

Alpine lake sediment records of the impact of glaciation and climate change on the biogeochemical cycling of soil nutrients

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Abstract

Lake sediment cores from the Coast Mountains of British Columbia were analyzed using chemical sequential extractions to partition the dominant geochemical fractions of phosphorus (P). The P fractions include mineral P (the original source of bioavailable P), occluded P (bound to soil oxides), and organic P (remains of organic matter). By comparing P fractions of soil and recent lake sediment samples, these fractions are shown to be a valid proxy for landscape-scale nutrient status. Changes in soil development for an alpine watershed (Lower Joffre Lake) are inferred from the P fractions in the basin's outlet lake sediments. Glacially sourced mineral P dominates at the base of the core, but several rapid shifts in P geochemistry are evident in the first ~3000 yr of the record. The latter indicates an interval of early and rapid soil nutrient maturation from ~9600 to 8500 cal yr BP and a significant influx of slope-derived material into Lower Joffre Lake. A substantial increase in mineral P occurs at ca. 8200 cal yr BP, consistent with the cold event in the vicinity of the North Atlantic at that time. The more recent record reveals a continual increase in the proportion of mineral P from glacial sources to the lake, indicating a trend toward cooler conditions in the Coast Mountains. © 2006 University of Washington. All rights reserved.

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Introduction

A key to understanding the interplay between soils and biota is insight into nutrient cycling on landscapes over suitably long time scales. Phosphorus (P) is an important nutrient that plays a limiting role in terrestrial productivity (Schlesinger, 1997), and it is perhaps one of the most critical nutrients to ecosystems on longer time scales because its only source is typically derived from the slow process of rock weathering. This contrasts with the abundant atmospheric source of nitrogen. Several forms of P are present in soils, and the relative proportions of each reflect soil maturity (Fig. 1). The forms of soil P include P in apatite minerals, P co-precipitated with and/or adsorbed onto

iron, manganese, and aluminum oxyhydroxides (termed “occluded” P), P in soil pore spaces (as dissolved phosphate), and adsorbed onto soil particle surfaces (these forms are termed “non-occluded” P), as well as P in soil organic matter. On newly exposed surfaces, nearly all of the P is present as P in apatite. With time and soil development, however, P is increasingly released from this mineral form and incorporated in the others (Fig. 1). Over time, the total amount of P available in the soil profile decreases, as soil P is lost through surface and subsurface runoff. Eventually, the soil P reaches a steady state, when soil P is substantially recycled and any P lost through runoff is slowly replaced by P weathered from apatite minerals at the base of the soil column. In recently deglaciated areas, the net result of this nutrient cycling change is a general decline in productivity after hundreds to thousands of years of deglaciation related to loss of the more labile mineralized nutrients (e.g., Engstrom et al., 2000).

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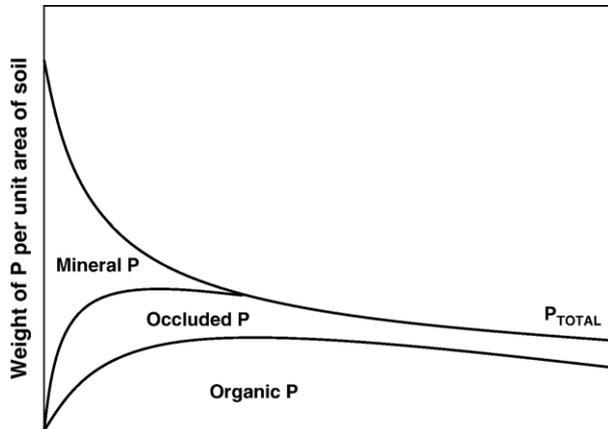


Figure 1. Conceptual model of change in soil P geochemistry over time (based on Walker and Syers, 1976) showing transformation of mineral P into occluded (oxide-bound) and organic forms. Note continual loss of total P from the system.

The effects of climate and soil development on P availability have been the focus of several studies (Walker and Syers, 1976; Gardner, 1990; Crews et al., 1995; Cross and Schlesinger, 1995; Vitousek et al., 1997; Schlesinger et al., 1998; Chadwick et al., 1999). Generally, these studies have used P extraction techniques to determine the biogeochemical speciation of P within soils (Fig. 1) (e.g., Tiessen and Moir, 1993). The extraction techniques have been applied to profiles in soils to assess the rate of soil P transformations, the role of climate on these processes, the bioavailability of P in these systems, and the limiting controls on plant productivity. As the current geochemical state of a given soil is an integration of all conditions acting since soil development began, most efforts have focused on settings in which climate is likely to have been relatively constant (e.g., tropical settings), and the beginning state of the system and its age are well known (e.g., soils forming on lava flows of known age). These studies have thus made the classic substitution of space for time with the inherent assumptions of constancy in climate and landscape history. Disadvantages of this approach are the low temporal resolution afforded by soil sequences and substantial Holocene climate variability in temperate environments (Mayewski et al., 2004).

Another approach to assess terrestrial P cycling that circumvents the temporal biases inherent in soil sequences is to analyze P in lake sediments. Lakes integrate past geomorphic and ecological processes and their sediments preserve these events through time (Oldfield, 1977). Thus, lake sediments have the potential to yield an integrated record of watershed-scale processes associated with P cycling on the landscape. This approach, however, requires a sediment record where P concentration reflects sediments that were eroded from the landscape. Oligotrophic lakes in small watersheds are ideal because autochthonous organic production is minimal and low concentrations of labile organic matter in the sediments limit the degree of diagenetic overprinting on the original sediment record.

