SY07	49.8	2772	427
SY08	62.8	3352	411
SY09	75.6	3950	417
SY10	86.3	4508	444
SY11	86.4	1843	387
SY12	92.3	3618	455
SY13	108.8	3685	456
SY04	124.4	3334	405
SY03	136.6	4420	427
SY02	144.8	3878	463
SY01	156.4	5676	437
SY16	175.7	3801	783
SY15	192.9	5090	481
SY14	209.8	7547	484

Table S3. Model input topographic profile for Bideford study site

Distance from cliff (m)	Elevation (m)
40	1.14
40.5	1.07
41	1.09
41.5	1.33
42	1.50
42.5	1.12
43	0.94
43.5	0.88
44	0.88
44.5	0.90
45	0.90
45.5	0.90
46	0.88
46.5	0.81
47	0.79
47.5	0.78
48	0.77
48.5	0.78
49	0.79
49.5	0.80
50	0.82
50.5	0.82
51	0.78
51.5	0.74
52	0.69
52.5	0.67
53	0.67
53.5	0.69
54	0.70
54.5	0.72
55	0.71
55.5	0.68
56	0.69
56.5	0.66
57	0.57
57.5	0.54
58	0.53
58.5	0.53
59	0.55
59.5	0.55
60	0.49
60.5	0.49
61	0.52
61.5	0.47
62	0.40
62.5	0.33
63	0.34
63.5	0.39
64	0.41
64.5	0.39
65	0.39
65.5	0.39
66	0.36
66.5	0.32
67	0.34
67.5	0.36
68	0.34
68.5	0.29
69	0.29

69.5	0.26
70	0.25
70.5	0.24
71	0.26
71.5	0.26
72	0.21
72.5	0.18
73	0.25
73.5	0.33
74	0.39
74.5	0.38
75	0.39
75.5	0.39
76	0.32
76.5	0.25
77	0.18
77.5	0.20
78	0.23
78.5	0.24
79	0.19
79.5	0.03
80	-0.08
80.5	-0.05
81	0.09
81.5	0.28
82	0.34
82.5	0.32
83	0.26
83.5	0.17
84	0.00
84.5	-0.17
85	-0.29
85.5	-0.35
86	-0.30
86.5	-0.21
87	-0.17
87.5	-0.10
88	-0.04
88.5	0.00
89	0.10
89.5	0.14
90	0.16
90.5	0.13
91	0.09
91.5	0.05
92	-0.02
92.5	-0.06
93	-0.07
93.5	-0.08
94	0.02
94.5	0.05
95	0.11
95.5	0.12
96	0.13
96.5	0.13
97	0.08
97.5	-0.02
98	-0.08
98.5	-0.07
99	-0.10
99.5	-0.18
100	-0.24
100.5	-0.35
101	-0.41

101.5	-0.44
102	-0.44
102.5	-0.35
103	-0.25
103.5	-0.19
104	-0.19
104.5	-0.20
105	-0.20
105.5	-0.19
106	-0.21
106.5	-0.25
107	-0.29
107.5	-0.31
108	-0.33
108.5	-0.37
109	-0.41
109.5	-0.42
110	-0.47
110.5	-0.51
111	-0.54
111.5	-0.55
112	-0.53
112.5	-0.51
113	-0.48
113.5	-0.48
114	-0.43
114.5	-0.38
115	-0.38
115.5	-0.40
116	-0.39
116.5	-0.43
117	-0.43
117.5	-0.41
118	-0.43
118.5	-0.55
119	-0.59
119.5	-0.58
120	-0.58
120.5	-0.55
121	-0.43
121.5	-0.44
122	-0.49
122.5	-0.49
123	-0.51
123.5	-0.55
124	-0.55
124.5	-0.55
125	-0.55
125.5	-0.53
126	-0.41
126.5	-0.28
127	-0.30
127.5	-0.32
128	-0.28
128.5	-0.28
129	-0.30
129.5	-0.30
130	-0.33
130.5	-0.34
131	-0.36
131.5	-0.38
132	-0.36
132.5	-0.33
133	-0.33

