8. THE SEDIMENTS OF LOCHNAGAR: DISTRIBUTION, ACCUMULATION AND COMPOSITION

NEIL L. ROSE (nrose@geog.ucl.ac.uk)
Environmental Change Research Centre
University College London
Pearson Building, Gower Street
London WC1E 6BT
United Kingdom

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Introduction

The c. 10000 year sediment record accumulated within the loch basin (Chapter 4: Hall this volume; Chapter 7: Birks this volume) has been central to much of the research undertaken at Lochnagar. The first major studies of the loch were palaeolimnological and assessed the acidification history of the site in relation to its contemporary water quality status (Chapter 14: Monteith et al this volume). This rapidly expanded into determining the sediment archived histories of long-term vegetation changes via the pollen record (Chapter 7: Birks this volume) as well as changes in the atmospheric deposition of trace metals (Chapter 15: Tipping et al. this volume), persistent organic pollutants (POPs) (Chapter 16: Muir et al. this volume) and fly-ash particles (Chapter 17: Rose and Yang this volume). These in turn have developed into monitoring programmes, the data from which form the basis for other chapters in this book. More recently the palaeolimnological focus has shifted to include the evidence for climatic change and its impacts (Dalton et al 2005; and below).

In the course of these studies information on the sediment itself has been gained in terms of its distribution (i.e., knowing the ‘best’ place to core in order to obtain appropriate records), its accumulation in various parts of the sediment basin (from ^{210}Pb-dating and other chronological markers) and its composition. The aim of this chapter is to provide this information as background for the other palaeolimnological studies described in this book as well as showing how temporal changes in the sediment matrix itself have been used to obtain useful information on environmental change within the loch and in its catchment.

N.L. Rose (ed.), Lochnagar: The Natural History of a Mountain Lake
Developments in Paleoenvironmental Research, 155–175.

Estimating the boundary of sediment accumulation

With the exception of the southeastern 'corner' of Lochnagar, the southern end of the loch, and stretches of the northeast and northwest shorelines, the littoral area is dominated by a boulder and stone substrate (Chapter 10: Flower et al. this volume). The substrate of the southeastern corner has a sandy nature being the result of coarse debris in-washed from the slopes of the Red Spout above (see Figure 6 in Chapter 4: Hall this volume), while the southern end continues the steep slope of the backwall (Chapter 2: Hughes this volume) and is composed of bed-rock below which rocks and gravels can be found. Along some parts of the northwestern and in particular the northeastern shores, the shoreline is affected by eroding peats.

Contiguous sediment accumulation within Lochnagar, estimated from both the UK Acid Waters Monitoring Network macrophyte surveys (Chapter 10: Flower et al., this volume) and attempts at coring along transects (Chapter 17: Rose and Yang this volume; Chapter 15: Tipping et al. this volume), therefore only starts beyond this rocky littoral area. This empirical estimate of the limit to sediment accumulation is shown in Figure 1a (pale yellow) although sediment deposits undoubtedly occur between the boulders and stones, especially in areas affected by the eroded catchment peats. This assessment of the boundary of sediment accumulation is, of course, only speculative and such estimates can lead to significant uncertainties in full basin sediment accumulation.

Evans and Rigler (1980a;b) discuss the distribution of sediments above and within apparently well-defined non-accumulating zones and suggest that the most likely situation is a rapidly decreasing sediment accumulation above this boundary rather than a sharp 'cut-off' or a gradual decrease from the accumulation zone to no accumulation at zero water depth. This would also be the most likely situation for Lochnagar were it not for the boulders within the littoral. Evans and Rigler (1980a) also suggest that the "depth above which no permanent sediments accumulate" can be defined by the bottom of the summer epilimnion. At Lochnagar, the mid-summer epilimnion occurs at about 6 – 8 m depth, well below the depth of permanent sediment accumulation (see below). Furthermore, the epilimnion in Lochnagar appears to get deeper as the summer progresses (see Figure 5 in Chapter 5: Thompson et al this volume for an example; Don Monteith UCL: unpublished data, for other years) and the loch is also well-mixed for 9 – 10 months of the year. Thus, this model does not work for Lochnagar. Hilton et al. (1986) suggest that there is negligible sediment accumulation on slopes greater than 14% (orange and red shading in Figure 3b in Chapter 2) and these slopes in Lochnagar account for 18% of the area of the loch basin mainly in the south and west. The distribution of shallow slopes within the basin agrees well with that of sediment accumulation in Lochnagar (see below).

Rowan et al. (1992) use estimates of wave energy as a means to define a mud deposition boundary depth ('Mud DBD') and show how this can be estimated from the fetch of a lake. They also show how this depth is altered by the effects of slope (Rowan et al. 1995 a; b). For Lochnagar, in the areas of least slope (< 4%) Rowan et al.'s mud DBD occurs at a depth of about 1 m while for slopes of 14% the mud DBD lies at c. 3m and for slopes approaching 30% (i.e., steepest parts of the loch basin in the south and west) the mud DBD is greater than the maximum depth of the loch implying no accumulation in these zones. Furthermore, Rowan et al. (1995a) show how the mud

