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Advances in Holocene mountain geomorphology inspired by sediment budget methodology

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Abstract

The sediment budget, which links sediment sources to sediment sinks with hydroclimatic and weathering processes mediating the response, is applied to the analysis of sediments in three alpine lakes in British Columbia. We provide two ways of using the sediment budget as an integrating device in the interpretation of mountain geomorphology. These approaches differ in their resolution and ability to budget the major components of the fine-sediment cascade in glaciated environments. Taken together, they provide an integrated index of landscape change over the Holocene. The first example compares the hydroclimatic controls of lake sedimentation for the last 600 years (A.D. 1370–1998) preserved in varved sediments from two of the lake basins. This hydroclimatological approach incorporates contemporary monitoring, air photo analysis, and detailed stratigraphy of sedimentation events within a single varve to infer the timing, sources, and preferred pathways of fine-grained sediments reaching the lake basins. The results indicate that glaciers, hillslope, and channel instability within the major subbasins are the principal sediment sources to the lake basins. Transitory sediment storage of glacially derived sediments within the channels is believed to modulate the episodic and more frequent delivery of sediments from adjacent hillslope and fluvial storage sites and direct routing of glacial rock flour during years of prolonged glacial melt. The second example, relying on the phosphorus geochemistry of sediments in an alpine lake basin, considers the evolution of phosphorus forms (from mineral to occluded and organic fractions) as a function of the soil development, inherent slope instability, and repeated cycles of glaciation and neoglaciation over the Holocene. This geochemical approach demonstrates that both neoglaciation and full glaciation have essentially zeroed the system in such a way that a high proportion of mineral phosphorus remains in the present lake sediments and the bioavailability of phosphorus (a key to ecosystem development) is low. Both examples illustrate the importance of variable sediment sources; the seasonality, frequency, and magnitude of sediment transfers; and the profound influence of ice cover over contemporary, neoglacial and Pleistocene time scales. They also signal the value of including both clastic and dissolved components in the sediment budget.
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1. Introduction

The macro-scale geomorphology of the Pacific ranges of the Coast Mountains of British Columbia,

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the product of tens of millions of years of tectonic evolution, is well understood (Ryder, 1981). Glacial modifications of that macro-scale geomorphology express themselves characteristically at meso-scales and result from the last 1–2 million years of recurring glaciation. These too are moderately well understood. By way of contrast, the fine-scale detail of geomorphic modification during the 10,000-year Holocene Epoch is not so well understood. This is because the effects of changing climate on weathering, soil formation and erosional processes, the thresholds of resistance presented by varying lithologies, and the

lag times between process change and landscape response are, in general, not known. Lake sediments provide an archive of information on past environmental changes. In particular, their analysis provides insight into variations in process rates and the activation of sediment sources. This paper describes results of analysis of both clastic sediment archives and the phosphorus geochemistry of those sediments preserved within a number of British Columbia's Coast Mountain lake basins (Fig. 1).