133.5	-0.38
134	-0.43
134.5	-0.48
135	-0.49
135.5	-0.50
136	-0.52
136.5	-0.59
137	-0.65
137.5	-0.73
138	-0.70
138.5	-0.59
139	-0.54
139.5	-0.46
140	-0.36
140.5	-0.35
141	-0.38
141.5	-0.39
142	-0.36
142.5	-0.33
143	-0.34
143.5	-0.37
144	-0.41
144.5	-0.44
145	-0.47
145.5	-0.50
146	-0.53
146.5	-0.62
147	-0.76
147.5	-0.87
148	-1.01
148.5	-1.12
149	-1.21
149.5	-1.25
150	-1.29
150.5	-1.31
151	-1.34
151.5	-1.37
152	-1.38
152.5	-1.38
153	-1.36
153.5	-1.35
154	-1.35
154.5	-1.34
155	-1.34
155.5	-1.35
156	-1.39
156.5	-1.43
157	-1.42
157.5	-1.41
158	-1.43
158.5	-1.43
159	-1.40
159.5	-1.30
160	-1.21
160.5	-1.14
161	-1.15
161.5	-1.16
162	-1.20
162.5	-1.24
163	-1.26
163.5	-1.28
164	-1.51
164.5	-1.75
165	-1.67

165.5	-1.67
166	-1.85
166.5	-1.88
167	-1.96
167.5	-2.03
168	-1.78
168.5	-1.58
169	-1.43
169.5	-1.36
170	-1.34
170.5	-1.32
171	-1.29
171.5	-1.26
172	-1.27
172.5	-1.28
173	-1.27
173.5	-1.25
174	-1.24
174.5	-1.29
175	-1.33
175.5	-1.36
176	-1.39
176.5	-1.39
177	-1.38
177.5	-1.39
178	-1.39
178.5	-1.40
179	-1.86
179.5	-2.08
180	-2.08
180.5	-2.05
181	-2.02
181.5	-2.05
182	-2.10
182.5	-2.16
183	-2.19
183.5	-2.20
184	-2.19
184.5	-2.15
185	-2.08
185.5	-2.03
186	-1.98
186.5	-1.97
187	-1.97
187.5	-1.97
188	-1.96
188.5	-1.96
189	-1.96
189.5	-1.99
190	-2.01
190.5	-2.17
191	-2.19
191.5	-2.20
192	-2.21
192.5	-2.19
193	-2.15
193.5	-2.11
194	-2.09
194.5	-2.11
195	-2.13
195.5	-2.19
196	-2.21
196.5	-2.22
197	-2.23

197.5	-2.25
198	-2.29
198.5	-2.20
199	-2.17
199.5	-2.30
200	-2.29
200.5	-2.25
201	-2.23
201.5	-2.19
202	-2.16
202.5	-2.18
203	-2.22
203.5	-2.29
204	-2.55
204.5	-2.66
205	-2.72
205.5	-2.90
206	-3.02
206.5	-2.93
207	-2.86
207.5	-2.83
208	-2.75
208.5	-2.71
209	-2.76
209.5	-2.91
210	-3.06
210.5	-3.17
211	-3.15
211.5	-3.08
212	-2.96
212.5	-2.80
213	-2.62
213.5	-2.51
214	-2.41
214.5	-2.36
215	-2.29
215.5	-2.33
216	-2.39
216.5	-2.49
217	-2.71
217.5	-2.79
218	-2.80
218.5	-2.81
219	-2.76
219.5	-2.68
220	-2.58
220.5	-2.54
221	-2.52
221.5	-2.57
222	-2.63
222.5	-2.72
223	-2.81
223.5	-2.86
224	-2.81
224.5	-2.76
225	-2.68
225.5	-2.62
226	-2.65
226.5	-2.68
227	-2.60
227.5	-2.54
228	-2.53
228.5	-2.57
229	-2.61

