Post-glacial temporal variability of sediment accumulation in a small alpine lake

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Abstract The sediment record contained within a lake provides an opportunity to determine the magnitude and temporal variability of sediment output from a drainage basin. This study uses the lacustrine sediment record in a small alpine lake in British Columbia to establish the temporal variability of sediment yield for three time periods over the full Holocene Epoch. Core correlation and chronology were established by the presence of two distinct tephra layers, dated at *c.* 2350 years BP and *c.* 6800 years BP, and by radiocarbon dating of material overlying a glacial till. The estimated sediment yields are very low (<5 kg km^{-2} year^{-1}), and exhibit noticeable temporal variability. In general, yields increase towards the present day. In this small pristine drainage basin, temporal variations in sediment yield appear to be related to palaeoenvironmental changes over the post-glacial period.

INTRODUCTION

According to Ryder (1981), the landscape of the southern Coast Mountains of British Columbia embodies elements of three distinct temporal and spatial scales. Firstly, at the regional level, the mountains, major structural lineaments, fragments of erosion surfaces and associated summit levels are the most extensive features. These are the product of tectonic processes and subaerial denudation that have operated over and since the Tertiary period. They provide the framework upon which more localized landforms have subsequently developed. Secondly, during the Pleistocene Epoch, valleys and mountain ridges were modified by glacial processes. The morphology of the resultant landforms exhibit some regional variability, with distinct features relating to the aggregate effect of glaciations throughout the Quaternary period. Thirdly, over the Holocene Epoch, only minor modification of valleys has occurred and the landforms which have resulted are entirely local in origin. However, immediately following the last deglaciation there was a period of intense geomorphic activity; termed the paraglacial period by Church & Ryder (1972). During this phase, erosional and depositional processes were controlled primarily by the susceptibility of glacial drift to redistribution under non-glacial conditions.

Despite the statements made above, several workers (cf. Fulton, 1989) have demonstrated considerable variation in geomorphic process rates over the post-glacial period in British Columbia. In relatively undisturbed drainage basins, the major controlling factors appear to be related to climate change over the Holocene Epoch (cf. Reasoner & Healy, 1986). Furthermore, some recent studies in the UK (e.g. Brooks *et al.*, 1993) have demonstrated that variations in both soil conditions and climate can produce a changing sensitivity of slopes to failure during the Holocene Epoch. In pristine alpine environments in British Columbia, therefore, one would expect to find evidence that changing geomorphic process rates over a time period of 10^3 years, or longer, relate to changing climate and catchment conditions.

Under certain conditions the sedimentary record contained in depositional environments can be used to provide information on the magnitude and temporal variation of sediment output from the contributing area. In many situations lakes (both natural and artificial) trap a large proportion of the material flowing into them. Generally, the sediments tend to remain within the lake for long periods of time and can be employed to investigate the magnitude and nature of variations in sediment fluxes from the drainage basin to the lake. Furthermore, the nature of the sediments themselves can be used to provide indirect information on conditions in the drainage basin. Peaty organic-rich sediments suggest different lake-basin conditions than those inferred from inorganic lacustrine silts. In this paper, we report on the use of the lacustrine sedimentary record contained in Gallie Pond, British Columbia, to investigate post-glacial variations in sediment yield and to suggest the cause(s) of these variations.

STUDY AREA AND METHODOLOGY

Gallie Pond (50°24′N 122°57′W) is a small (901 m^2) alpine lake located approximately 120 km north of Vancouver, in the Coast Mountains of British Columbia (Fig. 1). The altitude at the lake outlet is about 1850 m a.m.s.l., and this defines the lower limit of the Goat Meadows basin (Fig. 2). The lake occurs in a rock-bound hollow on a glacially scoured ridge between Miller Creek and the Lillooet River, and is fed by two ephemeral streams, Hummingbird and Mosquito. Losses occur through an ephemeral outlet stream on the northwest margin of the lake and by groundwater drainage through the lake sediment. The lake can be divided into two environments (Souch & Slaymaker, 1986): a deeper central portion, underlain by fine lacustrine silts; and a till shelf covered by coarse bouldery material (Fig. 2). The origin of this shelf feature is uncertain. However, as sediment accumulation only occurs in the deeper central portion of the lake, calculations of sediment yield are based only on this region of the lake.