Two approaches that depend heavily on applications of sediment budget methodology are described here.
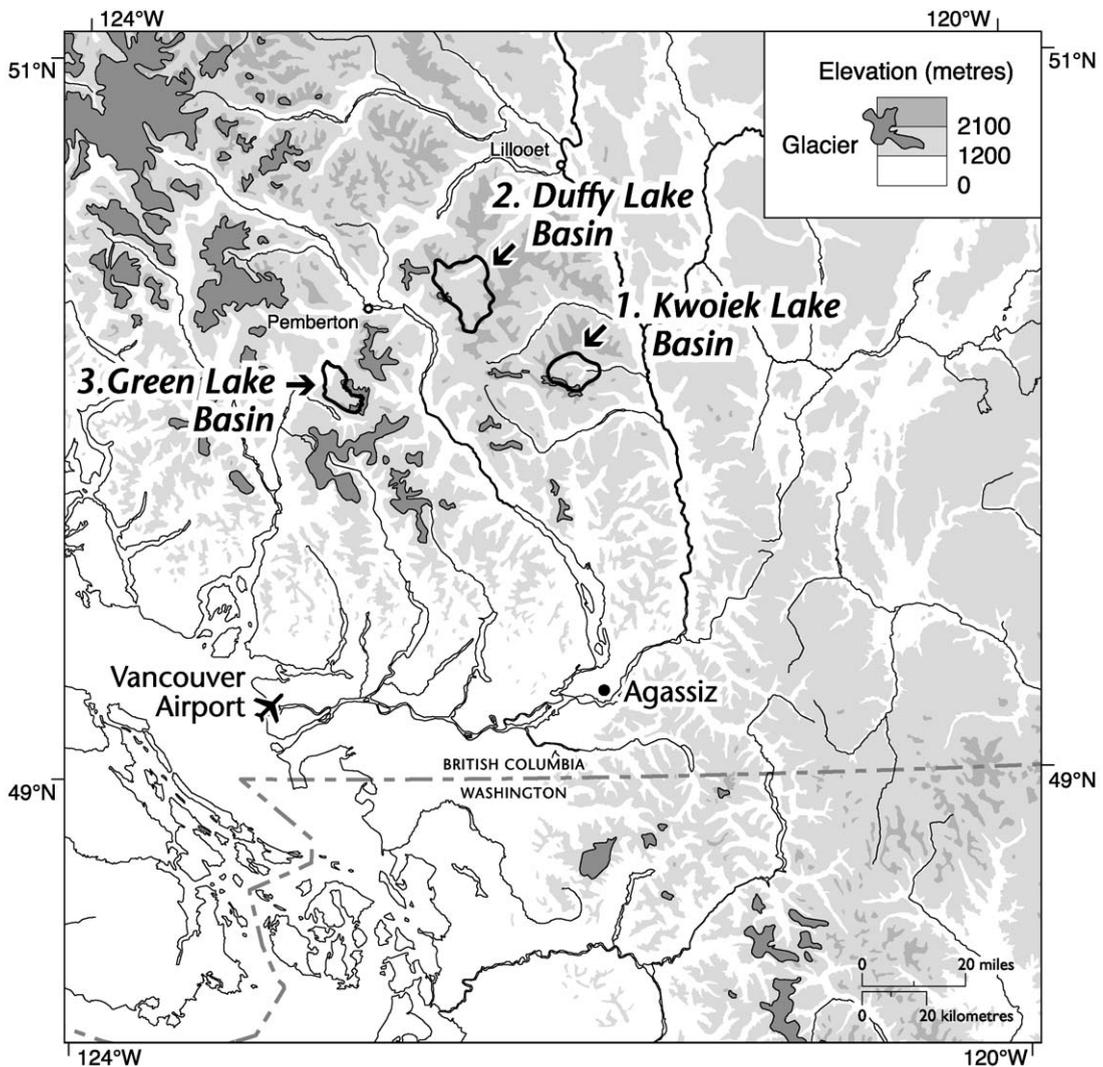

Fig. 1. Study sites: (1) Kwoiek, including Kokwaskey Lake; (2) Duffey Lake; and (3) Green Lake basins.

The first addresses the question of magnitude and frequency of geomorphic events during the Holocene (and can be labelled a hydroclimatological approach). The second considers soil development and slope stability (a geochemical approach). We will first review the origins and importance of sediment budget methodology. An explanation will follow of the premises on which the hydroclimatological and the geochemical approaches are based. We will then demonstrate the key role played by sediment budgeting in these applications and, finally, we will return to the landscape scale and suggest ways in which these findings affect our understanding of the regional geomorphology.

2. Variable source hydrology, variable solute sources, dynamic sediment sources, and sediment budgets

The idea of a sediment budget is disarmingly simple in that it is an accounting of the sources, movements, and sinks of sediment in the landscape. The first formal sediment budget was published by Jackli (1957) in the context of a study of the upper Rhine watershed and its geomorphology. Rapp (1960) emphasised the importance of including solutes; and Oldfield (1977) linked solute routing, nutrient cycling, and ecology in his lake basin sediment budgets. Subsequently, the solute fraction and the role of weathering vis-à-vis sediment budgeting have been comparatively neglected [though note Gallie and Slaymaker (1984) and, more recently, Hill and Brooks (1996) and Devito et al. (1996). Swanson et al. (1982) discussed the range of application of sediment budgets and Foster et al. (1985) formulated the sediment budget for lake basins. Reid and Dunne (1996) provided illustrations of ways in which sediment budgets could resolve environmental management problems. Sources, pathways, and sinks of clastic sediments within relatively small basins have been widely reinterpreted as a result of quantitative sediment budget calculations. The study of sources, pathways, and sinks of solutes and sediments relies, in a quantitative sense, on the understanding of variable runoff sources, pathways, and sinks in watershed hydrology (Slaymaker, 2000). Comprehensive studies of runoff, solutes, and clastic sediments are extremely time consuming and expensive; and a strong incentive exists, therefore, to define and use surrogate measures