229.5	-2.65
230	-2.65
230.5	-2.64
231	-2.62
231.5	-2.60
232	-2.58
232.5	-2.57
233	-2.61
233.5	-2.59
234	-2.58
234.5	-2.59
235	-2.56
235.5	-2.56
236	-2.59
236.5	-2.65
237	-2.67
237.5	-2.64
238	-2.59
238.5	-2.61
239	-2.63
239.5	-2.70
240	-2.73
240.5	-2.73
241	-2.75
241.5	-2.79
242	-2.84
242.5	-2.89
243	-2.94
243.5	-2.97
244	-2.99
244.5	-2.99
245	-3.02
245.5	-3.22
246	-3.45
246.5	-3.57
247	-3.37
247.5	-3.12
248	-3.07
248.5	-3.09
249	-3.12
249.5	-3.16
250	-3.21
250.5	-3.25
251	-3.39
251.5	-3.50
252	-3.56
252.5	-3.59
253	-3.64
253.5	-3.64
254	-3.62
254.5	-3.60
255	-3.62
255.5	-3.64
256	-3.65
256.5	-3.69
257	-3.66
257.5	-3.61
258	-3.61
258.5	-3.57
259	-3.48
259.5	-3.51
260	-3.55
260.5	-3.58
261	-3.66

261.5	-3.71
262	-3.71
262.5	-3.70
263	-3.72
263.5	-3.73
264	-3.90
264.5	-4.74
265	-4.88
265.5	-4.24
266	-3.67
266.5	-3.55
267	-3.26
267.5	-3.19
268	-3.17
268.5	-3.17
269	-3.15
269.5	-3.18
270	-3.21
270.5	-3.25
271	-3.33
271.5	-3.25
272	-3.20
272.5	-3.15
273	-3.05
273.5	-3.02
274	-2.99
274.5	-3.06
275	-3.16
275.5	-3.21
276	-3.16
276.5	-3.12
277	-3.24
277.5	-3.40
278	-3.46
278.5	-3.65
279	-3.73
279.5	-3.58
280	-3.50
280.5	-3.29
281	-3.45
281.5	-3.69
282	-3.70
282.5	-3.70
283	-3.71
283.5	-3.72
284	-3.72
284.5	-3.72
285	-3.72
285.5	-3.72
286	-3.72
286.5	-3.72
287	-3.72
287.5	-3.72

Table S4. Model input topographic profile for Scalby study site

Distance from cliff (m)	Elevation (m)
29.73	2.28
30.38	2.21
31.03	2.00
31.68	1.99
32.33	1.71
32.98	1.78
33.64	1.63
34.29	1.46
34.94	1.47
35.59	1.68
36.24	1.52
36.89	1.50
37.54	1.33
38.19	1.37
38.84	1.37
39.49	1.33
40.15	1.07
40.8	1.04
41.45	0.96
42.1	1.04
42.75	0.84
43.4	0.84
44.05	0.99
44.7	0.94
45.35	0.79
46	0.73
46.66	0.63
47.31	0.57
47.96	0.67
48.61	0.42
49.26	0.45
49.91	0.68
50.56	0.91
51.21	0.88
51.86	0.58
52.51	-0.15
53.17	-0.27
53.82	-0.28
54.47	-0.14
55.12	-0.04
55.77	-0.03
56.42	0.21
57.07	0.11
57.72	0.04
58.37	-0.04
59.02	-0.05
59.68	-0.14
60.33	-0.26
60.98	-0.39
61.63	-0.44
62.28	-0.47
62.93	-0.50
63.58	-0.50
64.23	-0.46
64.88	-0.46
65.53	-0.42
66.19	-0.35
66.84	-0.47
67.49	-0.15
68.14	-0.25