We studied phosphorus geochemistry of lake sediments from two alpine sites in the Coast Mountains of British Columbia, Canada, to better understand how climate affects soil development and nutrient cycling in this region. A complicating factor that arises in the interpretation of lake sediment records in glaciated alpine settings is changes in the dominant source of sediments through time, specifically the relative balance between slope sediments and glacial inputs (e.g., Leonard, 1986; Desloges and Gilbert, 1994; Souch, 1994; Menounos et al., 2004). We begin by validating the P method by comparing the P concentration of potential sediment sources to a lake basin (Green Lake) with the lake sediment record. Then, we analyze the P concentration for a second lake sediment record (Lower Joffre Lake) and infer soil development, soil erosion, and environmental change.

Study area

Two oligotrophic lakes (Green and Lower Joffre lakes), both in the southern Coast Mountains of British Columbia, Canada, were selected for analysis (Fig. 2). The Coast Mountains consist of a series of NNW–SSE trending mountain ranges with relief up to 3000 m and extensive snow and ice cover (Ryder, 1981). On the eastern side climate is semi-arid, but on the western side precipitation can exceed 2500 mm yr^{-1} (Clague, 1989). These climatic differences are also reflected in ecosystem zonation. In the Lillooet River basin, the region of study, Coastal western hemlock dominates to the southwest of Lillooet River (Green Lake), whereas more continental species, such as Engelmann Spruce, dominate to the northeast of the Lillooet River basin (Lower Joffre Lake).

Lower Joffre Lake receives its water and sediment from surrounding slopes and stream flow derived largely from glaciers. The lake is small (10 ha) and shallow (12 m maximum depth). Today, glaciers occupy 25% of the catchment (Fig. 2). The lake is situated at 1245 m above sea level (m.a.s.l.) and approximately 3.25 km down-valley from contemporary glaciers. Two lakes upstream of Lower Joffre Lake likely trap a sizable portion of glacial detritus. The size and depth (>60 m) of the uppermost lake, however, suggests that changes in trapping efficiency through time have been minimal. The bedrock is granodiorite and quartz diorite. Tree line lies at approximately 1800 m.a.s.l. Slopes in the watershed are steep. The topographic gradient from the lake to the nearest glacier is 275 m km^{-1} . The lake is ice covered in the winter.

The Green Lake watershed ($\sim 180 \text{ km}^2$) was chosen to evaluate the robustness of the soil–lake sediment P linkage (Fig. 2). The lake is located at approximately 540 m.a.s.l. Ridges and peaks in the contributing watershed range up to 2300 m and glaciers occupy just 7% of the watershed. The mean depth of Green Lake is 14 m and maximum depth is 40 m. Igneous rocks, including basalts, volcanics, and quartz diorite, dominate the bedrock. Tree line is at approximately 1800 m. The majority of glacial sediment input comes from Fitzsimmons Creek, draining the Fitzsimmons and Overlord glaciers (2250 m elevation), approximately 19.5 km upstream from the lake.

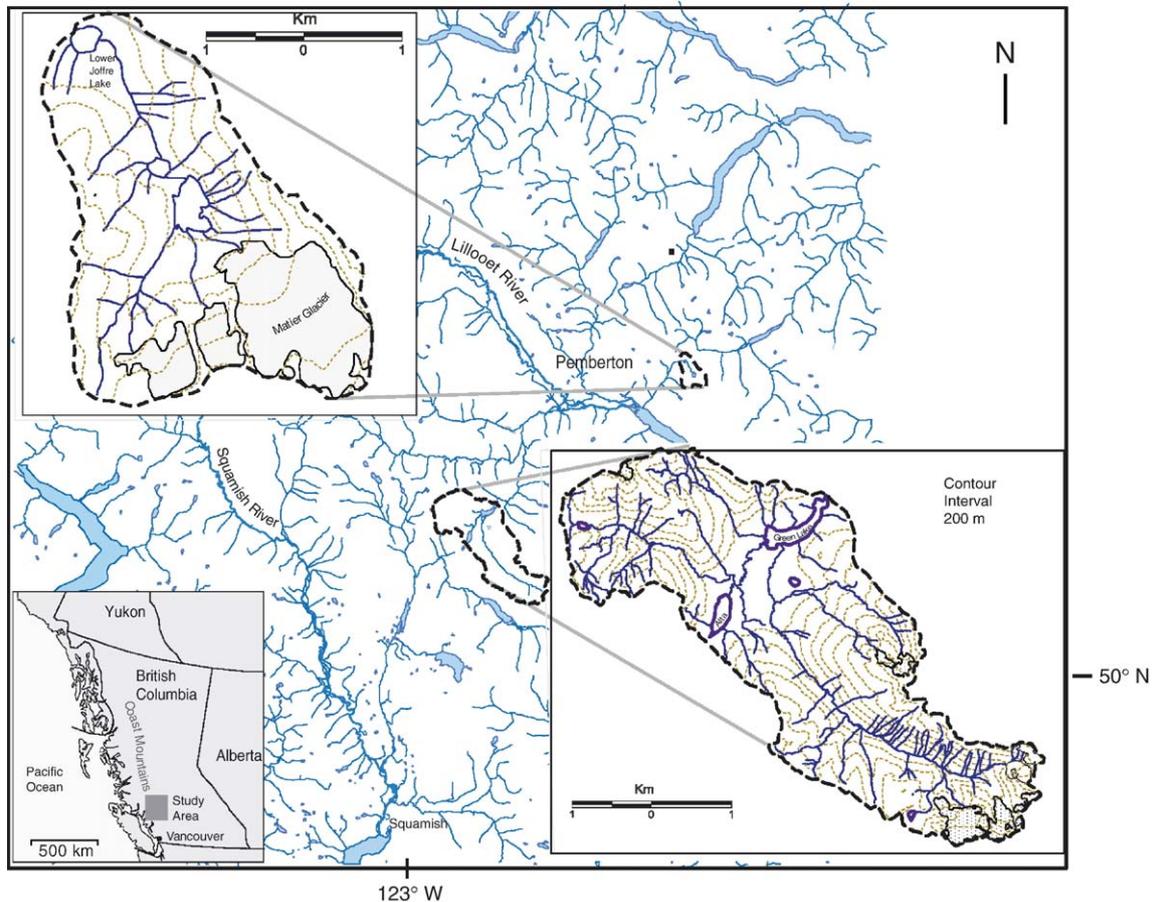


Figure 2. Location map of Lower Joffre Lake (inset upper left) and Green Lake (inset lower right), Coast Mountains, British Columbia.

