A Lateglacial age for the Main Rock Platform, western Scotland

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ABSTRACT

The sea-level record preserved in ancient shorelines forms a basis for studies of tectonic uplift, glacial loading, and the changing volume of the oceans. The existing record is derived largely from depositional features such as beach ridges and coral reefs, which contain material suitable for radiometric dating. Erosional shorelines have proved more difficult to date. Direct age estimates for shore platforms can now be obtained with exposure-dating techniques based on cosmic-ray–produced isotopes. Here we report measurements of cosmogenic ^{36}Cl on the Main Rock Platform in western Scotland that indicate its formation in a postglacial event spanning less than a few thousand years. Together with isostatic modeling, the ^{36}Cl results suggest cutting during the Younger Dryas (in Britain, the "Lateglacial" or "Loch Lomond") Stadial, when stable sea level and severe climatic conditions combined to enhance bedrock erosion.

INTRODUCTION

The Main Rock Platform is the most prominent and extensive ancient shoreline in western Scotland. It is best developed within the Firth of Lorn but also occurs within the Firth of Clyde and on the west coast as far north as Morven (Gray, 1974a; Dawson, 1988) (Fig. 1). It is commonly 10–20 m wide (but reaches ~100 m in places) and is generally backed by a former sea cliff 5–30 m high. Relics of marine erosion such as sea stacks and arches are found at a number of localities (Gray, 1974a). The platform has been uplifted and tilted by postglacial isostatic rebound. Originally formed at sea level, it is now submerged south of Arran and rises to a height of ~12 m at the head of the Firth of Lorn (Gray, 1974a, 1978). On the Isle of Lismore, the Main Rock Platform is cut into calcareous schists 7—8 m above present-day mean sea level and attains widths up to 40 m.

The Main Rock Platform was originally assigned a Holocene age (Wright, 1928). Because of the extreme erosion rate this age implied, other workers suggested cutting over a longer period (McCallien, 1937). Two contrasting views have developed from these early studies. Sissons (1974) suggested formation during the Lateglacial Stadial (otherwise known as the Loch Lomond Stadial, spanning the period ca. 11–10 ka in the radiocarbon time scale and considered equivalent to the Scandinavian Younger Dryas Stadial). This proposal is based on the following evidence: (1) The region occupied by the Main Rock Platform was entirely covered by ice during the Late Devensian glacial maximum (ca. 25–15 ka in the radiocarbon time scale), yet the platform shows little evidence of glacial erosion or overlying till. It must therefore have formed, or evidence of glacial cover must have been removed, after this period. (2) The platform is absent along stretches of the coast that were ice-bound during the subsequent Loch Lomond Stadial, suggesting formation before or during that time (Sissons, 1974, 1981). (3) The northeastward tilt of the platform is consistent with postglacial rebound centered on the central Western Highlands, the focus of Loch Lomond ice accumulation (Gray, 1978; Sissons, 1981). In this interpretation, the Main Rock Platform is correlated with the Main Lateglacial Shoreline of southeast Scotland, which is cut across glacial maximum till and contains radiocarbon-dated fossils of Lateglacial age. Sissons (1974) attributed the rapid formation of the platform to frost riving under periglacial climatic conditions.