Twenty three cores of lake sediment were taken at sampling sites selected on a 10 m by 10 m grid system, using a corer designed by the authors specifically for this remote alpine lake. Sediment chronology was established by radiocarbon dating of organic material overlying the till in one of the cores (Souch & Slaymaker, 1986), which gives a date of 10 500 $\pm$ 500 years BP, and by the presence of two tephra layers. Although there are several Holocene tephra deposits in British Columbia, only two tephra layers have been documented for the study region: Bridge River and Mazama. The two tephra layers present in the core stratigraphy were differentiated and identified in the field on the basis of their stratigraphic position, texture and colour (cf. Reasoner & Healy, 1986). Mount Mazama and Bridge River tephras have been dated at *c.* 6 800 years BP (cf. Fulton, 1989) and *c.* 2350 years BP (Read, 1977), respectively. Consequently, the former is expected to occur lower down the sediment profile. The two tephra layers also have different textures. Bridge River tephra is noticeably coarser than Mount Mazama,

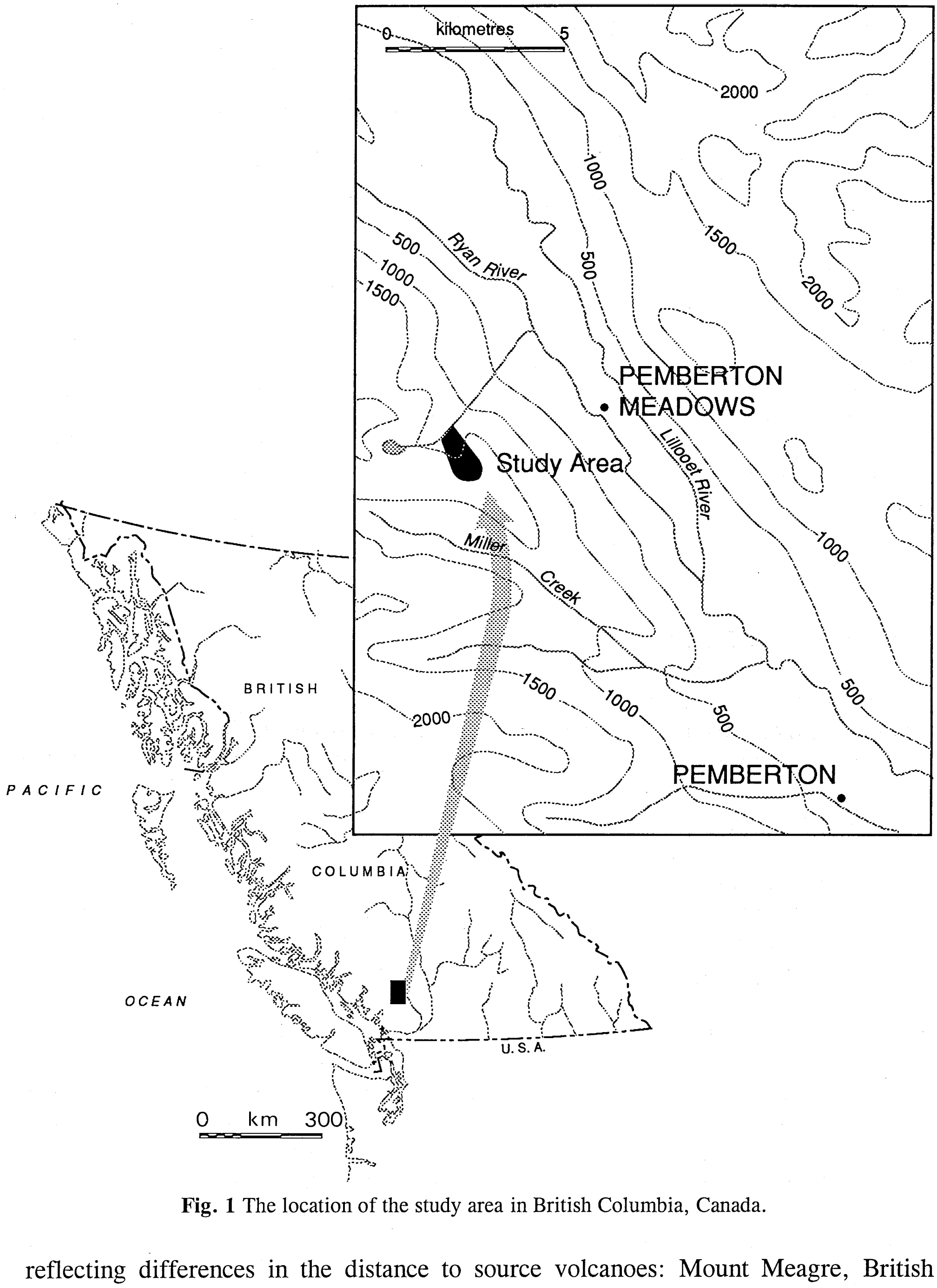

Fig. 1 The location of the study area in British Columbia, Canada.

reflecting differences in the distance to source volcanoes: Mount Meagre, British Columbia (*c.* 45 km) and Crater Lake, Oregon (*c.* 800 km), respectively. Mazama tephra is typically slightly reddish in colour (5YR 7/2), whereas Bridge River tephra is light grey (2.5YR 7/0). This preliminary classification was reinforced by examining samples of the two ash layers under a high-powered binocular microscope. "Bridge River glass shards are typically chunky and display lineated, lensoid gas vesicles,