Fitzsimmons Creek has an average channel gradient of 72 m km^{-1} (Menounos, 2002).

Sampling and analytic methods

Lake sediment cores were collected from Lower Joffre Lake by gravity coring, percussion coring, and vibra-coring. Detailed sediment core stratigraphy and discussion of trends in clastic sedimentation are discussed elsewhere (Menounos, 2002). Below 570 cm, the sediments are grey, rhythmically laminated, inorganic sandy silts (Fig. 3). Above 570 cm, sediments are abruptly overlain by less dense, organic-rich sediments (gyttja), which grade into less organic silty clays above 420 cm. For this study, subsamples of air-dried sediment ($\sim 5 \text{ g}$ each) from Lower Joffre Lake were collected at 2-cm intervals in the upper 580 cm of the core and 10-cm intervals from 580 to 1134 cm. The samples were disaggregated and analyzed by sequential extraction for P geochemistry (details below).

To characterize the P geochemistry of contemporary sediments, delta and soil samples surrounding Green Lake were collected in October 2000. Grab samples of approximately 200 g were taken from the surface of the Fitzsimmons delta at two locations in order to characterize the P geochemistry of different grain-size fractions: coarser (sand)

and finer (silt and clay) subenvironments. Five soil samples were taken at road cuts 4, 6, and 7 km upstream from Green Lake on slopes approximately 200 m from the river channel. Exposed sections of soil were cleaned off and grab samples were taken from the A and B horizons of the soil profile. Samples were also collected from surface (0–5 cm) lake sediment cores and analyzed for their P speciation (Slater-Atwater, 2004).

A sequential extraction technique (Filippelli and Delaney, 1996), similar to that of Tiessen and Moir (1993), was used to geochemically distinguish three pools of P related to mineral material, an occluded fraction (related to soil oxyhydroxides), and an organic fraction. This technique involved (1) a citrate–dithionite–bicarbonate reducing agent and magnesium chloride (occluded fraction), (2) dissolutions with sodium acetate + acetic acid solution and hydrochloric acid (mineral fraction), and (3) ashing followed by dissolution with hydrochloric acid (organic fraction). The procedure outlined by Anderson and Delaney (2000), which follows Ruttenberg (1992), was followed. Approximately 0.2 g of sample was weighed and combined with reagents, shaken, and centrifuged at 10,000 rpm for 10 min. Supernatants were decanted into acid-cleaned polyethylene bottles and saved for analysis. A Shimadzu scanning UV-Visible Spectrophotometer was used for the determination of P concentrations for the sequential P extraction using the

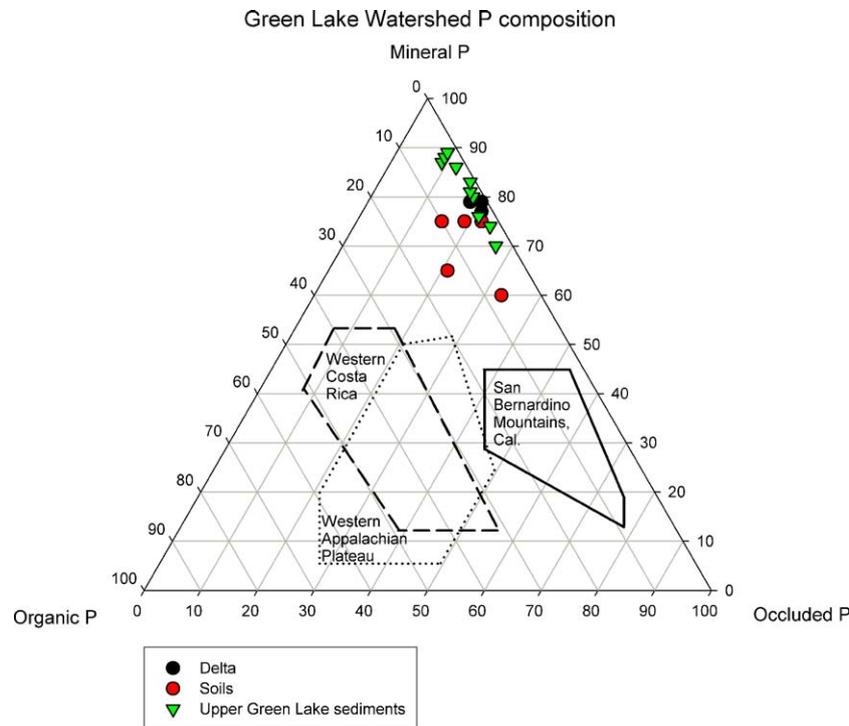


Figure 3. Phosphorus fractions, in percent of total P, for Green Lake surface core samples (upper 25 cm), soil samples, and delta samples. Outlined fields for P composition are from other oligotrophic lake systems previously studied.

molybdate blue technique for color development (Strickland and Parsons, 1972). Dithionite-extractable P concentrations were determined by ICP-AES because the CDB solution interferes with the standard color development. Randomly chosen replicate solutions were analyzed with an agreement within 6%. In this study, total P is defined as the sum of the three sequential extraction fractions.

