# Long-term Quaternary uplift rates inferred from limestone caves in Sarawak, Malaysia

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## ABSTRACT

**The rate of long-term (2 m.y.) base-level lowering estimated in an extensive sequence of limestone caves in Sarawak, Malaysia, from uranium series, electron spin resonance, and paleomagnetic dating is 0.19 +0.03/−0.04 m/ka. This rate has remained constant over at least the last 700 ka, as shown by comparison of the number and spacing of wall notches formed during phases of interstadial and interglacial aggradation with peaks in the deep-sea oxygen isotope curve. It is argued that base-level lowering occurs in response to epirogenic uplift of the more resistant limestones due to regional denudation of the softer shales, and to flexural isostacy associated with high rates of offshore sedimentation.**

## INTRODUCTION

Rates of uplift are needed to constrain models of relief generation (Pazzaglia and Gardiner, 1994) and tectonic processes (England and Molnar, 1990) over geologic time scales. Most estimates of uplift have come from tectonically active coasts, where emergent marine terraces can be dated using uranium series and other techniques (e.g., Bloom et al., 1974), and studies of river terraces using radiocarbon dating (e.g., Merritts et al., 1994). However, although long-term sequences of both coastal and river terraces have been obtained (Pirazzoli et al., 1993; Pazzaglia and Gardiner, 1994), the chronological control on these is often poor. Furthermore, fluvial terraces are not ubiquitous; their development depends on critical interrelations between uplift rate, basin area, and the effects of eustatic sea level (Merritts et al., 1994). Thus few well-constrained estimates of rates of uplift over the longer time scale are available. Here we provide estimates of the long-term rate of base-level lowering (Merritts et al., 1994) derived from uranium series and paleomagnetic dating of deposits from extensive cave systems in the Gunung Mulu National Park, Sarawak, Malaysia.

## GUNUNG MULU STUDY AREA

The study area is in equatorial northeast Sarawak, Malaysia, 180 km from the coast (Fig. 1). Morphologically, the region comprises three distinct units. The Gunung Mulu uplands (maximum elevation 2377 m) are developed on coarse sandstone of the Mulu Formation. Immediately to the northwest is the rugged, maturely karstified ridge of Gunung Api (maximum elevation 1692 m) composed of massive pure upper Eocene–lower Miocene Melinau Limestone (James, 1984). The rocks dip 60°–70° to the northwest and form the northwestern limb of the Mulu anticline. The most western unit is the alluvial plain of the Melinau River at an elevation of less than 30 m, an erosional feature incised in the limestones and overlying Setap shales. This difference in relief is perpetuated by high erosion rates on the alluvial plain caused by large influxes of undersaturated sediment-laden water flowing off Gunung Mulu via the Melinau Gorge, coupled with low erosion rates on the uplands, which lack any appreciable soil cover (Smart et al., unpublished data).

Underground drainage through the limestone ridge gives rise to some of the largest and most extensive caves in the world. The Clearwater-Blackrock system (Fig. 1) is more than 104 km long, and is the seventh-longest known cave in the world. The base level for cave development at the Clearwater resurgence (elevation 28 m) is controlled by the incision of the Tutoh River into the Mulu anticline, the northeast-southwest axis of which passes through Gunung Mulu, and forms an elongate dome with radial drainage (Smart et al., 1985). Continued erosion has generated a vertical sequence of abandoned cave passages, the highest (oldest) caves being some 400 m above the present resurgence level.

## ESTIMATION OF THE RATE OF BASE-LEVEL LOWERING

Initial dating studies used uranium series analysis of speleothems sampled from a range of elevations within the cave system. Of the 14 analyses available, 10 considerably postdate passage development, and a further two higher samples from 40 and 140 m are at the effective limit of the dating technique and may be uranium leached. Only two samples (26.7 ± 1.5 ka, and 15.7 ± 1.1 ka, both at 6 m) provide a satisfactory constraint on the short-term rate of base-level lowering, giving a minimum rate of 0.21 m/ka. Experiments with electron spin resonance dating of speleothems demonstrated that thermal detrapping would provide an effective limit on the technique, on the order of 600 ka (Smith et al., 1985). Thus, the age of 850 ± 210 ka determined for a sample from 120 m probably represents a minimum age, suggesting a maximum base-level lowering rate of 0.19 m/ka.