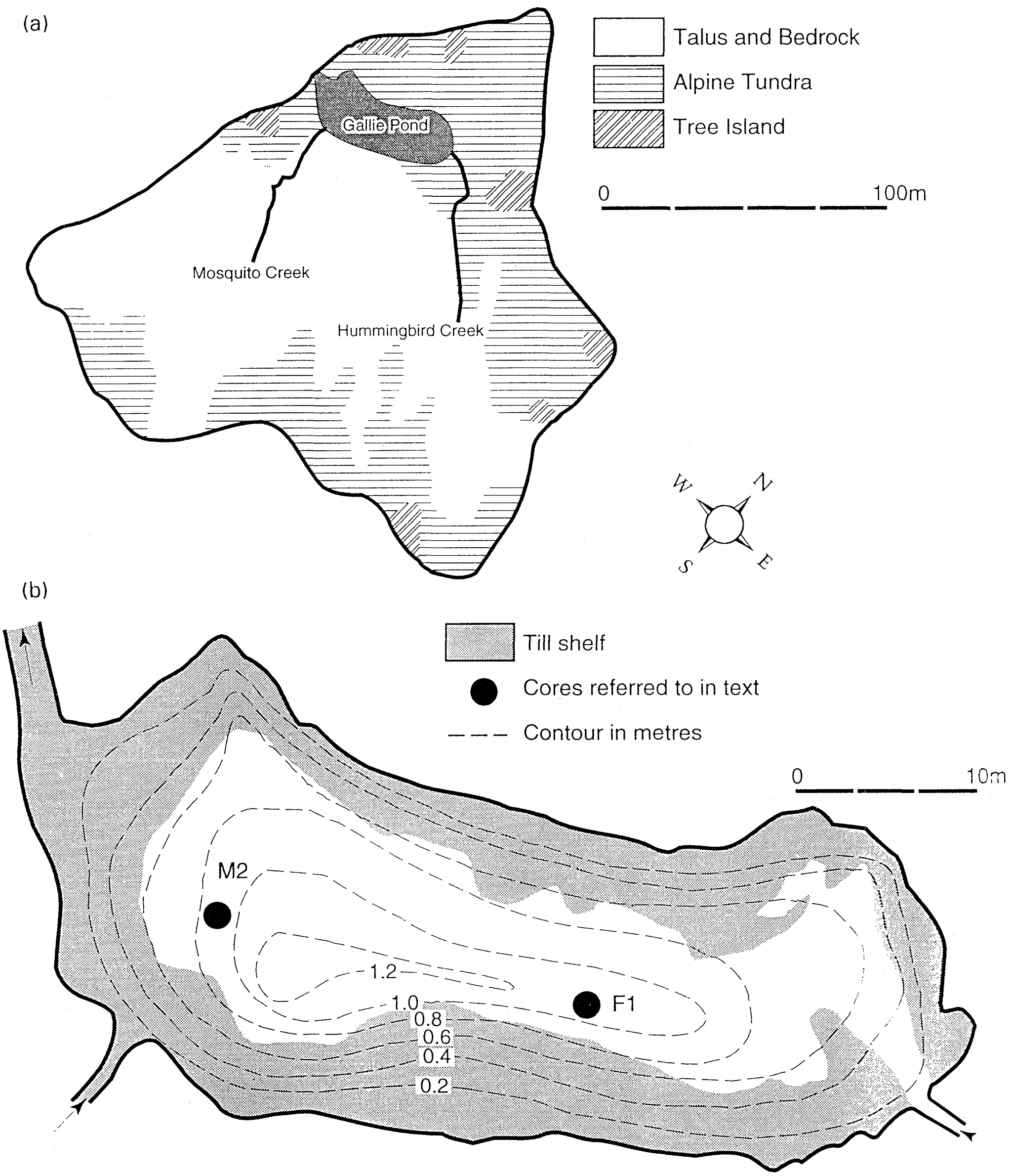

Fig. 2 (a) The Goat Meadows basin and (b) the bathymetry of Gallie Pond and the location of the cores referred to in the text.

whereas Mazama glass shards are commonly thin bubble-wall fragments" (Reasoner & Healey, 1986, pp. 1994-1995).

The dating of the base of the sediment core, and the presence of the tephra layers, separates the post-glacial sediment record into three roughly equal periods of time. Furthermore, the timing of the Mazama ash eruption is particularly useful because it approximately marks the boundary between warm, dry conditions during the well-documented hypsithermal interval, which began soon after deglaciation, and cool, wetter conditions during the middle and late Holocene. Also, because of their stratigraphic position and their quick and easy identification, the tephra layers were used for core correlation. Rates of sediment accumulation for each of the three time periods were estimated by calculating the mass of sediment contained between the relevant stratigraphic layers and the time period over which sedimentation had occurred. Because previous work on Gallie Pond (Owens & Slaymaker, 1993) demonstrated the importance of non-drainage basin derived material to the amount of sediment accumulating in this lake, a comprehensive lake sediment budget was developed. In order to convert sedimentation rates to estimates of sediment yield, corrections were made for material not derived from erosional processes operating within the Goat Meadows basin (i.e. tephra, aeolian material, autochthonous sediment and lake bank material) and for losses of sediment through the outflow channel.