Eight accelerator mass spectrometry (AMS) ^{14}C ages and the presence of Bridge River and Mazama tephra are the basis for age control for the Joffre Lake sediment core (Menounos et al., 2004). Other studies in the region have dated Bridge River tephra to 2300–2600 ^{14}C yr BP (Luckman and Osborn, 1979; Clague et al., 1995; Lian and Huntley, 1999) and Mazama to 6600–6850 ^{14}C yr BP (Luckman and Osborn, 1979; Luckman et al., 1993; Gavin et al., 2001) or 7500–7600 cal yr BP (Lian and Huntley, 1999). Radiocarbon ages were converted to calendric ages using the calibration program Calib 4.4 (Stuiver et al., 1998a,b). The calendar age model uses seven of the AMS ^{14}C dates (see details in Menounos, 2002).

Results and discussion

Calibration of the phosphorus geochemistry as a recorder of watershed nutrient status

Through careful choice of the lakes considered, we attempted to limit issues related to significant in situ production of organic phosphorus, as well as productivity-related suboxia and phosphorus diagenesis. In particular, our focus was on oligotrophic lakes with low organic matter production and thus low bottom and sedimentary reduction potential (e.g., Filippelli

and Souch, 1999). But this careful selection of sites alone does not verify the relationship between watershed nutrient status and lake sediment phosphorus geochemistry. Thus, we compared the geochemical nature of phosphorus in slope sediments from the watershed and the surface sediments of Green Lake itself.

Phosphorus fractionation was similar for all the soil samples, with composition dominated by the mineral P fraction and with lesser proportions of occluded P and organic P (Fig. 3). Surface horizons of the soil samples from up-valley contain higher concentrations of organic P than samples from the B horizon, consistent with higher organic matter in surface soils and higher oxyhydroxide fraction in B horizons. Additionally, the dominance of the mineral P fraction agrees with our earlier interpretations based on the nearby Kwoiek watershed (Filippelli and Souch, 1999). Sediments collected from 7 km up-valley have a higher occluded P concentration than the other soil profiles, but this profile also had a deeper B horizon that was included in the trench sample.

Deltaic sediments of Green Lake have P speciation similar to most of the soil samples (Fig. 3), with mineral P the dominant fraction, followed in relative importance by occluded P and organic P. The distribution of P geochemistry in the Green Lake sediments themselves is heavily weighted toward mineral P and occluded P fractions, with very little organic P compared to slightly higher organic P values for the soils (Fig. 3). This general result reveals the oligotrophic nature of the lake itself plus the dominance of glacially derived mineral-rich sediments over more organic-rich slope sediments deposited during the near-modern climatic regime. The watershed soil samples

cluster with the delta and upper Green Lake sediments compared to other lake systems that we have studied (Fig. 3), indicating that the landscape nutrient distribution is recorded in lake sediments.

Application of lake sediment phosphorus geochemistry to paleonutrient and paleoclimate dynamics

The Lower Joffre record provides an excellent context with which to understand the evolution of a landscape as ice retreats and climate changes. Several major climatic events are reflected well in the 11 m sediment core (Menounos, 2002). The oldest date from this core was a conifer needle found at a core depth of 5.59–5.61 m, which yielded a radiocarbon age of 9380 ± 160 ^{14}C yr BP (Menounos, 2002). This is consistent with estimated deglaciation ages, 9500–10,100 ^{14}C yr BP, of sites close to contemporary glaciers in the Canadian Cordillera summarized in Osborn and Luckman (1988). The lowest 5.0 m of the core is dominated by rhythmically laminated, inorganic clayey silts.

The sediments are predominantly organic rich (up to 35% loss on ignition) between 5.5 and 4.0 m [10,500 and 7700 cal yr BP], but there are several intervals where the sediments become clastic-rich (organic content only 1% or 2%). Thereafter, until about 3500 cal yr BP, the clastic fraction increases (organic matter content dropping to 5%), after which time modern sedimentation rates and bulk physical property characteristics are established (Menounos, 2002).

Results from the sequential extraction analysis for P geochemistry reveal both the interplay between glacial- and slope-derived sediments and the nature of soil nutrient cycling in surrounding slopes. Analysis of total P concentration in the lake sediments reveals some variations, with the lower glacial sediments having a moderate P concentration of about $22 \mu\text{mol g}^{-1}$ (Fig. 4a), equivalent to about 0.07 dry wt.% and near the average P concentration in crustal rocks (Filippelli, 2002). In the overlying sediments, the P concentration increases to a peak above $50 \mu\text{mol g}^{-1}$ just after 4000 cal yr BP, followed by a gradual decline to the present (Fig. 4a). In contrast, the three geochemical fractions of P vary through time (Fig. 4b). The mineral P fraction is generally the most abundant fraction in the core (Fig. 4b). The inorganic basal sediments have approximately $20 \mu\text{mol g}^{-1}$ of mineral P, decreasing to $10 \mu\text{mol g}^{-1}$ during the early Holocene (9500–8500 cal yr BP), and reaching locally maximum values near 5000 cal yr BP (Fig. 4b). Organic P is the least abundant fraction in the sediment record. It is near zero for the lowermost 7 m of the sediment record, peaks to about $8\text{--}10 \mu\text{mol P g}^{-1}$ from the onset of organic sedimentation to about 7500 cal yr BP, and then remains relatively low to the present (Fig. 4b). Organic P, as expected, shows most similarity to the organic matter content of the sediment core. Similar to P organic, P occluded has low, constant values for the basal sediments ($\sim 5 \mu\text{mol P g}^{-1}$) but reaches highest concentrations from ca. 6700 to 3200 cal yr BP (Fig. 4b).