68.79	-0.29
69.44	-0.42
70.09	-0.47
70.74	-0.44
71.39	-0.39
72.04	-0.42
72.7	-0.51
73.35	-0.52
74	-0.35
74.65	-0.38
75.3	-0.24
75.95	-0.28
76.6	-0.35
77.25	-0.29
77.9	-0.36
78.55	-0.53
79.21	-0.51
79.86	-0.51
80.51	-0.50
81.16	-0.52
81.81	-0.49
82.46	-0.53
83.11	-0.40
83.76	-0.39
84.41	-0.48
85.06	-0.57
85.72	-0.55
86.37	-0.48
87.02	-0.35
87.67	0.29
88.32	0.16
88.97	-0.25
89.62	-0.26
90.27	-0.24
90.92	-0.38
91.57	-0.26
92.23	-0.37
92.88	-0.63
93.53	-0.68
94.18	-0.63
94.83	-0.48
95.48	-0.47
96.13	-0.51
96.78	-0.45
97.43	-0.43
98.08	-0.34
98.74	-0.15
99.39	0.38
100	0.33
100.7	0.23
101.3	0.24
102	0.28
102.6	0.23
103.3	0.36
103.9	0.35
104.6	0.44
105.2	0.31
105.9	0.27
106.5	0.18
107.2	0.24
107.8	0.22
108.5	0.17
109.2	0.09
109.8	0.13

110.5	0.09
111.1	0.02
111.8	-0.07
112.4	-0.08
113.1	-0.16
113.7	0.14
114.4	0.08
115	-0.18
115.7	-0.32
116.3	-0.40
117	-0.38
117.6	-0.25
118.3	-0.20
118.9	-0.28
119.6	-0.36
120.2	-0.45
120.9	-0.49
121.5	-0.56
122.2	-0.53
122.8	-0.44
123.5	-0.56
124.1	-0.36
124.8	-0.55
125.4	-0.56
126.1	-0.58
126.7	-0.66
127.4	-0.64
128	-0.58
128.7	-0.57
129.3	-0.64
130	-0.66
130.6	-0.67
131.3	-0.50
131.9	-0.45
132.6	-0.35
133.2	-0.29
133.9	-0.29
134.5	-0.50
135.2	-0.57
135.8	-0.56
136.5	-0.48
137.1	-0.50
137.8	-0.48
138.4	-0.51
139.1	-0.53
139.7	-0.56
140.4	-0.58
141.1	-0.55
141.7	-0.56
142.4	-0.58
143	-0.49
143.7	-0.42
144.3	-0.40
145	-0.44
145.6	-0.54
146.3	-0.58
146.9	-0.63
147.6	-0.69
148.2	-0.74
148.9	-0.77
149.5	-0.83
150.2	-0.87
150.8	-0.89
151.5	-0.88

152.1	-0.82
152.8	-0.85
153.4	-0.87
154.1	-0.96
154.7	-0.85
155.4	-0.83
156	-0.92
156.7	-0.84
157.3	-0.84
158	-0.88
158.6	-0.92
159.3	-1.05
159.9	-1.08
160.6	-1.05
161.2	-1.12
161.9	-1.09
162.5	-1.07
163.2	-1.04
163.8	-1.09
164.5	-0.89
165.1	-0.85
165.8	-0.79
166.4	-0.78
167.1	-0.77
167.7	-0.71
168.4	-0.72
169	-0.73
169.7	-0.80
170.3	-0.82
171	-0.86
171.6	-0.89
172.3	-0.77
172.9	-0.82
173.6	-0.85
174.3	-1.04
174.9	-1.08
175.6	-1.10
176.2	-1.09
176.9	-0.83
177.5	-0.77
178.2	-0.82
178.8	-0.95
179.5	-1.03
180.1	-1.15
180.8	-1.18
181.4	-1.17
182.1	-1.17
182.7	-1.01
183.4	-1.26
184	-1.23
184.7	-1.18
185.3	-1.17
186	-1.17
186.6	-1.20
187.3	-1.22
187.9	-1.31
188.6	-1.28
189.2	-1.23
189.9	-1.27
190.5	-1.23
191.2	-1.25
191.8	-1.24
192.5	-1.31
193.1	-1.24