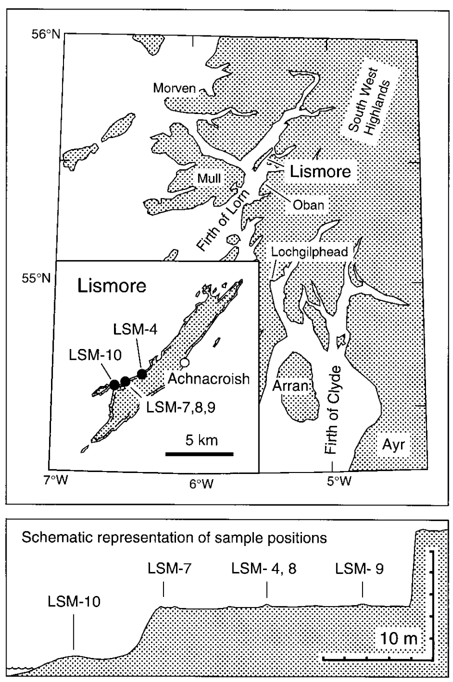

Figure 1. Southwest coast of Scotland. Main Rock Platform is developed almost continuously along eastern shore of Firth of Lorn and northern and eastern shores of Mull. Inset shows sample sites on Isle of Lismore. Lower diagram shows their positions with respect to platform.

The excavation rate required to shape the Main Rock Platform during the Lateglacial, believed to have lasted no more than ~1500 yr, remains the principal objection to assigning it this age. Formation during the Lateglacial would imply cliff retreat rates of 10–20 mm per year, greater than those of most present-day sea cliffs in similar rock types (Sunamura, 1983) and an order of magnitude greater than those of alpine rock walls in the Scottish highlands during the Lateglacial (Ballantyne and Kirkbride, 1987). Other workers have therefore suggested that the platform is older and formed over a longer period (McCallien, 1937; Gray, 1974a). Support for this interpretation comes from a U-series age of 103 +28/−20 ka for a stalagmite in a sea cave backing the platform on the Isle of Lismore, taken as a minimum age for the last episode of cliff retreat and platform broadening (Gray and Ivanovich, 1988). This conclusion warrants caution, as only one of six stalagmites dated yielded an old apparent age, whereas three gave ages that are clearly incorrect. Two of these "ages" fall within the Late Devensian glacial maximum, when Lismore lay beneath hundreds of metres of ice. A third sample yielded a ^{230}Th/^{234}U activity ratio substantially greater than 1, an impermissible result, which was attributed to U loss. Less severe U loss could have produced a false, but seemingly respectable, old "age" in the critical sample.

To reconcile evidence of Lateglacial marine erosion on the platform with the ca. 100 ka stalagmite age, Gray and Ivanovich (1988) suggested that the Main Rock Platform is an ancient feature that has been repeatedly broadened and "retrimmed" dur-

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ing interglacial periods of high sea level. Whether the platform is old, young, or an episodically active feature, there are implications for the comparative effects of glacial and marine erosion. A Lateglacial age requires removal of millions of cubic metres of rock by marine and periglacial processes in less than a few thousand years, whereas a preglacial age implies survival of fragile ornamentation—stalagmites and sea stacks—beneath hundreds of metres of ice during the Devensian.

EXPOSURE DATING

The age of a surface such as the Main Rock Platform can be resolved by exposure dating with cosmogenic isotopes such as ^{36}Cl. Cosmic-ray exposure of the platform surface began when the backing cliff retreated and uncovered formerly shielded rock. There are several possible scenarios: (1) If the Main Rock Platform is a Lateglacial feature, cut into rock already deeply scoured beneath the glacial-maximum ice sheet, its surface will have accumulated a low ^{36}Cl concentration from Holocence exposure alone. (2) If the platform was cut during the last interglacial, a much higher concentration is expected. The actual value would depend on the duration of prior interglacial exposure and the timing and duration of subsequent coverage by ice, interrupting exposure. (3) If the platform is an ancient feature "retrimmed," an intermediate ^{36}Cl concentration will result that is due to the combination of Holocene exposure (at the surface production rate) and prior exposure (at a lower production rate, beneath whatever cover was removed by retrimming). Episodic retreat of the backing cliff should lead to a progression of exposure ages, oldest at the seaward edge and youngest beneath the present cliff.

SAMPLING AND METHODS

Cosmogenic ^{36}Cl was measured in calcite from calcareous schists cropping out at the platform surface on the Isle of Lismore (Fig. 1). To avoid the possibility of shielding by peat, and to minimize errors due to erosion since formation of the surface, samples were taken from high-standing outcrops, up to 60 cm above the general level of the platform. The samples make up a morphological transect from beneath the backing cliff (LSM-9), across the platform (LSM-8, LSM-4) to its outer rim (LSM-7), and on to low ground beneath its seaward rampart (LSM-10).