Both organic and occluded P fractions result from the transformation of mineral P during soil formation. The P record

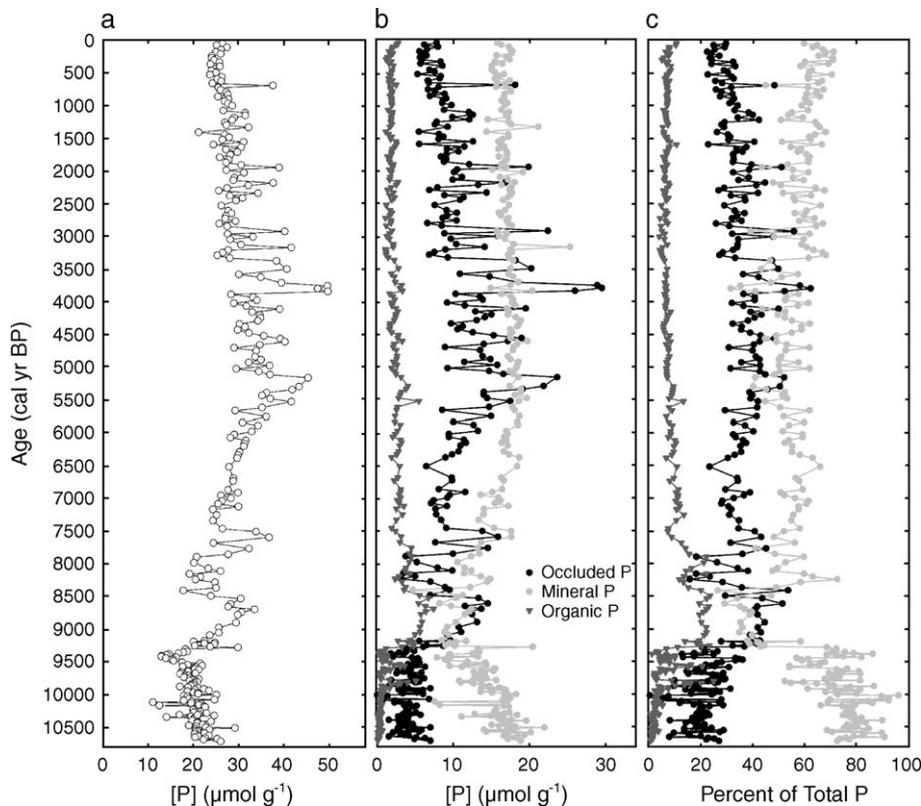


Figure 4. (a) Total P concentration ($\mu\text{mol P g}^{-1}$) (sum of the three fractions); (b) P concentration for each P-bearing fraction ($\mu\text{mol P g}^{-1}$); (c) and percent of total P for each fraction for Lower Joffre Lake.

indicates that little soil formation was occurring on proximal slopes during the early interval of glacial input and/or the dominant source of sediment to these lakes was largely unweathered glacial sediments (Fig. 4b). Several minor peaks in organic P occur in this lower interval. These peaks include several intervals of slightly higher organic P input to the lake sediments. These organic P increases are not accompanied by significant increases in occluded P and thus may have been due to the erosion of surface litter from the watershed.

After 9500 cal yr BP, mineral P decreases and the organic P concentration increases, a situation sustained until about 7500 cal yr BP (Fig. 4). In addition, the occluded P concentration increases sharply during this interval, becoming at times the most important P fraction. As noted from the core description of Menounos (2002), this marks an interval of higher organic matter and lower clastic sediment in the lake. After about 7500 cal yr BP, the concentrations of the three P fractions are relatively constant to the present. For example, the mineral P fraction increases to $\sim 20 \mu\text{mol P g}^{-1}$ by ~ 6000 cal yr BP, the value in early glacially derived sediments, and remains relatively constant to the present. The organic P fraction decreases after 7600 cal yr BP and remains low and constant throughout the rest of the record. The occluded fraction exhibits the most variability after 7600 cal yr BP, also displaying an increasing trend to about 4000 cal yr BP followed by decreases to the present. Variability in the record and the relatively high analytical error of the occluded P fraction mean the longer term trends should be interpreted with caution.

Although the temporal records of concentrations are relevant in terms of the net sediment accumulation of these components, the critical aspect of this record is the proportion of total P that each component constitutes (Fig. 4c). By examining this proportion, dilution by various non-P-containing constituents can be filtered out. Moreover, rapid changes in the relative fractions may give insight into changes in sediment sources and the relative importance of soil-derived and glacial sediment inputs through time.

In this context, the temporal record of P fractional geochemistry reveals several important aspects of soil nutrient cycling. First, the Lower Joffre Lake watershed is characterized by soils that are not substantially advanced along the soil nutrient development trajectory. With greater than 50% of total P present as mineral P for most of the record (Fig. 4c), the soils surrounding Lower Joffre Lake are relatively immature in the context of a typical development model (e.g., Fig. 1) and in terms of other settings that we have studied with more advanced soil nutrient status (e.g., the Western Appalachian Plateau; Filippelli and Souch, 1999) (Fig. 3). Second, although the occluded P fraction reaches values of 40% of total P in certain intervals, it never dominates, and organic P is always relatively low. Together, these factors also point to an equilibrium point that is not far along the soil development trajectory as conceptualized in Figure 1. In this case, chemical weathering and soil development are limited by relatively high erosion and low organic production.

Several shifts do occur, however, in the temporal records of P geochemistry that are significant. First, the lowermost record is

clearly dominated by direct glacial input of sediment, as noted earlier. During this interval, however, there is a gradual decrease in the mineral fraction and increase in the occluded fraction, perhaps indicating a trend toward pre-weathering of some of the glacial material entering the lake and/or a progressive increase in soil development in the watershed and importance of those sediment sources.