SEDIMENT DESCRIPTION AND YIELDS

Sediment description

Figure 3 illustrates the sediment stratigraphy of two of the 23 cores recovered from the lake. The stratigraphy of most of the cores is very similar and that of core M2 (which contains all of the stratigraphic units identified) can be considered to represent the general stratigraphic pattern in this lake. The units in most of the cores collected have distinct boundaries with adjacent units. This indicates that there was little mixing or redistribution of sediments once deposited in the lake. Nine units have been identified, unit VIII consisting of two distinct parts. The first unit (unit I) is a glacial till which consists of gravel and coarse sands. This is overlain by lacustrine silts and organic material (unit II). Above this is a dark organic-rich peaty unit (unit III), containing some partly decomposed fragments of wood. This is the thickest unit in the sequence. Unit IV is a thin layer (*c.* 1-2 cm) of Mazama tephra mixed with a small amount of drainage basin-derived sediment. Further information on this unit was presented in the previous section. Unit V also consists of peaty material and clearly resembles unit III. Overlying this unit is unit VI which contains lacustrine silts mixed with organic material. Following the general trend, unit VII is composed of lacustrine silts with very little organic material. Bridge River tephra (unit VIII) is also described in the previous section. It consists of two distinct units: the lower (unit VIIIa) is coarse unweathered shards of ash; whereas the upper (unit VIIIb) is a much finer deposit and is the product of direct ash deposition onto the lake surface intermixed with sediments and ash eroded from the drainage basin. The last unit (unit IX) consists of inorganic lacustrine silts and is similar to unit VII. Both units V and IX contain negligible amounts of tephra material. Thus, the post-glacial sediment record shows a general trend after unit II of decreasing organic matter content (loss on ignition) with time.

Sediment yields

Table 1 gives the estimated average sediment yield for each of the three time periods. Values are very low and support the contention that this is a low energy pristine environment (Owens & Slaymaker, 1992) and has been over the full post-glacial period. Despite this, there is significant temporal variation in sediment yields between the