The ^{36}Cl measurements followed the chemical preparation and measurement techniques described by Stone et al. (1996) and Fifield et al. (1990). Additional chemical analyses were made as described by Stone et al. (1996). Key analytical results and estimated ^{36}Cl production rates are shown in Table 1.[1] Production rates are referenced to the sidereal (rather than the radiocarbon) time scale and are based on the calibration measurements of Stone et al. (1994, 1996), Liu et al. (1994), and Phillips et al. (1996). Production of ^{36}Cl in calcite is predominantly due to Ca spallation, with an estimated rate of 48.8 $\pm$ 3.4 atoms (g Ca)$^{-1}$ a^{-1} at Lismore (Stone et al., 1996). Production by muon capture on ^{40}Ca is estimated at 4.8 $\pm$ 1.2 atoms (g Ca)$^{-1}$ a^{-1}. This value is slightly revised from the value in Stone et al. (1994) in accordance with revision to the Ca spallation rate given in that paper. Production by slow-neutron capture on ^{35}Cl varies with the Cl concentration and chemical composition of the samples. The capture rate is calculated by using the method of Liu et al. (1994), with the neutron production rate of 586 $\pm$ 40 neutrons (g air)$^{-1}$ a^{-1} given by Phillips et al. (1996). These production rates are calibrated at mid-latitude, high-altitude sites and scaled to Lismore by using the factors of Lal (1991). Swanson et al. (1994) suggested production rates higher than those we have adopted here. At present, we prefer to use the rates stated above, acknowledging the possibility of a systematic offset in our calculated ages. Higher production rates would imply younger exposure ages.

EXPOSURE AND FORMATION AGES FOR THE MAIN ROCK PLATFORM

Hypotheses for formation of the Main Rock Platform can be resolved by examining "effective irradiation ages" of the samples (Table 1). These are the times required to produce the amounts of ^{36}Cl measured, assuming continuous surface exposure. They provide a good indication of cumulative surface exposure, as breaks in the exposure of the platform envisaged in the formation models are too short and too recent, compared to the half-life of ^{36}Cl (301 ka), for radioactive decay to be significant. Effective irradiation ages for samples from the surface of the platform are 8.9–10.4 ka, short of the calibrated age of the Lateglacial termination (ca. 11.5 cal. ka B.P. [Stuiver and Reimer, 1993]). The age of sample LSM-10, from beneath the shoreward rim of the platform, is younger still. Irradiation ages for the platform samples are uniform within their $\pm$1 k.y. uncertainties, limiting the time interval for cliff retreat to less than a few thousand years during formation of the present surface. The short irradiation ages clearly rule out preglacial exposure of the present surface, for example during and since the last interglacial period. Two distinct "retrimming" scenarios can be envisaged. Because the attenuation length for ^{36}Cl production in the Lismore rocks is $\sim$70 cm, retrimming to erase the effect of a long prior exposure would require the removal of rock to a depth of several metres. This scenario raises the same problems with high rates of bedrock removal as the proposal that the platform was cut into fresh rock. The alternative, a shallow "retrimming" event, would not have reduced surface ^{36}Cl concentrations significantly. Thus, prior exposure would have to have been short (far less than the $\sim$100 k.y. conceivable for a last-interglacial precursor). Also, to arrive at the uniformity of irradiation ages observed across the platform, the precursor surface must have been cut in less than a few thousand years, contradicting the idea of gradual, episodic platform broadening that underlies the retrimming hypothesis (Gray and Ivanovich, 1988). Thus, though "retrimming" scenarios cannot be ruled out in general, the uniform irradiation times of the platform samples and their lack of discernible prior exposure favor a simpler exposure history—a single rapid episode of cliff retreat into a surface previously scoured beneath the Late Devensian ice sheet.