A preliminary study by Noel and Bull (1982) demonstrated the suitability of the fine-grained cave sediments for magnetostratigraphic methods. We thus constructed a composite paleomagnetic record by collection of 55 sets of six duplicate samples from freshly exposed sections representative of major laterally continuous sediment bodies. Particular effort was made to obtain a complete sequence of samples spanning all elevations, but above ~200 m this proved impossible owing to the more limited extent of cave passages. The natural remnant magnetization was measured using a Molspin spinner magnetometer. After using stepwise alternating field techniques to demagnetize preliminary pilot samples, we demagnetized all samples in a 30 mT field. Most samples had a small normal overprint and a weak, but generally stable primary magnetic com-

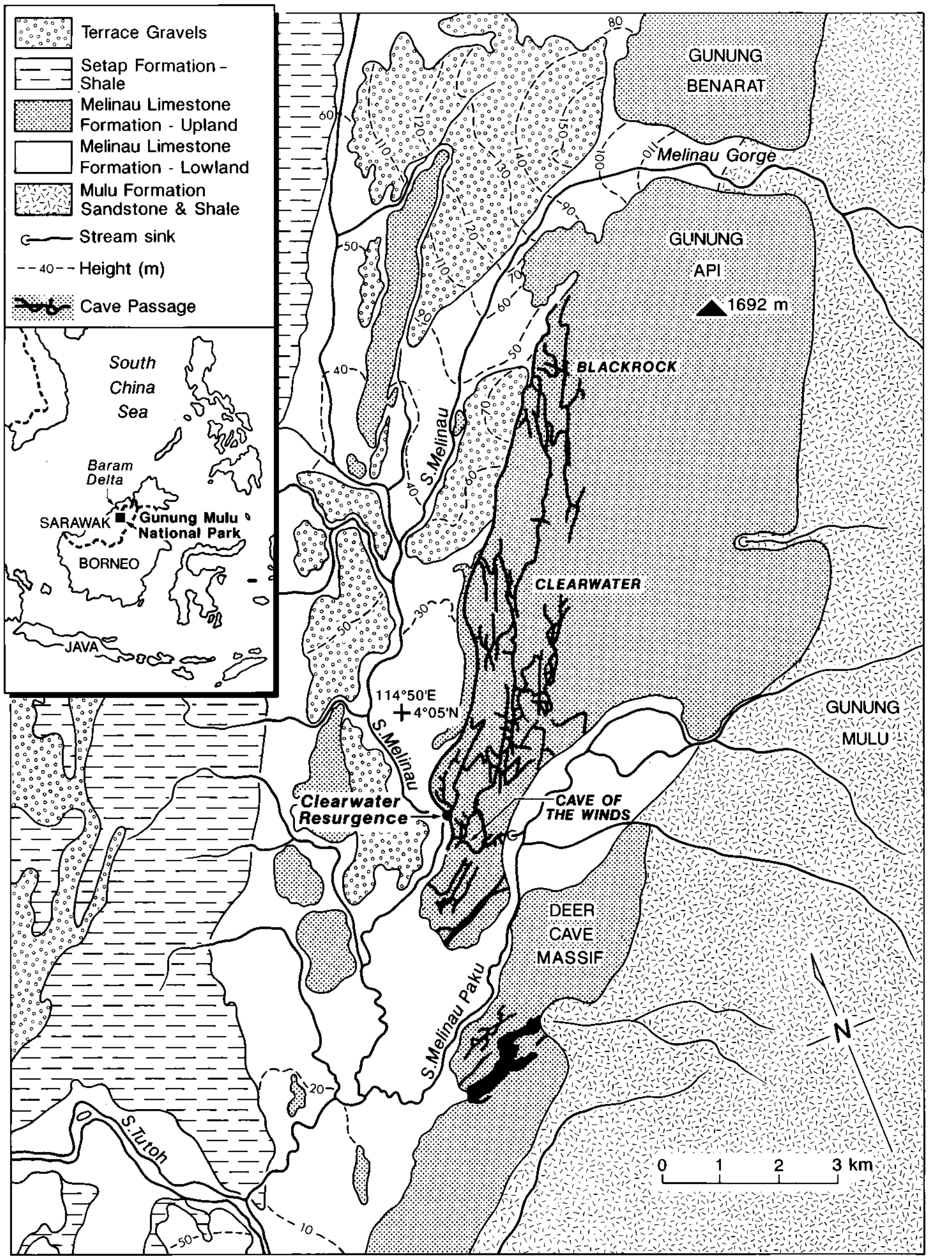


**Figure 1. Location of Gunung Mulu National Park (inset) and geology, topography, and caves of Gunung Api (after Smart et al., 1985).**

ponent. Primary magnetic intensities ranged from 43.3 mA/m to <0.01 mA/m.