The most striking feature of the P geochemical record is the rapid switch from a mineral P-dominated to a mixed system soon after 9500 cal yr BP (Fig. 4). This situation persists until about 8500 cal yr BP and is followed by an abrupt shift back to mineral P-dominated conditions at 8200 cal yr BP (Fig. 4). The rapid shift to more occluded and organic P may be interpreted in several ways. First, this state of a relative balance between the three P-bearing fractions could represent a rapid and progressive development of soil nutrient status along the trajectory outlined in the soil P model (Fig. 1). The rapidity of this shift (over only approximately 50 yr), however, would require an implausibly rapid landscape and soil change, especially in light of the more gradual changes in records of soil P development from other settings (Filippelli and Souch, 1999). Furthermore, the rapid shift after 8200 cal yr BP back to a P geochemical state similar to the earlier glacially dominated record would also require an equally rapid (and unlikely) retrogression of soil development.

One possible explanation for the organic-rich interval is that it reflects increased in-lake productivity, perhaps spurred by warmer temperatures and lower turbidity within the lake (Menounos, 2002). At face value, this interpretation is difficult to support given the P geochemical record because (1) the lake sediments show a $C_{\text{org}}-P_{\text{org}}$ ratio reflective of terrestrial organic matter (litter and soil organic matter) rather than algal or lacustrine vegetation (Slater-Atwater, 2004); and (2) they also show a high occluded P concentration, indicative of deeper soil-forming processes. Occluded P would be expected to decrease if the organic matter in the lake was from in situ productivity because the lability of this material leads to suboxic conditions in lake sediments and the consequent dissolution of soil-formed oxides, as represented by the occluded P fraction.

The most viable interpretation of the interval from 9300 to 7600 cal yr BP is that it represents a change in sediment sources and nutrient dynamics associated with rapid retreat of proximal glaciers and storage of glacially derived sediments up-valley of Lower Joffre Lake. Following the demise of the Cordilleran ice sheet, glaciers above Lower Joffre Lake (if present at all) were substantially less extensive than today and up-valley of the upper two lakes, which would have trapped most of the glacial sediments. Evidence is provided by the lower clastic input to Lower Joffre at this time. Significant nutrient transformations could occur in the watershed sediments because soil loss would be low but would be recorded by the lake sediments, as the latter would not be influenced by direct glacial sediment input. Moreover, if the lake was warmer at this time and lake levels dropped, shoreline erosion might also have provided an important source of weathered (organic and occluded) P

fractions. With growth of ice during the Holocene (discussed below), greater runoff would result in some of the weathered sediments rapidly removed from the upper watershed and higher lake levels would reduce direct erosion of the lake basin itself.

The increase in P mineral between 8500 and 8000 cal yr BP may signal a minor advance of alpine glaciers (Menounos et al., 2004). Though paleobotanical evidence indicates warm and dry conditions in the region (e.g., Clague and Mathewes, 1989; Hebda, 1995; Pellatt and Mathewes, 1997), the largest cold event of the Holocene occurred around 8200 cal yr BP (Alley et al., 1997; Morrill and Jacobsen, 2005), perhaps driven by a perturbation in the circulation pattern of the North Atlantic Ocean (Barber et al., 1999) (Fig. 5). It may have been that the cold event was too short to alter vegetation patterns (e.g., Bradley, 1999) but of sufficient magnitude to cause glaciers to advance. The P geochemical record reveals a rapid shift toward a greater proportion of mineral P (Fig. 5), suggesting that glacialic sedimentation increased. Thus, this British Columbia record of the 8200 cal yr BP cold event is an indication of the extent and impact of this climatic perturbation. Another early Holocene peak in mineral P is observed at ca. 7500 cal yr BP and followed by a trend of increasing P mineral toward the present time (Fig. 4). The rapid return of the P geochemical composition to earlier conditions after each mineral P peak

indicates that soil nutrient status on the slopes was not significantly impacted by these short-term climatic events that led to minor glacial advance.

The record of P geochemistry from 7000 cal yr BP to the present is marked by a low and nearly constant organic P fraction, a high and slightly increasing mineral P fraction, and a moderate occluded P fraction that decreases over the last 1200 yr (Fig. 4). The proportions of the three fractions reflect input both from slope soils and glacial sources. Mineral P increases abruptly at 3500 cal yr BP and peaks at ca. 3200, 2800–2300, 1400, and 250 cal yr BP (Fig. 5). Thus, in the uppermost part of the Lower Joffre Lake record, the mineral P fraction (% total) shows a strong correspondence with the terrestrial records of middle to late Holocene (3500–300 cal yr BP) glacial advances in the Canadian Cordillera (Ryder and Thompson, 1986; Souch, 1994). The onset of the Little Ice Age (800 cal yr BP) does appear to be reflected in the record, as the proportion of mineral P increases to values among the highest, since the retreat of Pleistocene ice whereas occluded P decreases (Fig. 4). This suggests that glacialic sedimentation rates were at their highest through the Little Ice Age, in agreement with most terrestrial evidence for maximum Holocene extent of Coast Mountain glaciers during this period (Ryder and Thompson, 1986; Osborn and Luckman, 1988; Luckman, 2000). The correspondence between the P mineral and the terrestrial record of glacier fluctuations is stronger than that exhibited by simple bulk physical properties of lake sediment cores (e.g., Menounos, 2002).

Conclusions

The temporal record of P geochemistry presented here reflects the impact of climate on landscapes and soil development. Results from P geochemistry reveal the interplay between glacial- and slope-derived sediments and the nature of soil nutrient cycling in surrounding slopes. The P record indicates minor soil formation on slopes immediately following deglaciation and the dominant sediment source to the lake was unweathered, glacialic sediments. After ca. 9300 cal yr BP, significant changes in the P geochemistry of the sediments indicate an interval of early and rapid soil nutrient maturation with decreased direct inputs of glacial sediments. The system was effectively “reset” ca. 8200 cal yr BP with an influx of mineral P-rich sediments, probably from a glacial source and temporally consistent with the 8200 yr BP cooling event. The remaining record reveals a continual increase in glacial-type nutrient conditions in the watershed, revealing a trend towards cooler and/or wetter conditions in the Coast Mountains from early Holocene to the end of the Little Ice Age. The importance of glaciers on clastic sediment delivery is noted in the correspondence between the mineral P and terrestrial record of Holocene glacier fluctuations but additional work is required to clarify whether these sediments are delivered during ice advance, standstill, or retreat. Overall, this setting is characterized by soils that are not substantially advanced along the soil nutrient development trajectory.