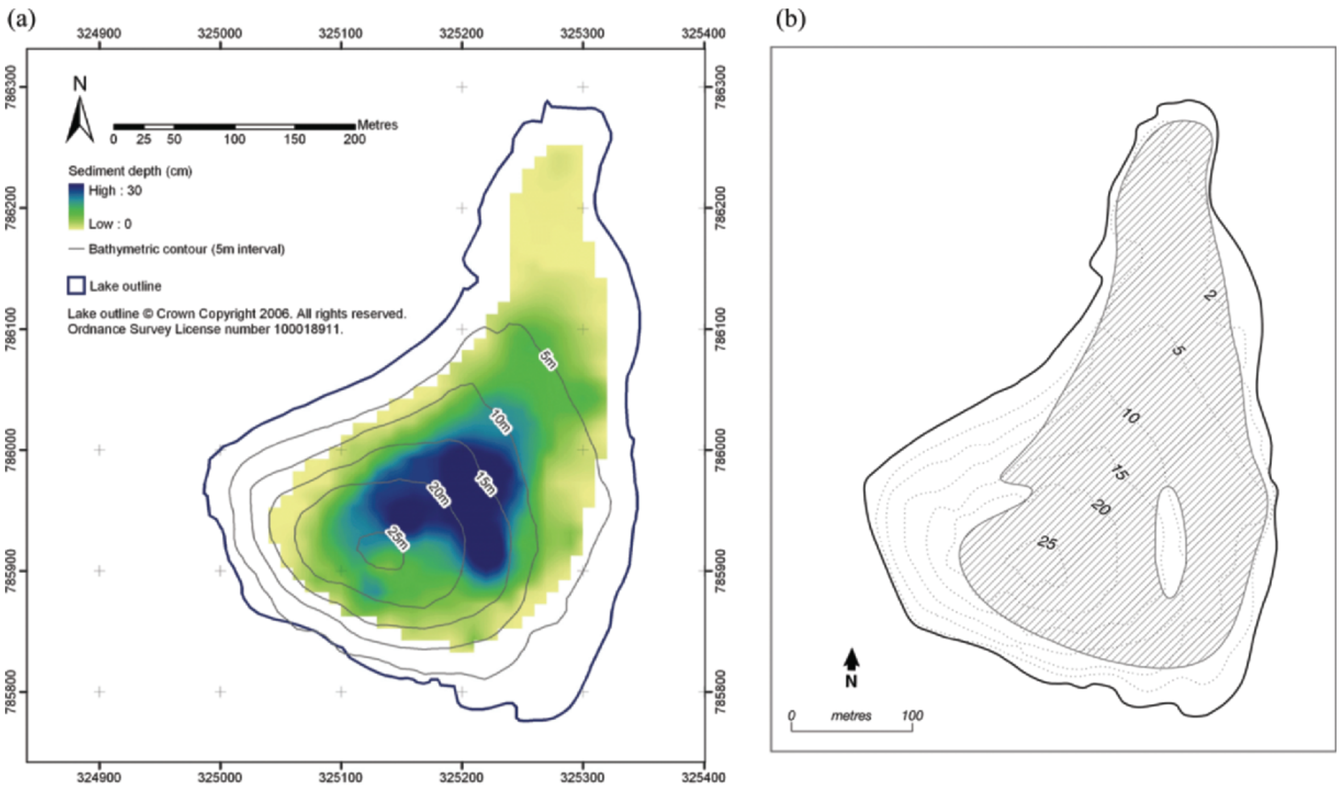

Figure 1. (a) Distribution of post-1850 sediment accumulation as determined by ^{210}Pb and spheroidal carbonaceous particle dated sediment cores. Pale yellow shading in littoral area denotes empirically estimated region of little or no sediment accumulation. (b) Region of sediment accumulation in Lochnagar estimated using the 'Mud DBD' approach of Rowan et al. (1992).

DBD at erosional sites impacted by the largest waves should be increased by a factor of 1.34. This increases the shallowest mud DBD estimate by only 20 cm, the 14% estimate by c. 1m (to 4 m) and makes little difference to the steepest slopes as they are already below the maximum depth of the loch. Plotting these areas onto a bathymetric map of Lochnagar shows the areas in which there should be accumulating sediment based on wave theory and slope. This is shown in Figure 1b and agrees reasonably well with the empirical estimate of this boundary. The implications of this mud DBD are that below these threshold depths (within the area of accumulation shown in Figure 1b) sediments do not become resuspended (Blais and Kalff 1993) and that any re-worked sediment from shallower areas is derived from above this threshold.

Sediment distribution and movement

A plot of the depth of sediment accumulated since 1850 (corrected for differences in date of coring to a uniform date of 2000) determined from radiometric and spheroidal carbonaceous particle (SCP) chronologies is presented in Figure 1a. It can be seen that, in agreement with other studies on sediment core variability (e.g., Anderson 1990a; b) there is considerable variation across the loch basin, but reasonable consistency in the central area of the basin. The greatest accumulation is in the centre of Lochnagar where c. 30 cm has accumulated in the 150 year period, but this area of maximum accumulation is not in the deepest part of the loch. In the deepest area (see bathymetry in Hughes: Chapter 2 this volume) sediment accumulation seems to be more heterogeneous, with some cores showing a moderate post-1850 depth of accumulation (e.g., NAG6 – 17cm; NAG8 – 16 cm; NAG23 – 17cm) while other cores show little (e.g., NAG3 – 8cm; NAG17 – 4cm) (see Figure 2 for core locations). Elsewhere in the basin, the depth of post-1850 sediment accumulation decreases from the central 'high' accumulation area outwards towards the estimated sediment limit suggesting considerable sediment focussing is taking place within the loch. Sediment accumulation in Lochnagar cannot therefore be simply explained by water depth alone as found in other studies (Evans and Rigler 1980a; b) in agreement with the work of Rowan et al (1995b).

A great many factors have been cited as being the cause of, or at least influential in, sediment accumulation patterns. Lehman (1975) states that the lake morphology is the critical criterion especially with respect to the changing nature of accumulation patterns as the lake in-fills, Håkanson (1977) suggests a large number of influencing factors including frequency, velocity and duration of winds, fluctuations in water level, water circulation, fetch, water depth, lake bottom roughness and sedimentological factors such as compaction and, of course, rate and source of input. Håkanson (1977) also states that water content of the surficial sediments provides an indication as to the dynamic process dominating in that part of the lake, thus for sediment with a water content of < 50%, 50 – 75% and > 75%, the dominant processes are erosion, transportation and accumulation respectively. Rowan et al (1995b) suggest that 60% water content is the critical threshold for erosional and depositional zones.

Applying Håkanson's water content thresholds to Lochnagar sediments suggests that the only non-accumulating area is in the southwest of the loch (Figure 3a) and that the majority of the loch basin is an accumulation zone. However, Håkanson goes on to state that for slopes within accumulation zones transport also occurs where the slope is greater than a value generated by:

$$W_{0-1} = -8.55s + 114.7 \qquad (1)$$

where W_{0-1} is the water content of the surface sediment and 's' is the slope. Thus for Lochnagar where a typical water content across the accumulating area is 87%, slopes >3.2 % correspond to transportation zones. As 79% of the Lochnagar sediment basin has a slope >3.2% this would imply significant transport within the accumulation area which may explain the level of focussing observed from the post-1850 sediment accumulation data (Figure 1a). In contradiction to this, Blais and Kalff (1995) suggest that sediment water content does not denote the boundary of the transportation zone and that this is better defined by using the mean slope of the lake basin. They suggest that this is the "single best determinand" for this definition as the slope is not only critical to the water turbulence which moves sediment downslope but also, in steeper areas, to

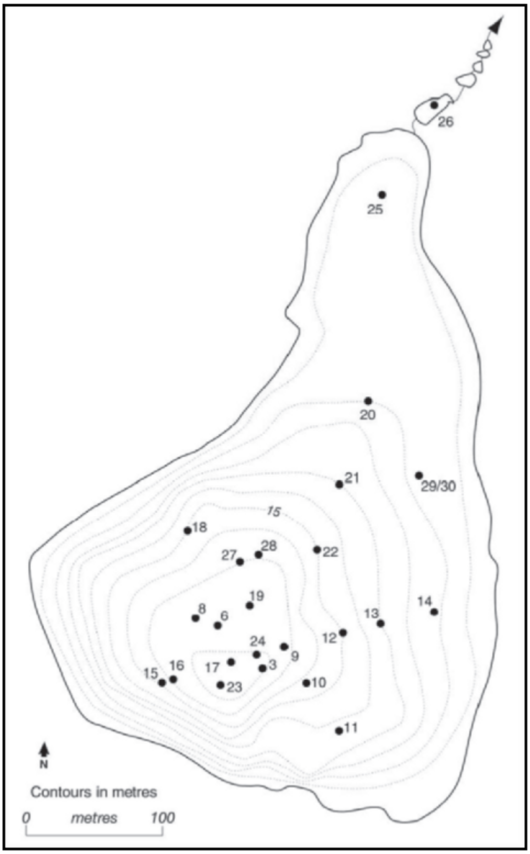

Figure 2. Sediment coring locations. (i.e., 9 denotes the location of core NAG9 etc.)