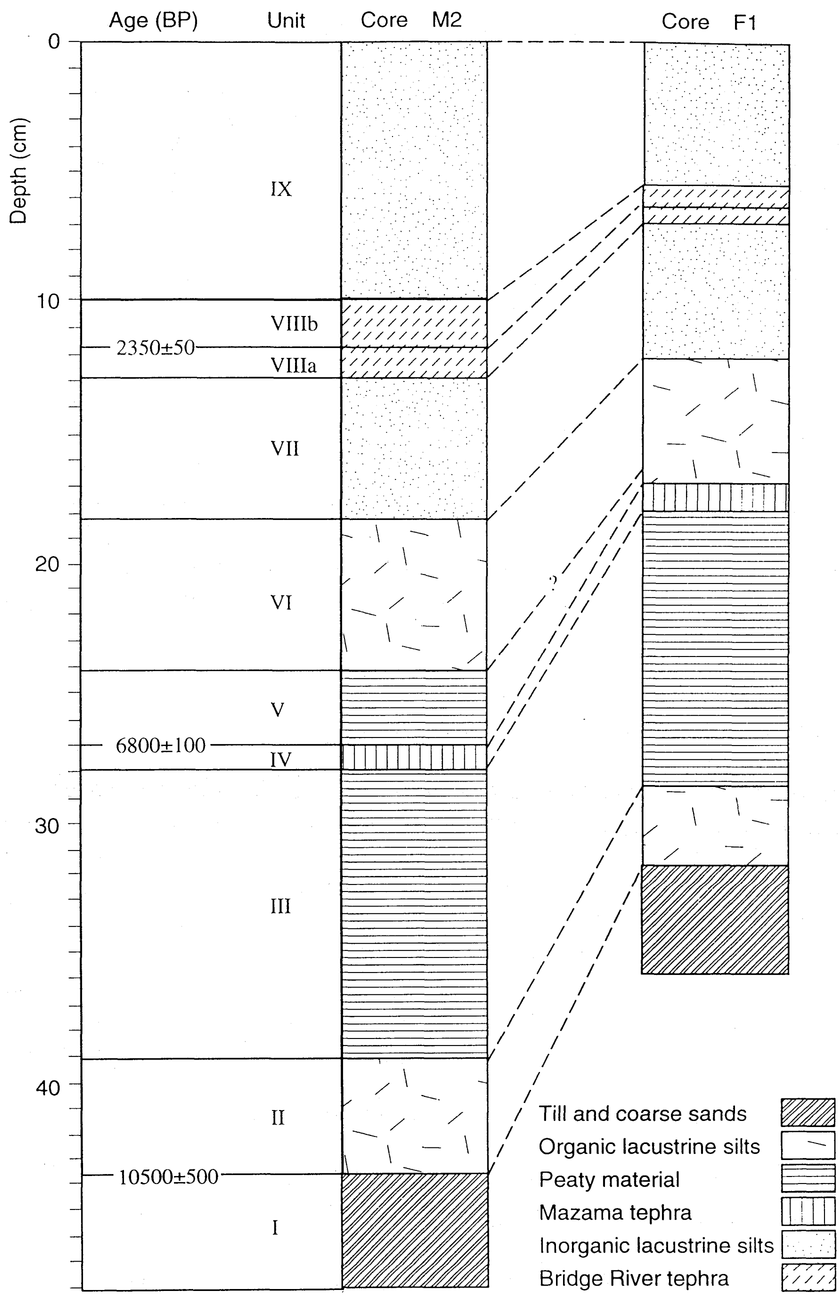

Fig. 3 The stratigraphy of cores M2 and F1.

different time periods. Estimated sediment yields range from 1.8 ± 1.1 kg km^{-2} $year^{-1}$ to 4.5 ± 1.9 kg km^{-2} $year^{-1}$. The general trend over the Holocene Epoch is one of increasing sediment yield with time, so that the most recent time period is also the one with the highest yield. This trend is in broad agreement with the findings of Souch & Slaymaker (1986). The magnitude of the sediment yields calculated in this study are

Table 1 Average sedimentation rate and sediment yield for each time period (yields have been corrected for non-drainage basin derived material and for outflow losses).

Time period (years)	Sediment mass (kg)*	Sedimentation rate (kg m^{-2} $year^{-1}$)*	Sediment yield (kg km^{-2} $year^{-1}$)*
0-2350	16 184 ± 3 484	0.018 ± 0.004	4.5 ± 1.9
6800-2350	13 110 ± 3 466	0.008 ± 0.002	3.4 ± 1.5
10 500-6800	11 692 ± 2 947	0.008 ± 0.004	1.8 ± 1.1

* ± values reflect the variability of the data and cumulative measurement errors.

considerably lower that those estimated by Souch & Slaymaker (1986), as the latter study did not make corrections for the contribution of non-drainage basin sources to the amount of sediment contained in Gallie Pond for each of the time periods. Furthermore, owing to the numerous assumptions outlined earlier and the cumulative errors associated with the calculation of the sediment yields, emphasis should be placed on the general trend of the estimated sediment yields, rather than in their precise values. Although the observed difference in yields may be a result of the calculation procedure, it is felt that the overall trend is correct.

HOLOCENE PALAEOENVIRONMENTAL CHANGE

As this drainage basin and lake have been ice free over the Holocene Epoch with almost no human interference, temporal variations in sediment accumulation are likely to be related to palaeoenvironmental changes. It is possible to use both the sediment yield data and the description of the sedimentary record to infer palaeoenvironmental changes over the post-glacial period. However, it is important to note that this involves association rather than causal connection (Brooks *et al.*, 1993).