193.8	-1.22
194.4	-1.19
195.1	-1.20
195.7	-1.35
196.4	-1.31
197	-1.23
197.7	-1.14
198.3	-0.91
199	-0.91
199.6	-0.92
200.3	-0.95
200.9	-0.75
201.6	-0.67
202.2	-0.74
202.9	-0.84
203.5	-0.97
204.2	-1.00
204.8	-0.95
205.5	-0.97
206.2	-1.00
206.8	-0.93
207.5	-1.04
208.1	-1.00
208.8	-1.08
209.4	-1.07
210.1	-0.99
210.7	-1.07
211.4	-1.12
212	-1.07
212.7	-1.07
213.3	-0.97
214	-0.78
214.6	-0.67
215.3	-0.65
215.9	-0.64
216.6	-0.68
217.2	-0.75
217.9	-0.75
218.5	-0.66
219.2	-0.64
219.8	-0.66
220.5	-0.71
221.1	-0.71
221.8	-0.86
222.4	-0.90
223.1	-0.91
223.7	-0.71
224.4	-0.68
225	-0.73
225.7	-0.76
226.3	-0.78
227	-0.77
227.6	-0.79
228.3	-0.83
228.9	-0.87
229.6	-1.01
230.2	-0.98
230.9	-0.94
231.5	-0.88
232.2	-0.90
232.8	-1.01
233.5	-1.05
234.1	-0.97
234.8	-1.02

235.4	-1.20
236.1	-1.28
236.7	-1.31
237.4	-1.36
238	-1.30
238.7	-1.45
239.4	-1.34
240	-1.19
240.7	-1.25
241.3	-1.37
242	-1.41
242.6	-1.31
243.3	-1.47
243.9	-1.38
244.6	-1.39
245.2	-1.43
245.9	-1.43
246.5	-1.43
247.2	-1.40
247.8	-1.23
248.5	-0.74
249.1	-1.28
249.8	-1.38
250.4	-1.35
251.1	-1.34
251.7	-1.48
252.4	-1.37
253	-1.32
253.7	-1.42
254.3	-1.25
255	-0.94
255.6	-1.30
256.3	-1.39
256.9	-1.40
257.6	-1.58
258.2	-1.58
258.9	-1.35
259.5	-1.54
260.2	-1.53
260.8	-1.50
261.5	-1.49
262.1	-1.56
262.8	-1.60
263.4	-1.61
264.1	-1.61
264.7	-1.62
265.4	-1.60
266	-1.63
266.7	-1.52
267.3	-1.35

Table S5. Model input RSL history for Bideford study site

Time (years BP)	RSL (m)
20000	-87.4
19000	-86.6
18000	-85.7
17000	-83.3
16000	-80.5
15000	-78.3
14500	-74.1
14000	-65.1
13500	-53.6
13000	-51.8
12000	-48.2
11500	-46.0
11000	-43.7
10000	-31.5
9000	-24.1
8000	-16.2
7000	-9.2
6000	-6.5
5000	-4.5
4000	-3.1
3000	-1.9
2000	-1.0
1000	-0.4
0	0

Table S6. Model input RSL history for Scalby study site

Time (years BP)	RSL (m)
20000	-76.9
19000	-78.0
18000	-78.4
17000	-76.8
16000	-75.3
15000	-75.0
14500	-71.6
14000	-63.4
13500	-52.6
13000	-51.0
12000	-47.9
11500	-45.8
11000	-43.6
10000	-31.4
9000	-24.2
8000	-16.1
7000	-9.0
6000	-6.2
5000	-4.2
4000	-2.8
3000	-1.6
2000	-0.8
1000	-0.3
0	0