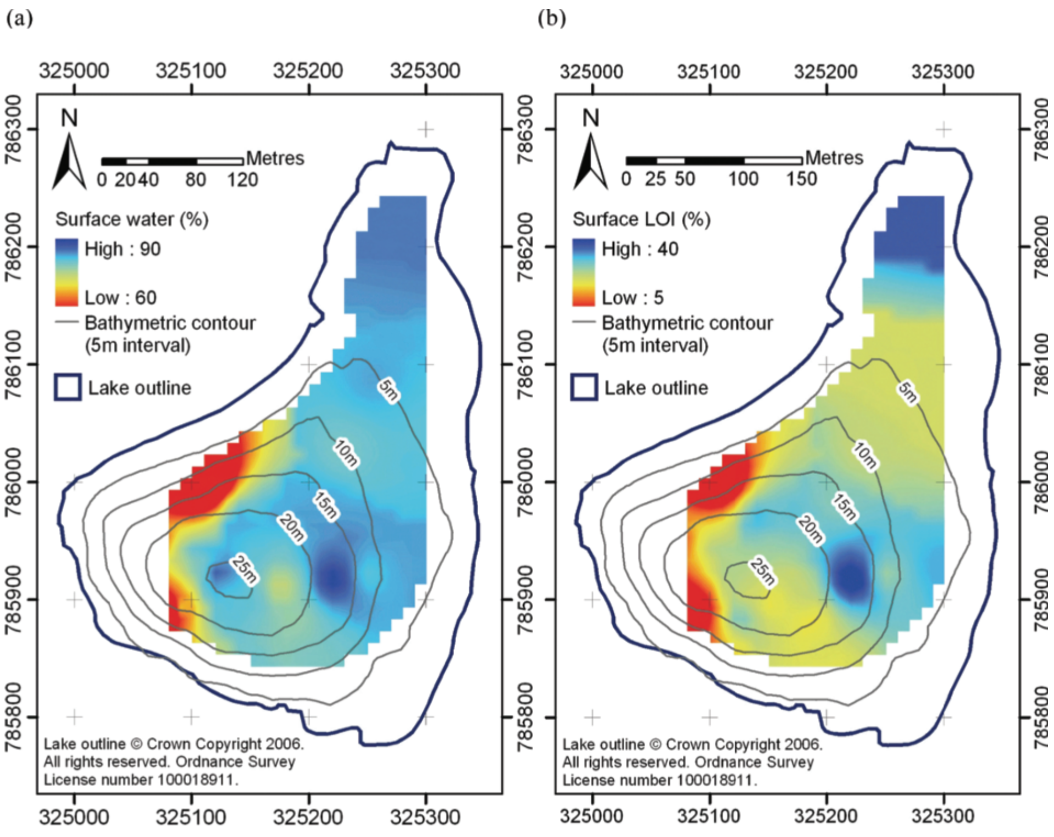

Figure 3. (a) Water content and (b) organic matter content (as estimated by loss-on-ignition at 550 ºC) for Lochnagar surface sediments.

sediment slumping. Focusing is therefore a function of lake form. The percentage of the basin in the accumulation zone (%ZA) using this approach is defined as:

$$\%ZA = 49.92(\pm 3.73) - (2.5\ (\pm 0.31)\acute{\alpha}_p) \tag{2}$$

where $\acute{\alpha}_p$ is the mean basin slope (Blais and Kalff 1995). For Lochnagar, the mean basin slope is 8.4% (range 0 - 28.45%, SD 5.97%; Chapter 2: Hughes this volume) and hence, using Equation 2, 22.6 – 35.2% of the loch basin is in the accumulation zone.

An alternative approach to estimating these dynamic process areas is proposed in Shteinman and Parparov (1997) where the percentage of the lake bed subject to erosion and transportation (a_{E+T}) (i.e., with a high probability of resuspension) and the area of sediment accumulation (a_A) are given by:

$$a_{E+T} = 100 - a_A = 25*(DR)*41^{0.061/(DR)} \tag{3}$$

where DR, the dynamic ratio = $\sqrt{(a/D)}$; a is the lake surface area in km^2 and D is the average depth of the lake in metres. Substituting values of ‘a’ and ‘D’ for Lochnagar into Equation 3 results in the estimate that 22% of the loch basin is subject to erosion and transportation and therefore 78% is accumulating (a_A).

Estimates of the area of the Lochnagar basin that form the sediment accumulation area therefore vary considerably from 30% using the Blais and Kalff (1995) approach to 87% employing that of Håkanson (1977). In reality it is likely that the accumulation area lies between these two extreme estimates and the approaches of Shteinman and Parparov (1997), Rowan et al (1992) and an estimate based on empirical evidence provide values of 78%, 62% and 60% respectively. Without more detailed surveying it is not possible to determine which of these is the more accurate.

In terms of the uneven distribution of sediments within any defined accumulating zone, Hilton et al. (1986) suggest ten distribution mechanisms that could result in sediment focussing. Of these, ‘riverine delta formation’ and ‘river plume sedimentation’ are obviously not applicable at Lochnagar due to the lack of major inflows. ‘Continuous complete mixing’, where sedimenting material is continuously mixed over the entire volume of the lake, can also be discounted as this results in shallow and deep water sediment traps recording similar fluxes and this is not the case here (see Figure 4). Similarly, ‘organic degradation’, where deep water traps record lower fluxes than shallow traps due to organic decomposition in the water column, is also discounted by these data and further, is usually only applicable to sites with high algal productivity. Neither ‘intermittent complete mixing’ whereby sediment is resuspended from all over the lake-bed and completely mixed such that sediment accumulation is proportional to depth, nor ‘intermittent epilimnetic complete mixing’, where sediment cores below the epilimnion show constant accumulation rate, explain the sediment distribution in Lochnagar as the deepest areas show both variable accumulation and accumulation rates lower than other, shallower areas of the loch.

Of Hilton et al.’s four remaining distribution mechanisms, ‘peripheral wave attack’ would seem to be a likely means by which sediment deposited amongst the boulders and stones in the littoral area could be resuspended and moved to deeper water. However, it is suggested that if this is the dominant process then sediment accumulation rates should increase linearly with water depth and that the regression line of this linear

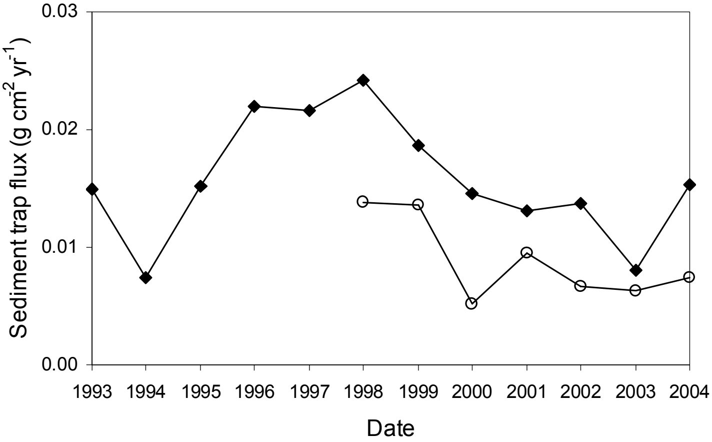

Figure 4. Annual dry matter fluxes for deepwater (filled symbols) and shallow water (open symbols) sediment traps in Lochnagar 1993 – 2004.

relationship intercepts the depth axis at the depth where the areas of transport and accumulation meet. Such a linear relationship does not exist at Lochnagar, where a plot of accumulation versus depth is far more random (Figure 5) and thus more indicative of 'random redistribution'. However, 'random redistribution' also leads to sediment accumulation in traps being far higher than cores (Hilton et al. 1986) which is clearly not the case at Lochnagar (compare data in Figure 4 with Figure 6).