All sediment sampled below an elevation of 142 m is of normal magnetic polarity (Fig. 2). Above this elevation reversely magnetized sediment is found, with a return to normal polarity between 182 and 186 m. Above this the distribution of suitable sediment is too sparse for certain interpretation; reversed sediment dominates the interval from 216 to 256 m, with single normal samples at 220 m and 300 m, and reversed polarity in the sediment above 380 m. We interpret the transition at ~140 m to represent the Brunhes-Matuyama polarity reversal at 783 ka (Baksi et al., 1992), whereas the next normal period (180–200 m) is correlated with the Jaramillo reversal, the single normal sample at 220 m possibly equating with the brief Cobb Mountain event at 1.19 Ma (Turrin et al., 1994). The transition at ~300 m is tentatively correlated with the normal Olduvai subchron. The mean rate of base-level lowering thus derived is 0.19 (+0.03/−0.04) m/ka, although a much smaller uncertainty of ±0.01 m/ka is indicated for the last 1.2 m.y. by precise definition of the Bruhnes/Matuyama transition and Cobb Mountain event. Within error limits, this rate is comparable to that determined by electron spin resonance dating and to the minimum rate obtained from the uranium series ages.

## CONSTANCY OF BASE-LEVEL LOWERING WITH TIME

The major problem with the paleomagnetic time scale is that it is based on discrete tie points that provide an exact but very coarse time frame (seven units over 2 m.y.), and thus identification of short-term variation in rates of base-level lowering is not possible. Application of a higher resolution discrete chronology based on the timing of interglacial and interstadial events derived from the oxygen isotope record of global ice volume in deep-sea cores (Shackleton et al., 1990) was therefore considered. Previous studies (Rose, 1982) have shown that fragments of terrace gravel in the Melinau valley (Fig. 1) comprise part of a major alluvial fan derived from the Melinau Gorge. Rose argued that aggradation is paleoclimatically controlled, occurring during the wetter interglacial periods in response to increased rainfall, land slipping, and sediment production, whereas incision occurs during the drier glacial climate (Verstappen, 1975; Barmawidjaja et al., 1993). Within the caves, morphologically distinctive wall notches are present, the elevations of which are controlled by the past aggradation limits of the Melinau alluvial fan (Smart et al., 1985). If base-level lowering was constant, there should be a clear association between the timing of interglacial and interstadial events in the deep-sea core record and the elevation (= age) of notches in the Mulu caves.

Careful underground mapping has allowed identification of more than 20 vertically distinct notches, some of which occur together in a single passage (Fig. 3). Individual notches are laterally continuous for up to 3 km, and may be present in several separate passages. The elevation of these notches relative to resurgence datum is known from surveys with an uncertainty of less than 5 m (equivalent to ±26 ka at a constant rate of base-level change of 0.19 m/ka). In Figure 4 we compare the astronomically calibrated oxygen isotope chronology of Shackleton et al. (1990) with notch elevations, assuming a constant rate of base-level lowering of 0.19 m/ka. In the interval 0–700 ka (0–130 m) there are 11 major interglacial peaks (>0.5‰ change in $\delta^{18}O$; Fig. 4), all of which are associated with aggradational events. In addition, four other notches can be matched to significant smaller peaks or doublets, although five minor peaks do not have associated notches. This excellent match, confirmed by application of the $\chi^2$ test on a 2 × 2 contingency