Table S7. MCMC simulation and Model inputs

Category	Model input	Bideford	Scalby
MCMC Dakota	**Proposal covariance**	0.1	0.5
	Topographic scale	0.58	0.73
	^{10}Be scale	932	455
Tides	**Tidal range**	8.4	4.6
	Tidal period	12.42	12.42
	Subtital efficacy	0.005	0.005
Waves	**Mean wave height (m)**	3	3
	Mean wave period	6	6
	Standing coefficient	0.1	0.1
	Breaking coefficient	10	10
	Broken coefficient	1	1
General RPM	**Cliff failure depth (m)**	0.1	0.1
	Initial gradient (tan β)	1	1
	Cell resolution (m)	0.1	0.1

Table S8. MCMC results for all weighted simulations

Site	Topographic weighting (%)	^{10}Be CRN weighting (%)	F_R (b)			K (c)			y (a)		
			Best fit	**16%**	**84%**	**Best fit**	**16%**	**84%**	**Best fit**	**16%**	**84%**
Bideford	**50**	**50**	1.93	1.37	2.61	-6.14	-8.94	-5.97	-1.45	-1.69	-1.36
	25	**75**	2.33	1.39	2.61	-6.78	-9.09	-6.12	-1.55	-1.66	-1.34
	75	**25**	2.68	1.44	2.62	-6.65	-9.11	-5.89	-1.70	-1.70	-1.38
	5	**95**	2.82	1.40	2.63	-6.36	-9.19	-6.05	-1.63	-1.61	-1.26
	95	**5**	1.43	1.36	2.60	-6.40	-8.72	-5.12	-1.38	-1.69	-1.37
Scalby	**50**	**50**	2.04	1.28	2.14	-4.94	-8.55	-3.86	-1.97	-1.96	-1.80
	25	**75**	1.87	1.30	2.19	-5.53	-7.76	-3.02	-1.96	-1.96	-1.75
	75	**25**	1.37	1.23	2.08	-5.01	-8.16	-3.52	-1.88	-1.87	-1.77
	5	**95**	1.37	1.33	2.28	-5.00	-6.60	-2.56	-1.88	-1.86	-1.68
	95	**5**	2.01	1.20	2.09	-8.65	-5.41	-3.56	-1.98	-1.87	-1.75

Figure S1. Accepted chain results for 50 – 50% MCMC, 10,000 iteration simulation for Bideford free parameters, *Fr* (calibration parameter *a*), *y* (calibration parameter *b*) and *K* (calibration parameter *c*). Cumulative moving median and 5%, 16%, 84% and 95% confidence intervals shown. Note well-defined burn-in period for *Fr* and *y* parameters that ends after ~2000 samples. When *K* (*c*) falls below -5 and negligible weathering is acting on the shore platform, the value for *K* has no further influence on both topographic profile and ^{10}Be profile, hence movement across the parameter space and chain convergence to a single value for *K* is not possible. Increasing the *K* proposal distribution would have no impact on the final acceptance chain convergence in this case.