Movement down-slope is also undoubtedly a factor in the redistribution of sediments in Lochnagar especially in the steeper southern and western parts of the loch. Hilton et al. (1986) suggest that there should be negligible accumulation on slopes greater than 14% (also Blais and Kalff 1995) whilst for slopes between 4% and 14% accumulation is reduced with respect to accumulation on more horizontal areas. For Lochnagar this means that 18% of the loch basin area should not accumulate sediment. Conversely, 82% of the basin has a slope of < 14% and should accumulate sediment to a greater or lesser degree, with 29% of the basin area having a slope of less than 4% and 53% having a slope of 4 – 14%. From this it would be expected that the flattest 29% of the basin would be the area in which the greatest accumulation occurs, but this is not the case and the area of maximum post-1850 accumulation (Figure 1a) lies predominantly within the 4 – 14% slope region.

Even in areas of lake basins unaffected by any of the sediment redistribution mechanisms discussed above, and it is debateable whether there are any areas of the Lochnagar basin where this is the case, significant spatial heterogeneity is known to occur, even at quite small spatial scales. Downing and Rath (1988) state that sediments can exhibit this spatial heterogeneity in ways unrelated to focussing or other large-scale redistribution processes. Therefore, it should be expected that spatial patchiness will occur in the sediment record of Lochnagar and data from multiple cores used for interpretation wherever possible. A number of processes leading to this heterogeneity are proposed by Downing and Rath (1988). These include: accumulation in the shadow

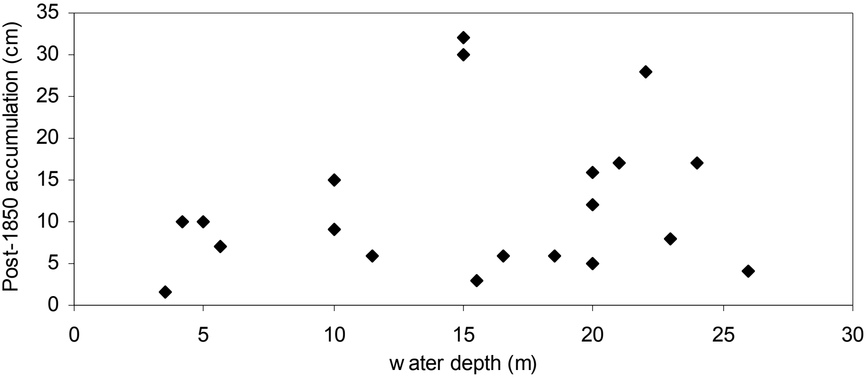

Figure 5. Depth of post-1850 sediment accumulation versus water depth for all sediment cores taken from Lochnagar.

of macrophytes and outcrops; local temperature differences resulting from groundwater leading to differential decomposition of organic matter; patchily distributed benthic invertebrates accumulating material around them; redistribution by slow, deep currents; small scale variations in the bottom profile and ice-rafting of debris to deepwater areas. Of these, the latter two would seem to be of most relevance to Lochnagar. Rockfalls from the back-wall could easily have produced variations in the bottom profile and may explain the irregularity of the sediment record in the deepest area. Ice-rafting is also known to occur and debris falling from the backwall could be transported to any point in the loch by this route. However, dominant wind directions (Chapter 5: Thompson et al. this volume) are such that the last remaining ice tends to move towards the back-wall and hence most debris is likely to remain in this area of the basin.

In summary, it seems likely that no single dominant process explains the distribution of sediment and focussing within Lochnagar. The movement of sediment from littoral areas to deeper waters by wave resuspension, movement downslope and ice-rafting are all potential and likely factors. Rock-falls in the past may have influenced the bottom topography and could explain the heterogeneous sediment record in the deepest areas. However, none of these processes explain why the main area of accumulation is not in the deepest water, but in an area central to the loch.

One hypothesis for this distribution is that suspended sediment is moved towards the back-wall in surface waters driven by prevailing wind directions (Chapter 5: Thompson et al. this volume). The return flow from this movement must be either around the edges of the loch or below the surface. The steep back-wall is the most shaded area of the catchment and has snow patches lingering until June (and much longer in the past). The cooling of the surface water in this shaded area and input of cold meltwater from the catchment could therefore cause waters in this area to descend, making the return flow via deeper waters. Suspended sediment could then be deposited as the water moves back slowly at depth and this could result in sediment deposition in the central area. This process is described in Hilton et al (1986) as ‘current redeposition’ and is thought to occur where cooling surface waters move down adjacent steep slopes eroding sediment on those slopes and redepositing them in central areas. This would seem to fit the situation for Lochnagar, where the northern end of the loch is both the coolest, as a result of shading and meltwater inputs, and also the steepest (Figure 3b in Chapter 2).

Scale of sediment focussing in Lochnagar

Sediment focussing describes the non-uniform distribution of the sediment over the lake bed due to erosional processes in some parts of the lake (see above) transporting material and preferentially depositing it in other areas. In Lochnagar, the main area of focussing appears to be the central, rather than the deepest, part of the basin. The scale of this process can be estimated using ^{210}Pb data (Peter Appleby, University of Liverpool pers. commun.).

If the total input to the loch is Q Bq m^{-2}, and the inventory at a particular point is A Bq m^{-2} then the focussing factor (f) would be defined as:

$$f = A/Q \tag{4}$$

The term A can be determined by measurements on a sediment core from that location while Q will be the sum of direct deposition from the atmosphere onto the surface of the loch itself plus erosional inputs from the catchment. Using the data from three dated sediment cores (NAG3, 6 and 8) taken from the deep area of the loch (Figure 2) and assuming that these cores are equally representative of this deep area, then Q is the mean of the inventories for these cores:

$$Q = (6823 + 9144 + 7422)/3 = 7796 \text{ Bq m}^{-2} \tag{5}$$

The focussing factors for each core would then be 6923/7796 = 0.88, 9144/7796 = 1.17, 7422/7796 = 0.95 respectively. However, as these cores are all from the deeper parts of the loch they will overestimate the value of Q, and the focussing factors will all be larger than these. If erosional inputs from the catchment are negligible then:

$$Q = 113/0.03114 = 3628 \text{ Bq m}^{-2} \tag{6}$$

where 113 Bq m^{-2} is an estimate of the direct fallout of ^{210}Pb at Lochnagar from soil core (106 Bq m^{-2} yr^{-1}) and rainfall (120 Bq m^{-2} yr^{-1}) measurements. The focussing factors for the three cores would then be 1.88, 2.52, and 2.05, with a mean value of 2.15. Although the three cores are from deep area of the loch it is probably mis-leading to assume that the influence of the catchment is zero at these points. The focussing factor for the deep area of the loch is therefore likely to be slightly below this latter estimate, in the region of 2.0.