The first time period extends from 10 500 to 6800 years BP. In this basin, deglaciation occurred before 10 500 years BP as indicated by the radiocarbon dating of material immediately above the glacial till (unit I). Deglaciation initiated a period of intense redistribution of glacial materials by fluvial and colluvial processes (paraglacial sedimentation). This can be identified in the sedimentary record in Gallie Pond by unit II, which has a similar mineralogy to the underlying till and is a much coarser deposit than the overlying material (Souch, 1989). As unit II is a relatively thin deposit, it seems likely that the paraglacial phase occupied a short period of time in this basin. This is followed by an organic-rich unit (unit III) which probably represents a decrease in water level and the development of a peaty wetland environment. This is consistent with the idea that following the paraglacial period there was a period of climatic amelioration with warm and dry conditions, called the hypsithermal interval. The average sediment yield during the period between deglaciation and the deposition of Mazama tephra (1.8 ± 1.1 kg km^{-2} $year^{-1}$) is the lowest during the Holocene Epoch, and this mainly reflects the prolonged warm and dry conditions just mentioned. Lacustrine sedimentation during the hypsithermal interval (i.e. unit III), in particular, was likely to have been very low, not only because of the dry climatic conditions, but also because sediment delivery to the lake following the paraglacial period decreased as slopes stabilized. Souch (1989) determined that the dominant sources of sediment during the hypsithermal interval were probably the till shelf and sparsely vegetated areas near the lake and tributary streams.