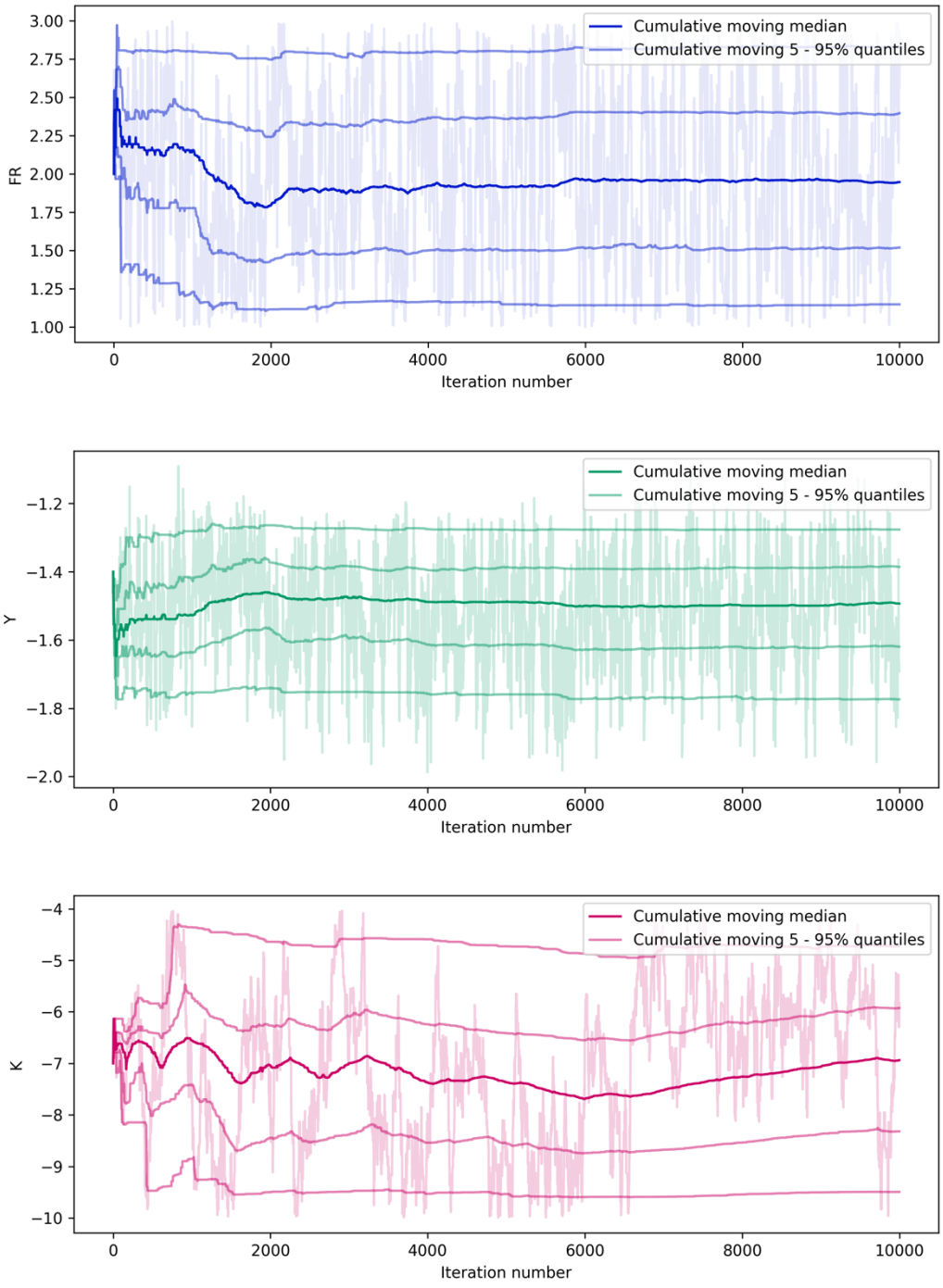

Figure S2. Accepted chain results for 50 – 50% MCMC, 10,000 iteration simulation for Scalby free parameters, *Fr* (calibration parameter *a*), *y* (calibration parameter *b*) and *K* (calibration parameter *c*). Cumulative moving median and 5%, 16%, 84% and 95% confidence intervals shown. Note well-defined burn-in period for *Fr* and *y* parameters. When *K* (*c*) falls below -5 and negligible weathering is acting on the shore platform, the value for *K* has no further influence on both topographic profile and ^{10}Be profile, hence movement across the parameter space and chain convergence to a single value for *K* is not possible. Increasing the *K* proposal distribution would have no impact on the final acceptance chain convergence in this case.