Sediment accumulation rates

Four sediment cores taken from the deep area of Lochnagar (NAG3 – 1986; NAG6 – 1991; NAG8 – 1996; NAG23 - 1998) (See Figure 2 for locations) have been radiometrically dated. Although the records contained within these cores show good agreement with respect to ecological changes and the record in atmospherically deposited contaminants (e.g. Chapter 15: Tipping et al. this volume; Chapter 16: Rose and Yang this volume) the post-1850 sediment accumulation is found to vary considerably (see above). This is in agreement with multi-core studies from other lakes (e.g., Anderson 1989; 1990a; Rose et al 1999). The cores from Lochnagar reflect this variability both in total accumulation since 1850 (8cm, 16cm, 15cm and 17 cm respectively) and in temporal variability in accumulation rates over this period.

Earliest sediment accumulation rates in NAG3, 6 and 23 show reasonable agreement and range between 0.0068 and 0.012 g cm^{-2} yr^{-1} (Figure 6) whilst early sediment accumulation rates in NAG8 vary considerably from rates at the same sort of magnitude as these other cores (0.05 – 0.08 g cm^{-2} yr^{-1} for 1868 ± 30 to 1887 ± 25) to a period of much higher sediment accumulation between 1890 ± 23 and 1908 ± 13 of 0.11 – 0.17 g cm^{-2} yr^{-1}. This period of rapid sedimentation coincides with an increase in sediment density and therefore could be due to slumping of catchment derived inorganic material (Peter Appleby, University of Liverpool pers. commun.). An earlier and less distinct episode of a similar nature may have occurred in the mid-19th century and may explain the elevated accumulation rates at the very base of the core (Figure 6). The accumulation rate of NAG8 between these events is similar to that of the other cores at this time suggesting, that under normal conditions, there is a reasonable agreement in sediment accumulation rate in this part of the loch. However, it also highlights the vulnerability of this deep area to these events. Analysis of mineral magnetism of the NAG8 core provides supporting evidence for this interpretation of the sediment accumulation data. The upper part of the core shows a signal typical of increasing atmospheric pollution since the 1890s and the suggestion of a recovery in the few surface samples. However, prior to this late-19th century increase the magnetic record suggests an episode of erosion that transported haematite-rich minerals to the sediment (John Dearing, University of Liverpool pers. commun.). Such an event agrees with the input of catchment derived inorganic material at this time indicated by the sediment accumulation rate data.

Variability in sediment accumulation rate also occurs between the temporal records of these cores. In NAG3 and NAG8 accumulation rate increases to the surface of the core, with maxima at the surface of 0.026 and 0.041 g cm^{-2} yr^{-1} respectively (0.16 and 0.15 cm yr^{-1}) corresponding to an increase by a factor 2 and 3.8 over the uppermost 150 years (Figure 6). Alternatively, NAG6 shows an increase in accumulation rate from 0.0095 g cm^{-2} yr^{-1} (0.098 cm yr^{-1}) before 1930 to over 0.025 g cm^{-2} yr^{-1} (0.22 cm yr^{-1}) in the mid-1980s before declining again to lower values at the surface of 0.02 g cm^{-2} yr^{-1} (0.18 cm yr^{-1}). NAG23 differs again by showing no particular trend (Figure 6) but varying between 0.01 and 0.015 g cm^{-2} yr^{-1} throughout.

Over the longer time-scale Dalton et al. (2001; 2005) reported ^{14}C AMS dates for the centrally located core NAG27 taken from 20.6 m and NAG30 taken from 4.2 m nearer the eastern shore (Figure 2). Although the dating interval is rather coarse, the depth / date profile for NAG27 (Figure 7) appears to be remarkably consistent over the 5000 years between the oldest and most recent ^{14}C dates, with accumulation rates estimated to range between 0.026 and 0.054 cm yr^{-1} throughout. The depth / date profile for NAG30 covers an older time period (5100 – 8400 BP) and shows even slower accumulation rates of 0.007 – 0.033 cm yr^{-1} (Dalton et al. 2005). These data are thus in agreement with the spatial distribution shown in Figure 1a where slower accumulation rates are observed closer to the limits of the accumulating zone within Lochnagar, but

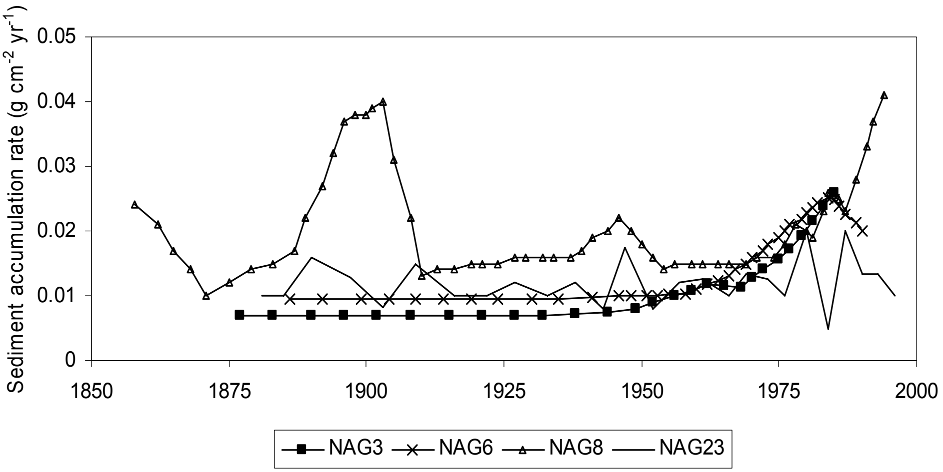

Figure 6. Sediment accumulation rates for sediment cores NAG3, 6, 8 and 23 determined by radiometric dating.

they also show sediment accumulation rates up to an order of magnitude slower than those observed at the bases of the four ^{210}Pb-dated cores.

Earlier ^{14}C dates in NAG27 show reasonable agreement with expected pollen changes (e.g., elm decline c. 5900 years BP; Dalton et al. 2005) while dating of the uppermost section of NAG27 using spheroidal carbonaceous particles (Rose unpublished data) shows that the mid-19th century is at c.20 cm depth, in good agreement with the post-1850 sediment accumulation from other cores in this area of the loch (Figure 1a). Therefore the lowest presence of SCPs (20cm) is very close to the uppermost ^{14}C date (29.6 – 30cm; 1094 – 1302 years BP). If all these data are correct, and there is no hiatus in sediment accumulation, then there is a dramatic increase in sediment accumulation at this depth although there is no other reported sediment data to suggest this has occurred in these (i.e., Dalton et al. 2001; 2005) or any other core from Lochnagar. Combining these dating approaches suggests that sediment accumulation rates in Lochnagar have increased in at least two phases. First, an increase over the estimated basal rate 5 – 6000 years BP and second, a further doubling of accumulation rate over the last 150 – 200 years.

The influence of climate change on future sediment accumulation rates

Anecdotal and modelled evidence indicate that Lochnagar now has a shorter and more ephemeral period of winter ice cover than it did in the past (Chapter 5: Thompson et al. this volume) and future climate predictions for the site suggest that the loch could be completely ice-free by the end of the 21st century (Chapter 18: Kettle and Thompson this volume). The loch water is therefore predicted to increase in temperature and this will result in a potentially longer growing season for algae and aquatic macrophytes.