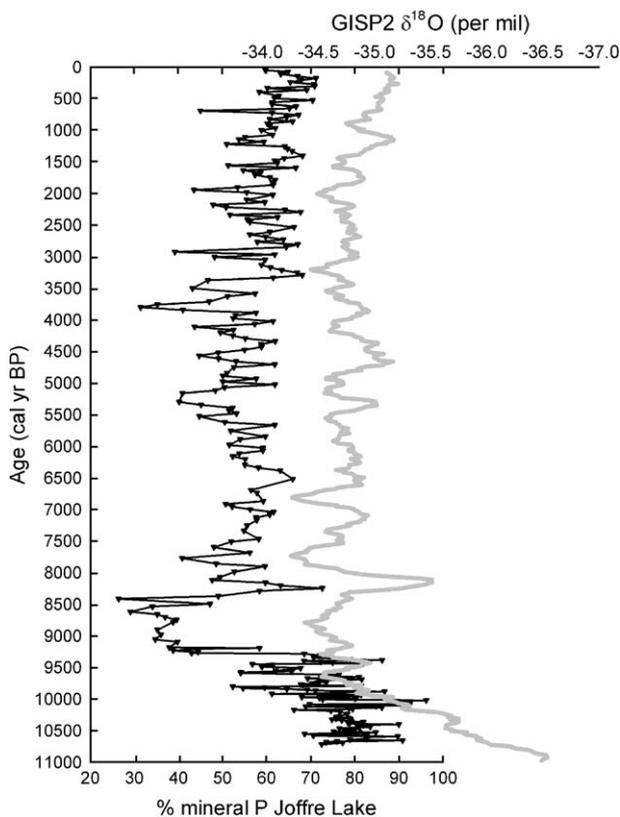


Figure 5. Fraction (%) of mineral P for Lower Joffre Lake (black line) compared with GISP2 ice core record of oxygen isotopic variation (Cross, 1997) (grey line). The ice core record reveals the 8200 cal yr BP cold event observed in the North Atlantic region, which is temporally consistent with a spike in mineral P related to a minor advance of glaciers in the southern Coast Mountains.