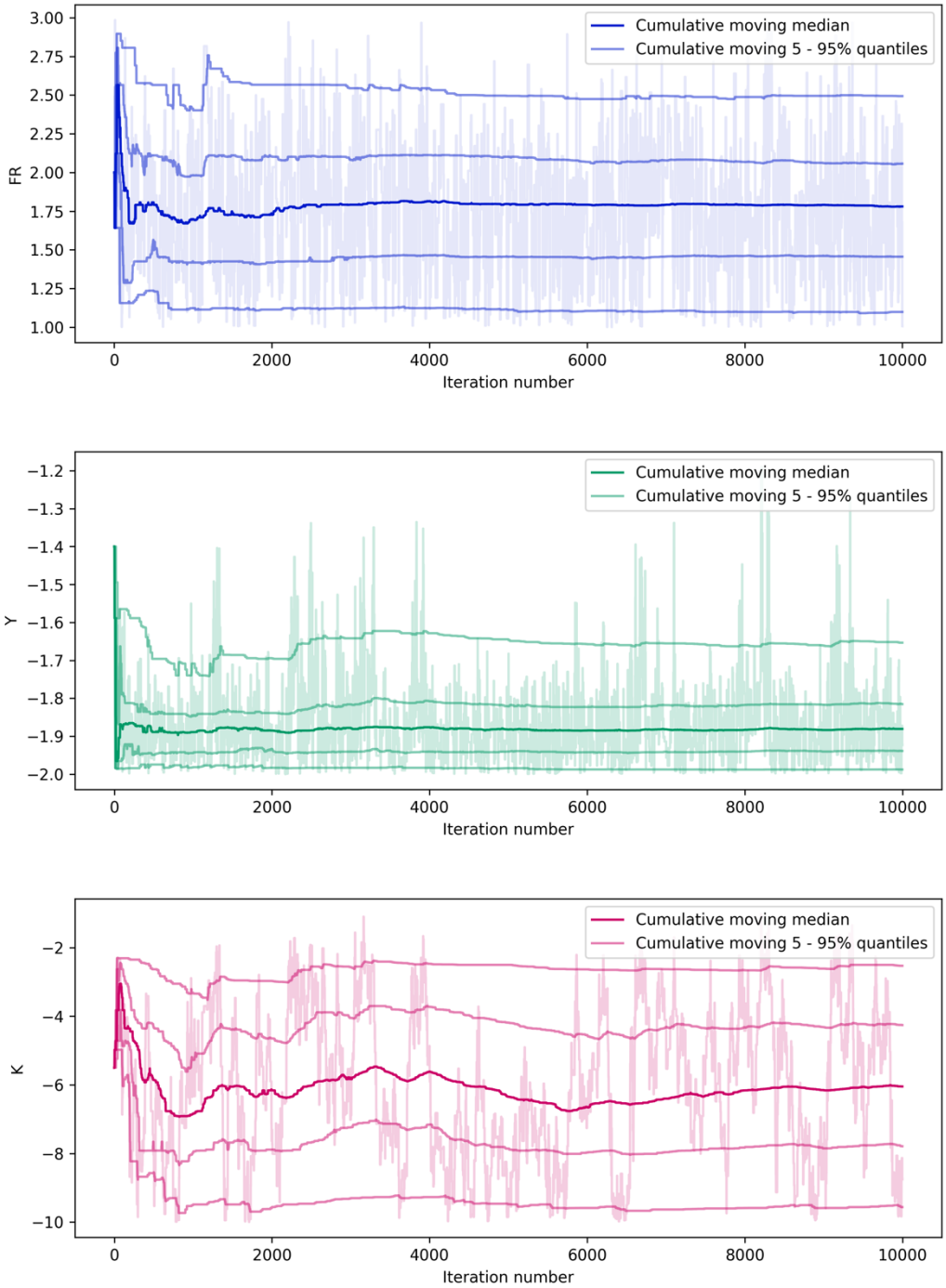

Figure S3. Objective function surface for the ^{10}Be concentration RMSE at Bideford. This was from a preliminary investigation with the upper range of weathering rates (*c*) included. The most likely results (yellow) are only found at the lowest weathering rates (*c*) ~ -5. So that posterior destitutions were not considerably skewed, a secondary simulation was performed that lowered the weathering rate values beyond -5 (these are the results included in the main text).