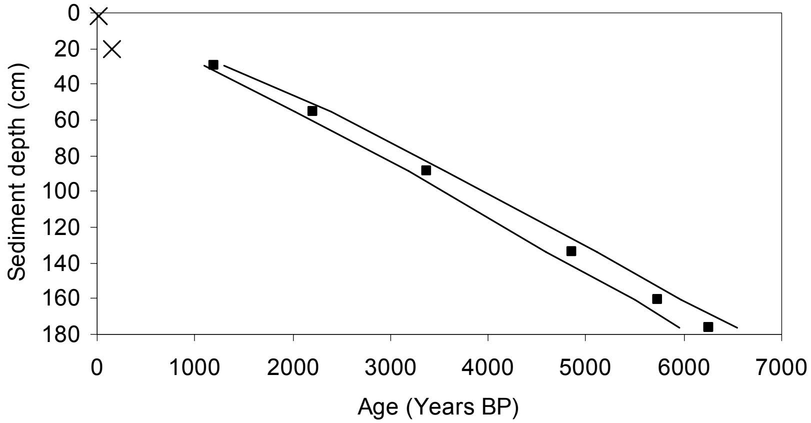

Figure 7. ^{14}C AMS (filled symbols) and SCP (×) dates determined for the core NAG27. Errors for ^{14}C dates are shown by the lines. (Errors for SCP dates are too small to be shown on this scale, but are ± 25 years for the lower date and ± 5 years for the upper date.)

Further, warmer temperatures would elevate the rate of mineralisation of organic matter in catchment soils releasing both carbon and nitrogen. While the lengthened growing season would increase biological demand and the elevated nitrogen may lead to phosphorus limitation in the loch, increased soil temperatures could enhance soil microbial activity leading to higher phosphorus as well as nitrogen loading from catchment soils. Particulate phosphorus input may also be elevated from increased erosion of catchment soils while recovery from acidification may reduce aluminium complexation of phosphorus (Kopáček et al. 2001) thereby also making it more biologically available. In short, the effects of climate could elevate both nitrogen and phosphorus inputs to the loch as water temperatures increase resulting in more productivity, reduced light penetration and greater autochthonous inputs to the sediment Chapter 19: Rose and Battarbee this volume).

Predicted changes in climate also include increased summer drought and higher winter rainfall and these could elevate catchment peat erosion which is already quite severe in some areas of the Lochnagar catchment (Chapter 6: Helliwell et al. this volume). This would also increase the amount of allochthonous material reaching the sediment record.

An increase in both autochthonous and allochthonous inputs to the sediment will increase the sediment accumulation rate at Lochnagar. The sediment accumulation rate at Lochnagar is known to have doubled in the last 200 years and these climate induced increases in sediment accumulation rate will increase this further to an unknown extent. As the lake infills, there will be changes in sediment distribution as the mean basin slope decreases and the sediment accumulation zone widens (Blais and Kallf 1995). If sediment deposition in shallow waters exceeds that which can be transported downslope by the available energy of the basin then sediments will accumulate in shallower areas and be permanently deposited in littoral areas (Engstrom and Swain 1986). Sediment resuspension will increase, affecting the light regime and influence the habitats and growth patterns of aquatic plants in the loch and the fauna dependent upon them.

Sediment description

Except in the southwestern area of the loch, where the sediments can be paler and coarse as a result of in-wash from the backwall, the sediment of Lochnagar is largely homogeneous in texture and colour. A description of the 1986 core, NAG3, describes the uppermost 50 cm of sediment as dark brown (Munsell Colour 10YR/2/2) and fine-grained (Patrick et al. 1989). Between 50 – 60 cm the sediment became greyish-brown and more sandy (Munsell Colour 10YR/5/2) becoming darker again lower down (Munsell Colour 10YR/3/3). Gritty, and slightly lighter coloured layers were observed at 9 – 13 cm and 29 – 30 cm and a gritty fibrous layer at 40 – 43cm. It was suggested that these changes were due to major fluxes of terrestrially-derived debris and terrestrial plant remains as a result of accelerated phases of catchment erosion (Patrick et al. 1989).

Sediment composition and sources

The sediment of Lochnagar shows considerable variation in the composition of its major fractions. The percentage water content of recent sediments varies from more than 80% (and frequently up to 90%) over the majority of the area of accumulating sediment to less than 60% in the southwest of the loch in the area dominated by coarse inputs from the back-wall (Figure 3a). Similarly, organic matter content (estimated by loss-on-ignition (LOI) at 550 °C) ranges between 20 – 30% over the majority of the basin, falling to less than 10% in the southwest corner but also with occasional areas of elevated organic content (35 - 40%) in central and northern areas (Figure 3b). These higher values are almost certainly due to the in-wash of eroded peat material from the northwest and, in particular, the northeastern shores. This hypothesis is supported by the organic content of the sediment from the outflow pool which reaches almost 80% due to the eroding peat almost entirely surrounding the area.

The water and organic matter content also vary considerably through time at sites within the loch. Figure 8 shows the temporal trends in percentage dry weight (Figure 8a) and LOI (Figure 8b) for cores NAG27 and 28 taken from the central area of the loch and, from ^{14}C dating, estimated to cover c. 6000 years (Dalton et al. 2005). The cores, taken close together, show remarkable temporal agreement in trends over their full length. Dry weights are typically 10 – 20% but there are three prominent departures from this to higher values. These occur at 155 – 170 cm, 125 – 140cm and 70 – 100cm in NAG27 dated to 5500 – 6000 BP, 4500 – 5000 BP and 2500 – 3500 BP respectively. The latter feature comprises three very distinct dry weight peaks within it, the largest reaching almost 60%. All these features are replicated in NAG28. The LOI profiles similarly show very good replication between the cores and considerable variability through time. In the lower 100 cm of the cores (80 – 180 cm in NAG27 – Figure 8b) there appears to be a cyclicity to the data with LOI peaks of c. 30% occurring at 175cm, 145 – 155 cm and 105 – 115 cm (dated to 6200 BP, 5000 – 5500