The second time period extends from 6800 to 2350 years BP. The sedimentary units in this time period are characterized by a trend of increasing mineral content with time, so that unit VII is composed of inorganic lacustrine silts. Unit V represents the end of the hypsithermal interval in this region and the return to cooler, wetter conditions. Consequently, the lake water level rose towards the end of this period. Units VI and VII are composed of lacustrine silts. The clastic sediments were derived from the hillslopes in the basin (Souch, 1989). The particle size composition of the sediments (cf. Souch, 1989) suggests that the predominant erosional events transported finer material derived from the winnowing of slope deposits, and that sediment was delivered to the lake by events of a high frequency and low magnitude. Because of the increase in precipitation and the decrease in temperature, the delivery of sediment to the lake by slope and channel processes increased and, as a result, the average sediment yield for this time period (3.4 ± 1.5 kg km^{-2} year^{-1}) is greater than the preceding period. While this observation is not unexpected, it is the opposite of that described in Souch & Slaymaker (1986) for this basin. The difference between the two estimates reflects the different methods and assumptions used in calculating sediment yields.

The third time period extends from 2350 years BP to the present day. The sediments deposited over this time period are dominated by inorganic lacustrine silts, and unit IX is similar to unit VII. The average sediment yield for the last 2350 years is 4.5 ± 1.9 kg km^{-2} year^{-1} and is the highest of the three post-glacial time periods. This reflects the continuation of the cool, wet conditions which started after the deposition of Mazama tephra and, consequently, the increased delivery of sediment from the hillslopes to the lake, probably by slope wash and channel processes (Souch, 1989). Furthermore, continuing soil development is likely to have increased the susceptibility of slopes to failure (Brooks *et al.*, 1993) and increased sediment availability.

The sediment yields presented in Table 1 refer to average values over long periods of time (i.e. 10^3 years). There is also evidence to suggest that within each time period there was significant temporal variation of sediment accumulation in Gallie Pond. Detailed examination of the sediment above the Bridge River tephra in several of the cores demonstrates that the accumulation of minerogenic material derived from the drainage basin over periods of time of 10^2 years or less has probably varied by at least one order of magnitude since 2350 years BP. Within this time period, yields may have varied between <1 kg km^{-2} year^{-1} and >10 kg km^{-2} year^{-1}. Unfortunately, the lack of a more detailed chronology prevents the examination of the extent of the variability of sediment yields within this period of time. However, it seems likely that a similar degree of variability also applies to the other two time periods. The variability of sediment yields over short periods of time (i.e. 10^2 years or less) is probably related either to pulses of sediment delivery during erosional events of a higher magnitude or to more prolonged changes in palaeoenvironmental conditions, such as the several neoglacial phases which have been inferred from evidence of glacier and timberline fluctuations and palynological studies in other parts of south western British Columbia (cf. Ryder, 1981; Fulton, 1989). In Gallie Pond, the particle size characteristics of the sediment within each unit tends to support the latter argument.

CONCLUSION

The sediment record contained in Gallie Pond suggests that the magnitude of sediment output from the drainage basin has been low over the post-glacial period and that the Goat Meadows basin has been a relatively stable, low energy environment over the Holocene Epoch. This finding supports the view of Ryder (1981). There is, however, evidence to suggest significant variability in sediment yield, which appears to be related to palaeoenvironmental changes, particularly changes in climate and sediment availability.

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