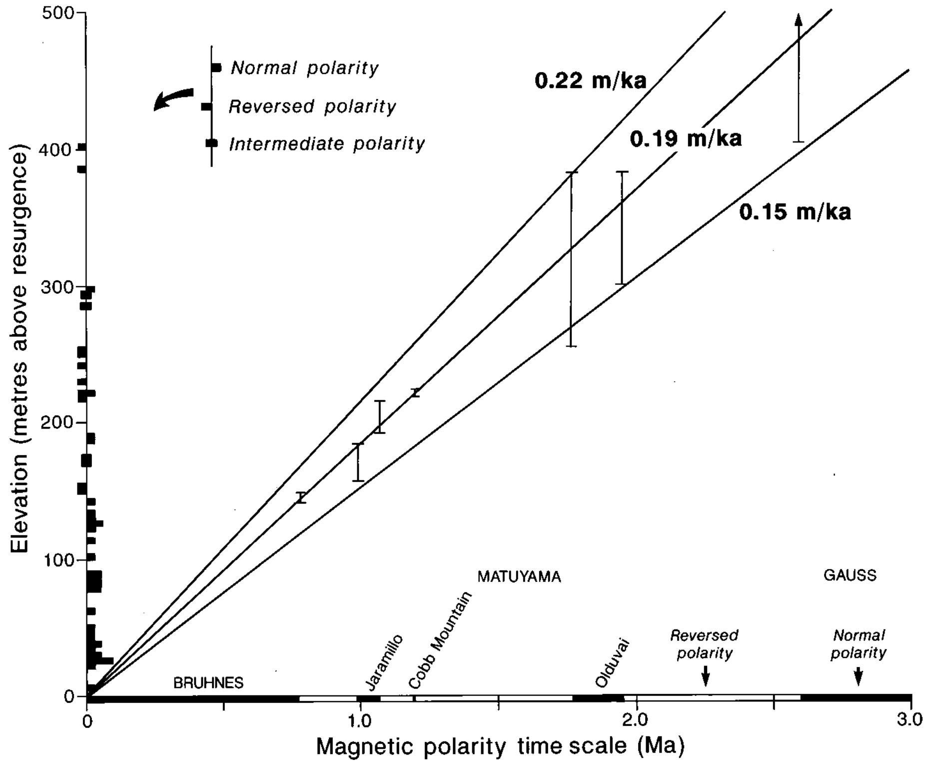


**Figure 2. Distribution of polarity of sediment samples from Clearwater-Blackrock system with elevation, together with best fit line for constant rates of base-level lowering, derived from paleomagnetic time scale. Each sample site is represented by one block on elevation axis; bars define minimum and maximum possible positions of polarity changes. Four sites yielded intermediate polarities.**

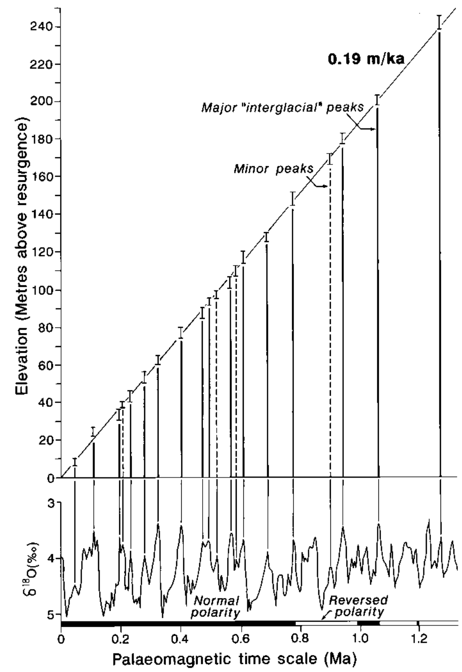


**Figure 4. Comparison between elevation of cave wall notches (above resurgence level), and benthic $\delta^{18}O$ isotope record of Shackleton et al. (1990) from Ocean Drilling Program Site 677. Chronology is derived from paleomagnetic time scale and astronomical tuning. Single notches are also present at 168, 180, 200, and 242 m.**

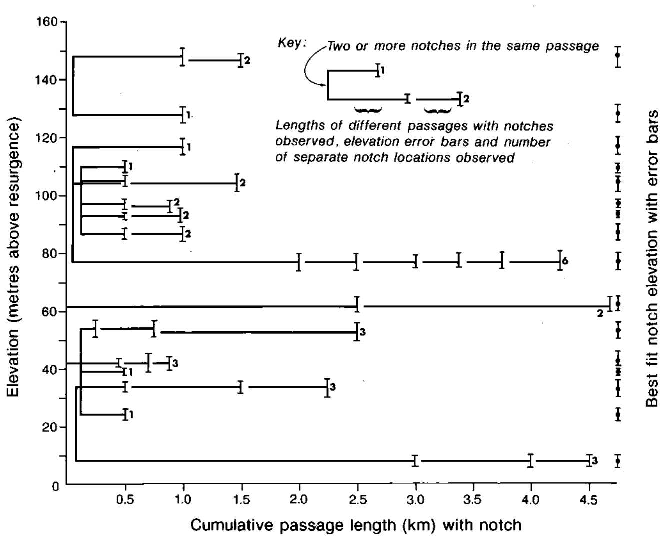


**Figure 3. Elevation of cave wall notches above present Clearwater resurgence, and length of passage in which they are observed.**

matrix ($\chi^2 = 10.87$, significant at the 99% confidence interval), demonstrates that the rate of base-level lowering has remained constant over at least the past 700 ka, and that aggradation is not a result of episodic uplift.