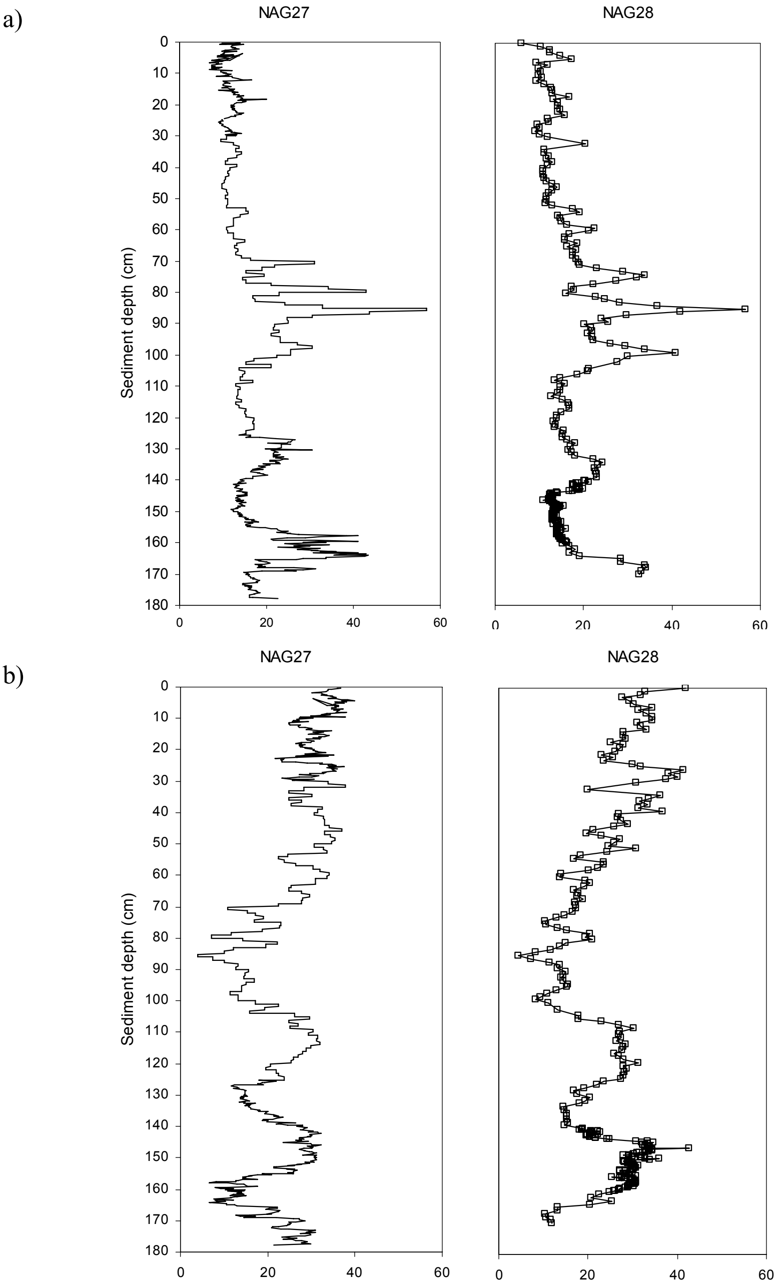

Figure 8. (a) Dry weight and (b) loss-on-ignition (at 550 ºC) profiles for the two long cores NAG27 and NAG28, showing the LOI cycles in the early part of the records. Data from Dalton et al. (2001).

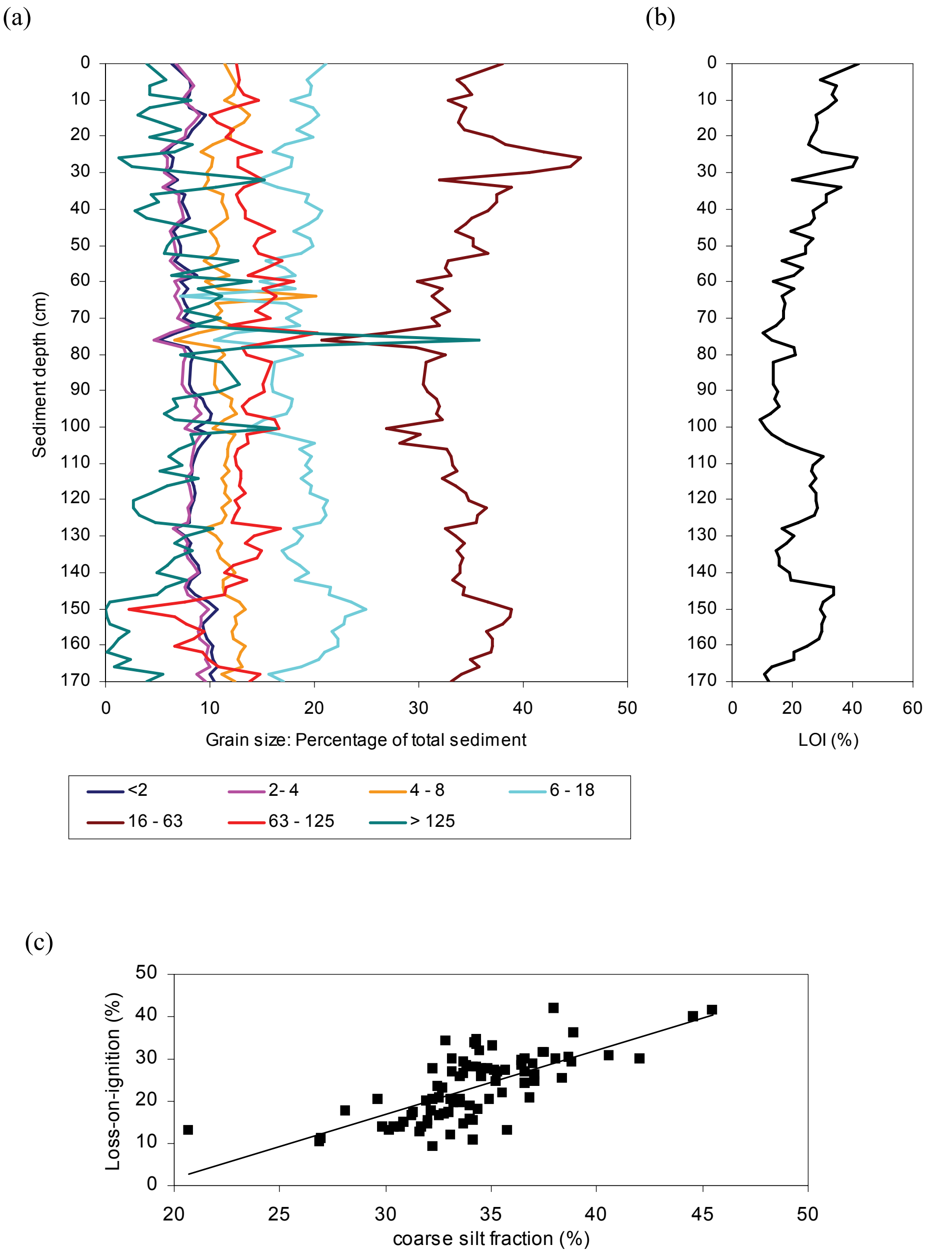

Figure 9. Particle size data for NAG28 as percentage of the total sediment showing the dominance of the coarse silt fraction; (b) the profile of organic matter content as estimated by loss-on-ignition; and (c) the relationship between loss-on-ignition (at 550ºC) and the coarse silt fraction ($R^2 = 0.486$).

BP and 3750 – 4250 BP respectively; Dalton et al. 2005) and LOI ‘troughs’ of 10 – 15% in-between. Above 80cm, however, this cyclicity breaks down as LOI values increase to c. 30% at 60cm depth and remain at 25 – 35% for the remainder of the more recent period. This early cyclicity is intriguing as it covers c. 3000 years and Dalton et al. (2001; 2005) used a range of sediment proxies to determine that the cause was predominantly driven by catchment-derived sources. Their evidence is briefly outlined below.

C:N ratios

Carbon: nitrogen ratios vary between 12 – 20 and average around 15. These levels are consistent with those of higher plants, but not algae. Autochthonous organic matter generally has lower C:N of below 10. A change to higher C:N (c. 20) is observed at about 20cm in NAG28 (Dalton et al. 2001) which is dated to c. 1000 years BP using the Dalton et al. ^{14}C chronology, but possibly only occurs 150 – 200 years BP if the SCP dating for NAG27 is used and cross-correlated to NAG28. If the SCP dating is used, then the change in C:N could be due to post-Little Ice Age peat erosion from the catchment (Rick Battarbee, University College London pers. commun.).