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References

- Alley, R., Mayewski, P., Sowers, T., Stuiver, M., Taylor, K., Clark, P., 1997. Holocene climate instability a prominent widespread event 8200 yr ago. *Geology* 25, 483–486.
- Anderson, L.D., Delaney, M.L., 2000. Sequential extraction and analysis of phosphorus in marine sediments Streamlining of the SEDEX procedure. *Limnology Oceanography* 45, 509–515.
- Barber, D., Dyke, A., Hillaire-Marcel, C., Jennings, A., Andrews, J., Kerwin, M., Bilodeau, G., McNeely, R., Southon, J., Morehead, M., Gagnon, J., 1999. Forcing of the cold event of 8200 years ago by catastrophic draining of Laurentide lakes. *Nature* 200, 344–348.
- Bradley, R.S., 1999. *Paleoclimatology: Reconstructing Climates of the Quaternary*, Second Edition. Harcourt Academic Press, San Diego, CA, p. 613.
- Chadwick, O.A., Derry, L.A., Vitousek, P.M., Hubert, B.J., Hedin, L.O., 1999. Changing sources of nutrients during four million years of ecosystem development. *Nature* 397, 491–497.
- Clague, J.J., 1989. Quaternary Geology of the Canadian Cordillera Chapter 1 in *Quaternary Geology of Canada and Greenland*. In: Fulton, R.J. (Ed.), *Geology of Canada*, vol. 1. Geological Survey of Canada, pp. 17–98.
- Clague, J., Mathewes, R., 1989. Early Holocene thermal maximum in western North America new evidence from Castle Peak British Columbia. *Geology* 17, 277–280.
- Clague, J.J., Evans, S.G., Rampton, V.N., Woodsworth, G.J., 1995. Improved age estimates for the White River and Bridge River tephros, Western Canada. *Canadian Journal of Earth Science* 32, 1172–1179.
- Crews, T.E., Kitayama, K., Fownes, J.H., Riley, R.H., Herbert, D.A., Mueller-Dombois, D., Vitousek, P.M., 1995. Changes in soil phosphorus fractions and ecosystem dynamics across a long chronosequence in Hawaii. *Ecology* 76, 1407–1424.
- Cross, M. compiler. 1997. Greenland summit ice cores. Boulder, CO National Snow and Ice Data Center in association with the World Data Center for Paleoclimatology at NOAA-NGDC, and the Institute of Arctic and Alpine Research. CD-ROM.
- Cross, A.F., Schlesinger, W.H., 1995. A literature review and evaluation of the Hedley fractionation applications to the biogeochemical cycle of soil phosphorus in natural ecosystems. *Geoderma* 64, 197–214.
- Desloges, J.R., Gilbert, R., 1994. Sediment source and hydroclimatic inferences from glacial lake sediments the postglacial sedimentary record of Lillooet Lake British Columbia. *Journal of Hydrology* 159, 375–393.
- Engstrom, D.R., Fritz, S.C., Almendinger, J.E., Juggins, S., 2000. Chemical and biological trends during lake evolution in recently deglaciated terrain. *Nature* 408, 161–166.
- Filippelli, G.M., 2002. The global phosphorus cycle. In: Kohn, M., Rakovan, J., Hughes, J. (Eds.), *Reviews in Mineralogy and Geochemistry*, vol. 48, pp. 391–425.
- Filippelli, G.M., Delaney, M.L., 1996. Phosphorus geochemistry of equatorial Pacific sediments. *Geochimica et Cosmochimica Acta* 60, 1479–1495.
- Filippelli, G.M., Souch, C., 1999. Effects of climate and landscape development on the terrestrial phosphorus cycle. *Geology* 27, 171–174.
- Gardner, L.R., 1990. The role of rock weathering in the phosphorus budget of terrestrial watersheds. *Biogeochemistry* 11, 97–110.
- Gavin, D.G., McLachlan, J.S., Brubaker, L.B., Young, K.A., 2001. Postglacial history of subalpine forests Olympic Peninsula, WA, U. S. A. *The Holocene* 11177–11188.
- Hebda, R., 1995. British Columbia vegetation and climate history with focus on 6 KA BP. *Geographie Physique et Quaternaire* 49, 55–79.
- Leonard, E., 1986. Use of sedimentary sequences as indicators of Holocene glacial history Banff National Park, Alberta. *Quaternary Research* 26, 218–231.
- Lian, B., Huntley, D.J., 1999. Optical dating studies of post-glacial aeolian deposits from the south-central interior of British Columbia Canada. *Quaternary Science Reviews* 18, 1453–1466.
- Luckman, B., 2000. The little ice age in the Canadian Rockies. *Geomorphology* 32, 358–384.
- Luckman, B., Osborn, G.D., 1979. Holocene glacier fluctuations in the middle Canadian Rocky Mountains. *Quaternary Research* 11, 52–77.
- Luckman, B., Holdsworth, G., Osborn, G.D., 1993. Neoglacial glacial fluctuations in the Canadian Rockies. *Quaternary Research* 39, 144–153.
- Mayewski, P.A., Rohling, E., Stager, J.C., Karlen, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R.R., Steig, E.J., 2004. Holocene climate variability. *Quaternary Research* 62, 243–255.
- Menounos, B., 2002. *Climate, fine-sediment transport linkages, Coast Mountains, British Columbia*. PhD thesis, The University of British Columbia, Vancouver, Canada, 259 pp.
- Menounos, B., Koch, J., Osborn, G., Clague, J.J., Mazzucchi, D., 2004. Early Holocene glacier advance, southern Coast Mountains British Columbia, Canada. *Quaternary Science Reviews* 23, 1543–1550.
- Morrill, C., Jacobsen, R.M., 2005. How widespread were climate anomalies 8200 years ago? *Geophysical Research Letters* 32, L1970110.1029/2005GL023536.
- Oldfield, F., 1977. Lakes and their drainage basins as units of sediment based ecological study. *Progress in Physical Geography* 1, 460–504.
- Osborn, G., Luckman, B., 1988. Holocene glacier fluctuations in the Canadian Cordillera. *Quaternary Science Reviews* 7, 115–128.
- Pellatt, M.G., Mathewes, R.W., 1997. Holocene tree line and climate change on the Queen Charlotte Islands Canada. *Quaternary Research* 48, 88–99.
- Ruttenberg, K.C., 1992. Development of a sequential extraction method for different forms of phosphorus in marine sediments. *Limnology and Oceanography* 37, 1460–1482.
- Ryder, J.M., 1981. Geomorphology of the southern part of the Coast Mountains of British Columbia. *Zeitschrift für Geomorphologie* 37, 120–147.
- Ryder, J.M., Thompson, B., 1986. Neoglaciation in the southern Coast Mountains of British Columbia chronology prior to the late-neoglacial maximum. *Canadian Journal of Earth Science* 23, 273–287.
- Schlesinger, W.H., 1997. *Biogeochemistry an Analysis of Global Change*. Acad. Press, San Diego.
- Schlesinger, W.H., Bruijnzeel, L.A., Bush, M.B., Klein, E.M., Mace, K.A., Raikes, J.A., Whittaker, R.J., 1998. The biogeochemistry of phosphorus after the first century of soil development on Rakata Island Krakatau, Indonesia. *Biogeochemistry* 40, 37–55.
- Slater-Atwater, S., 2004. The effects of climate and weathering on terrestrial phosphorus cycling in an alpine system, Coast Mountains, British Columbia. MS Thesis, Department of Geology, Indiana University-Indianapolis, 111 pp.
- Souch, C., 1994. A methodology to interpret downvalley lake sediments as records of neoglacial activity Coast Mountains British Columbia, Canada. *Geografiska Annaler* 76A, 169–186.
- Strickland, J.D.H., Parsons, T.R., 1972. *A practical handbook of seawater analysis*. Fisheries Research Board Canada Bulletin 167, 311.
- Stuiver, M., Reimer, P.J., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., van der Plicht, J., Spurk, M., 1998a. INTCAL98 radiocarbon age calibration 24,000–0 cal BP. *Radiocarbon* 40, 1041–1083.
- Stuiver, M., Reimer, P.J., Braziunas, T.F., 1998b. High-precision radiocarbon

- age calibration for terrestrial and marine samples. *Radiocarbon* 40, 1127–1151.
- Tiessen, H., Moir, J.O., 1993. In: Carter, M. (Ed.), *Characterization of Available P by Sequential Extraction*, in *Soil Sampling and Methods of Analysis*. Lewis, Boca Raton, FL, pp. 75–86.
- Vitousek, P.M., Chadwick, O.A., Crews, T.E., Fownes, J.H., Hendricks, D.M., Herbert, D., 1997. Soil and ecosystem development across the Hawaiian Islands. *GSA Today* 7, 1–8.
- Walker, T.W., Syers, J.K., 1976. The fate of phosphorus during pedogenesis. *Geoderma* 15, 1–19.