Between 700 ka and 1.3 m.y. (130–250 m), the match is not as good; four out of eight major peaks and six out of seven minor peaks are unmatched, and the statistical association is not significant ($\chi^2 = 0.149$). This poor correspondence may be because there are fewer known cave passages (<15% of the total known passage length); either additional notches remain to be discovered in unexplored passages, or they have been destroyed by surface lowering. Furthermore, at this time the 100 ka Milankovitch cycle becomes less pronounced, so it is possible that the more frequent interglacial periods may have been too short to permit the development of an alluvial fan extensive enough to affect the resurgence, before dissection during the ensuing glacial period. Notches are also imperfect recorders of aggradational events and do not form if gravel is not in transport, perhaps because of a boulder blockage at the input end of the cave system, or simply because the major allogenic rivers were routed elsewhere at the time.

## DISCUSSION

The Mulu cave sequence could be traditionally interpreted as a product of fluvial incision (exhumation; England and Molnar, 1990) into an elevated block subject to orogenic uplift during development of a fold-thrust belt associated with subduction of the South China Sea eastward beneath Sulawesi (Hutchinson, 1989). However, subduction terminated in mid-Miocene time, and it is inconceivable that terrain elevated at this time would persist to the present (an initial elevation of almost 4 km would be required), or that substantial isostatic adjustments would not have occurred. Furthermore, at the observed rate of base-level lowering, the Clearwater resurgence would be lowered to sea level within 150 ka, abruptly terminating the demonstrably continuous sequence of cave development. It is therefore clear that isostatic adjustments occurring in response to regional denudation dominate landform development.

The Baram is a major river (average discharge 1590 $m^3/s$) is well adjusted to present sea level, and downstream of Mulu the channel slope is very low (19.4 m over the 320 km channel length). Within the study area, active incision into the Setap Shale bedrock is occurring, and the river course has not been affected by postglacial aggradation. Despite the high rainfall, surface erosion rates on the limestone uplands of Gunung Api are very low because of limited soil cover and short residence times. Unpublished estimates (Smart et al.) based on weight loss of limestone pills and solute budgets give rates of 0.05–0.1 m/ka. A much higher figure (0.23 m/ka) is obtained for the surrounding Setap Shale from the sediment load of the Baram (Staub and Esterle, 1994), giving a calculated isostatically compensated regional uplift rate of 0.19 m/ka. Although possibly fortuitous given uncertainties in the data, this is identical to the rate of base-level lowering obtained from the caves, which are preserved in a less-eroded block elevated by this regionally determined epirogenic uplift. There is thus strong coupling between base-level lowering (incision), denudation, mass loss, and epirogenic uplift, as would be expected with a graded river system and dominance of isostacy. We conclude that our observed rate of base-level lowering rate is thus a measure of the rate of epirogenic uplift of rocks (England and Molnar, 1990).

Rapid erosion in northwest Borneo is matched by a high rates of sedimentation offshore in major slope basins fed by deltas such as that of the Baram. Here a considerable thickness of Tertiary sediments has accumulated (>7 km), and folding associated with gravity sliding and listric growth faults indicate substantial isostatic adjustment. The Baram delta developed to the south of the Luconia microcontinent is underlain by oceanic lithosphere (James, 1984), which probably extends inland to the Mulu area. Thus offshore loading may lead to additional uplift inland by flexural isostacy, as has recently been modeled for Atlantic passive margins (Pazzaglia and Gardiner, 1994). Our study has demonstrated that limestones caves that preserve morphological information and deposits suitable for dating provide an important source of data to constrain such numerical models of large-scale landform evolution.

## ACKNOWLEDGMENTS

Supported by Natural Environmental Research Council grant GT4/91/GS/04 (to Farrant), and the Winston Churchill Memorial Trust (Fellowship to Whitaker), the Malaysian Airline System, Ghar Parau, the Tratman Fund, and the Royal Geographical Society. Permission to work in the Gunung Mulu National Park was granted by the State Secretary for Sarawak. We also thank National Park Officers Oswald Brekan Tisen and Victor Luna Amer, the park staff and guides, and participants in the Mulu Caves '91 expedition. This paper benefited substantially from a constructive review by Tom Gardiner.

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Manuscript received July 11, 1994
Revised manuscript received December 16, 1994
Manuscript accepted January 12, 1995