Lipid analysis

The lipid fraction, in particular the n-alkanes and n-alkanoic acids indicate a dominantly terrestrial input. Total n-alkanes show two major periods of elevated concentration in NAG28, at 100 – 120cm and above 20 cm (4000 – 5000 yrs BP and after 500 years BP respectively (using Dalton et al. (2005) ^{14}C chronology). It is suggested that these reflect periods of peat in-wash from the catchment. The more recent n-alkane concentration increase is coincident with the step-change in C:N ratio and therefore using the SCP chronology, could also support the idea of a post-Little Ice Age enhancement in peat erosion. The alcohol and sterol fractions are dominated by dinostanol (4α,23,24-trimethyl-5α-cholestan-3β-ol) (Dalton et al 2005) an unambiguous marker of dinoflagellate derived organic matter. The concentration of chlorins, an early diagenetic product of chlorophyll, can be used as a proxy for lake productivity and shows a peak at 40 – 60cm depth in NAG28. The ^{14}C dates would put this peak at 3 - 4000 years BP.

Particle size analysis

Particle size data covering c. 6000 years from the ^{14}C dated NAG28 core (Dalton et al. 2005) are shown in Figure 9. The dominant fraction of Lochnagar sediment throughout this period is coarse silt-sized particles (16 – 63 µm), with minor fractions of clay and sand (Figure 9a and 10a). The coarse-silt fraction includes a high component of diatom frustules and is positively correlated with LOI (Figure 9b, 9c and 10b) indicating that biogenic sources are a major component. Percentage dry weight is positively correlated to the sand fraction and both sand and clay fractions seem to be catchment derived, the clays from erosion and the sands from coarse inputs probably via winter snow falls from the corrie backwall and ice-rafting. The balance between catchment inputs and lake productivity therefore probably drive the fluctuations in dry weight and LOI as

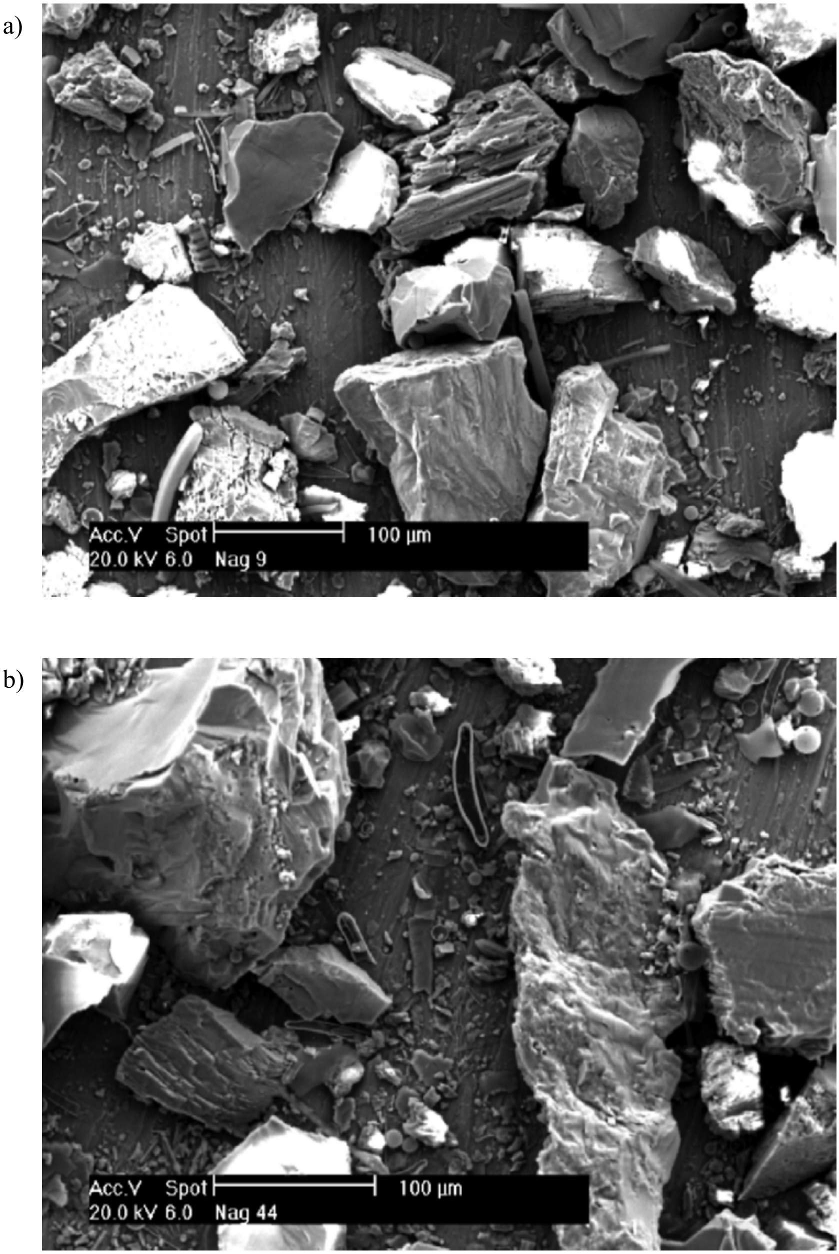

Figure 10. Scanning electron micrographs of sediment samples from (a) 16.2 – 16.4 cm and (b) 88 – 88.2 cm from NAG28. The latter is taken from a dry weight peak (see Figure 8a).

well as temporal changes in particle size spectra. These particle fractions lead to multi-peaked spectra and there is considerable variability through time from a mean particle size of c. 35 µm to 110 µm in more sandy layers (Dalton et al. 2005) for example at 74 – 76 cm (c. 3000 years BP from ^{14}C dates).

Summary

- There is considerable variability both spatially and temporally in sediment composition and distribution within Lochnagar. While there is a great deal of evidence for the catchment being a major source of sediment, the composition is driven by the balance between mineral inputs from the back-wall, phases of peat erosion and lake productivity (evidenced by the dominance of diatom frustules in the coarse silt fraction).
- Distribution of sediment within the loch is focussed on the central area of the basin, rather than the deepest point, and accumulation decreases away from this area to the limit of sediment accumulation at the base of the steep slopes or beyond the rocky littoral (although sediment temporarily settles between the boulders).
- While the reasons for this distribution pattern remain uncertain, movement of sediment towards the centre of the loch is likely to be a combination of resuspension of littoral sediment by wave action, slumping and sliding of material on steep slopes, ice rafting of snow-fall material, and water movements within the loch affected by cold melt-water input from the back-wall.
- Rates of sediment accumulation in this central area also appear to have increased both over a millennial time-scale and by a factor of 2-4 within the last 200 years. Given the composition of the sediment it seems likely that this recent increase is due to increasing catchment inputs and / or lake productivity.
- Catchment inputs are probably derived from increased peat erosion while elevated lake productivity could be due to warmer waters and a longer algal growing season.
- Future climate scenarios for Lochnagar over the 21st century (Chapter 18: Kettle and Thompson this volume) predict that the criteria for further exacerbation of both these processes will continue and hence it would appear that sediment accumulation rates at Lochnagar will also continue to accelerate over this period.

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