Two aspects of the data remain to be explained. First, irradiation times for the platform samples fall short of the most likely formation period, the Lateglacial Stadial. Second, the exposure time of LSM-10, collected below the seaward face of the platform (Fig. 1), is much shorter than the exposure times of the platform samples. Both observations can be accounted for by the shielding effect of postglacial sea-level changes on the cosmic-ray flux received by the samples.

Relative sea level at Lismore since the last glacial maximum has been influenced by changes in ocean volume and the local isostatic response to changing ice and water loads. Calculations of these effects and detailed comparisons with observed sea-level changes elsewhere in Britain are given by Lambeck (1993a, 1993b). The sea-level curve calculated for Lismore (Fig. 2A) is in accordance with ^{14}C-dated records at Oban (Gray, 1974b) and Lochgilphead (Peacock et al., 1977) (see Fig. 1 for locations). It shows an early period of falling relative sea level, when local rebound outstripped ocean refilling, followed by several thousand years when balance between the processes held mean sea level close to the present height of the Main Rock Platform. This stillstand,

[1]Data Repository item 9639, full chemical data and production rates calculated from them, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

TABLE 1. ^{36}Cl RESULTS, ISLE OF LISMORE

Sample	Analytical results			^{36}Cl production rates+				Age estimates	
	Cosmogenic ^{36}Cl* (10^5 atom g^{-1})	[Ca] ($g\,g^{-1}$)	[Cl] ($\mu g\,g^{-1}$)	Calcium spallation (atom $g^{-1}\,a^{-1}$)	Muon capture (atom $g^{-1}\,a^{-1}$)	Neutron capture (atom $g^{-1}\,a^{-1}$)	Total (atom $g^{-1}\,a^{-1}$)	t_{exp}§ (cal. ka)	t_{model}# (cal. ka)
LSM-4	2.10 ± 0.19	0.391	26 ± 3	18.5 ± 1.3	1.8 ± 0.4	1.2 ± 0.2	21.5 ± 1.4	9.9 ± 1.0	11.9 +2.0/-1.6
LSM-7	2.23 ± 0.26	0.395	98 ± 12	18.7 ± 1.3	1.8 ± 0.4	4.9 ± 0.7	25.5 ± 1.5	8.9 ± 1.1	10.5 +1.6/-1.4
LSM-8	2.93 ± 0.22	0.392	173 ± 3	18.2 ± 1.3	1.8 ± 0.4	8.6 ± 0.7	28.5 ± 1.5	10.4 ± 0.9	12.2 +1.9/-1.5
LSM-9	2.61 ± 0.28	0.394	124 ± 5	18.6 ± 1.3	1.8 ± 0.4	5.1 ± 0.6	25.6 ± 1.5	10.3 ± 1.2	11.9 +∞/-1.7**
LSM-10	1.42 ± 0.17	0.395	126 ± 10	18.4 ± 1.3	1.8 ± 0.4	6.8 ± 0.8	27.0 ± 1.5	5.3 ± 0.7	12.1 +∞/-3.0**

*Concentration after subtraction of background ^{36}Cl produced by capture of fissiogenic and (α, n) neutrons. Background concentrations, calculated from measured U, Th and major element concentrations using the method of Fabryka-Martin (1988), range from 10^3 - 7×10^3 atom g^{-1}, 1% - 3% of total ^{36}Cl.

+Sample production rates after correction for thickness and irradiation geometry. Exponential thickness corrections for spallation assume 160 g cm^{-2} attenuation length (Brown et al., 1991). Thickness corrections for neutron capture according to Liu et al. (1994). Sample thicknesses are: LSM-4, LSM-7: 13 g cm^{-2}, LSM-8: 19 g cm^{-2}, LSM-9: 8 g cm^{-2}, LSM-10: 15 g cm^{-2}. Corrections relative to 2Π exposure geometry for spallation and neutron capture production rates assume $\mathrm{Sin}^{2.3}(\theta)$ zenith angle distribution for incident cosmic ray flux. Geometry correction factors applied are: LSM-4, LSM-7, LSM-10: 1.0, LSM-8: 0.99, LSM-9: 0.97. No sample thickness or geometry corrections have been applied to production by muon capture.

§Effective irradiation time assuming continuous surface exposure (see text). Uncertainties (±1 σ) include analytical and production rate uncertainties.

#Surface formation age calculated from production history shown in Figure 2, as described in text. Errors estimated as above. Model-dependent uncertainties (e.g., in the sea-level history and depth-dependence of ^{36}Cl production) have not been propagated.

**Upper uncertainty bound not delimited, because production rate goes to zero. See Figure 2.

commencing in the Lateglacial and extending into the early Holocene, was followed by a transgression of several metres. The Main Postglacial Shoreline, widely developed around southwest Scotland, was formed during this event (Gray, 1974b). At Lismore, peak sea level reached during the transgression would have flooded the Main Rock Platform to a depth of several metres. The final phase of falling sea level extending to the present reflects continuing isostatic rebound. Note that sample LSM-10 would have emerged from the sea only recently.

Shielding during periods of immersion would have lowered ^{36}Cl production rates in the samples (Fig. 2B). During immersion, production by spallation decreases with an attenuation length of ~1.6 m (e.g., Brown, 1992). Production by neutron capture drops with initial immersion owing to the higher neutron-moderating power and absorptivity of seawater compared to air (O'Brien et al., 1978), then decreases with the same attenuation length as spallation. Production by muon capture increases slightly to ~2 m water depth, then decreases with an attenuation length of ~10 m (Stone et al., 1994). Total ^{36}Cl production in the Lismore samples would have been dominated by spallation to water depths of ~4 m and by muon reactions at greater depths. Tidal variation (±1.15 m at Lismore) adds a final complication, moderating the transition between continuous surface exposure (when mean sea level stood more than 1.15 m below the height of the platform) and continuous immersion (when it submerged the platform by more than 1.15 m).

"Formation" ages for the samples are obtained by integrating their production rates back through time until measured ^{36}Cl concentrations are reached, as shown in Figure 2C and Table 1. The integrations start from ^{36}Cl concentrations equal to radiogenic "background" values and hence assume no prior cosmic-ray exposure. Ages calculated in this way should provide good estimates for the time of cliff retreat or deep "retrimming" but would overestimate the age of a shallow retrimming event that only partially removed preexisting cosmogenic ^{36}Cl. Formation ages for the platform samples range from 10.7 to 12.2 ka, ~2 k.y. greater than the effective exposure times discussed above, and correspond more closely with the Lateglacial period. The model explains the low ^{36}Cl content of the low-lying sample LSM-10—the result of heavy shielding beneath the sea for most of postglacial time. The calculation gives a "formation age" of ca. 12 ka for this sample, much older than its effective exposure age. Within its large uncertainty (due to attenuated ^{36}Cl production prior to ca. 3 ka [Fig. 2B]), this age is not inconsistent with the value expected for a surface scoured by ice during the glacial maximum, but submerged too deeply to have been affected by Lateglacial marine erosion. In fact, the lack of evidence for prior exposure of this sample, unaffected by the processes that cut the platform, argues against the "retrimming" hypotheses discussed above.

RAPID COLD CLIMATE SHORELINE EROSION

The model ages shown in Figure 2 make a strong case for rapid excavation of the Main Rock Platform during the Lateglacial Stadial. While acknowledging the possibility of systematic errors in the production rates and sea-level history and the assumption of negligible erosion since formation, the ages obtained are plausible for two reasons. First, the Lateglacial corresponded to a time of stable sea level when marine erosion processes would have been concentrated at the height of the Main Rock Platform for several thousand years (Fig. 2A). Second, periglacial conditions during this period would have accelerated bedrock erosion (Sissons, 1974). Processes that can be invoked are rock shattering by diurnal freezing in the intertidal zone (e.g., McGreevy, 1981), loosening of blocks by deep penetration of winter freezing into joints in water-saturated bedrock (Matthews et al., 1986; Dionne and Brodeur, 1988), and abrasion and leveling by ice push and tidal heaving of fast ice (e.g., Nielsen, 1979). These processes are operating at present in arctic regions and would have been activated by climatic conditions during the Scottish Lateglacial, with sea-level winter mean temperatures as low as −15 °C (Ballantyne, 1984). Nor is the Main Rock Platform a unique example of rapid cold-climate shoreline erosion. Other examples include the lake shorelines of Glens Roy, Gloy, and Spean in Scotland, formed over intervals of a few hundred years during the Lateglacial (Sissons, 1978) and those of glacial Lake Bonneville in North America, which attained widths similar to the Main Rock Platform in periods of less than a few hundred years (Currey and Oviatt, 1985). Broad and extensive shorelines like the Main Rock Platform need not be interpreted as products of gradual erosion over long time spans. Instead, they provide evidence of accelerated erosion under drastically different climatic regimes.

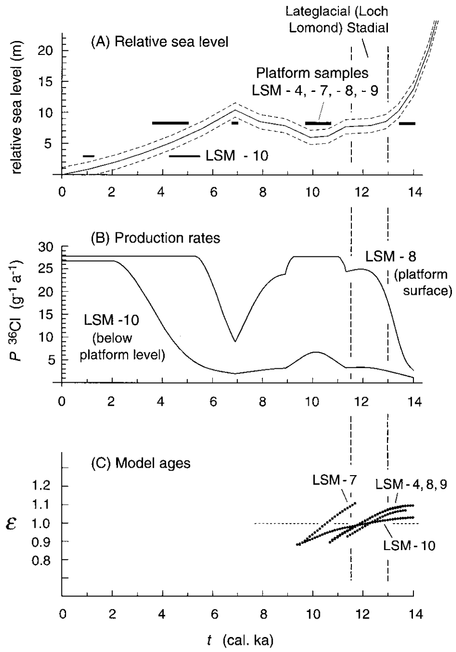

Figure 2. A: Relative sea level at Lismore since Late Devensian glacial maximum, calculated as described by Lambeck (1993b). For comparison with exposure-dating calculations, radiocarbon time scale has been converted into sidereal time (*t*) by using the calibration of Stuiver and Reimer (1993). Elevations are given relative to present-day mean sea level, which is 0.55 m higher than the British Ordnance Datum at Lismore. Dotted lines indicate diurnal tide range, taken as ±1.15 m, the average of mean spring (±1.7 m) and neap (±0.6 m) tides. Comparison of sea-level curve with sample elevations shows periods of exposure and immersion. B: Time-dependent ^{36}Cl production rates ($P\ ^{36}Cl$) for samples LSM-8 and LSM-10, based on the sea-level history shown in A. Production histories for LSM-4, -7, and -9 are similar to that of LSM-8. C: Model ^{36}Cl concentrations for samples, shown as the ratio (ε) of time-integrated ^{36}Cl production to measured ^{36}Cl concentration. Times (*t*) corresponding to $\varepsilon = 1$ are taken as model ages for samples. Age ranges in which model ^{36}Cl concentrations fall within the $\pm 1\sigma$ limits of the measured ^{36}Cl data are plotted, giving (random) error bounds on the model ages. Full error bounds, incorporating ±10% uncertainty in ^{36}Cl production rate, are given in Table 1.

ACKNOWLEDGMENTS

We thank Colin Ballantyne for advice on field work and for discussions on the glacial geology of Scotland. Paul Bierman, Fred Phillips, and Ed Brook provided helpful and constructive reviews of the original manuscript.

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Manuscript received November 13, 1995
Revised manuscript received April 18, 1996
Manuscript accepted May 3, 1996