or, alternatively (as much of the literature does), to ignore two of the three components of the budget. Recently, increasing emphasis has been placed on the quantification of storage elements, their size and longevity in the landscape, and their response to environmental change as a surrogate for detailed sediment budget calculations. We have followed this trend by examining sediments stored in lakes and on slopes and estimating their magnitude and frequency of deposition as a basis for first estimates of components of the sediment budget. Sediment storage elements in the landscape, whether in lakes or on slopes, are the medium through which transport processes act and, therefore, their quantification is critical input to the sediment budget.

Common to all the watersheds discussed in this paper is the presence of glacial ice and a more extensive ice cover in the recent past. The major sediment sources believed to be important for this study include the following:

(i) rock flour derived from subglacial erosion and glacier forefields—these glacial sediments have been directly coupled with downstream storage sites, such as lake basins;
(ii) fluvioglacial deposits derived from paraglacial valley fill and terraces from the early Holocene;
(iii) fluvioglacial deposits derived from exposed forefields and moraines during neoglacial advances; and
(iv) sediments originating from hillslope instabilities.

Any inferences about sediment sources drawn from the sediments in lakes at the lower end of these systems require careful checking against air photo analysis and field site visitation. In addition to this more standard sourcing methodology, the present study introduces a technique of examining the status of the phosphorus geochemistry of the sediments that allows a potentially greater accuracy in the identification of basin sediment sources.

3. A hydroclimatological approach to sediment budgeting

Because the majority of sediment moving through a basin is transported by water, sources, pathways,

and sinks of water in a basin normally are determined first and then sediment transport is estimated via a sediment concentration versus discharge relation at a number of sites in the basin. This method gives a good first estimate of total sediment flux during "normal" discharge events. Under high flow conditions, rating curves tend to break down and samplers are rarely in place at the peak of the discharge. This means that a purely hydrologic approach will normally underestimate the total sediment flux. This is a recurring problem with hydrologic estimates of magnitude and frequency of occurrence of extreme hydrological events.

The availability of records of sedimentation in lakes and deltas for periods of time greatly in excess of the monitored record is a critical archive of past events (e.g., Desloges and Gilbert, 1994; Menounos et al., 2000). Where lake sediments are varved, the sedimentation history can be learned by measuring variation of the mass properties of each sedimentation unit with depth. Typically, studies of this kind engage in a detailed statistical analysis of discharge and sediment transport over a shorter monitored period of record (of perhaps the last 50–100 years). At the same time, they supplement this analysis with analysis of the sediment properties over millennia. A central premise in patching the monitored records and the accumulated sediment records is that the thickest varves correspond with the highest magnitude discharge events. The censoring of medium to low magnitude events in the varve record contrasts with the comprehensive record of all hydrologic events included in the monitored record (Menounos and Slaymaker, 2000).

Secular trends and cycles are therefore analysed separately and compared. Decomposing the sediment records provides insight into sediment source changes over seasonal to millennial time scales. Although the low frequency component of clastic sediment delivery agrees with well-constrained periods of ice advance in the Coast Mountains and Canadian Cordillera more generally, the complexity and difficulty of assessing sediment sources in this way becomes greater as finer detail is examined. Phosphorus geochemistry, which relies on totally different premises from those of the hydroclimatological approach, is a useful method for checking consistency of the interpreted record.

4. A geochemical approach to sediment budgeting

The basic premise of this approach is that the geochemistry and accumulation rates of the phosphorus fraction in lake sediments over time reflect changing conditions in the contributing watersheds, specifically the nature of the soils on the slopes and other up-system sources. A simple conceptual model of these changes, based on what we know about phosphorus cycling in soils (Walker and Syers, 1976; Gardner, 1990; Crews et al., 1995; Cross and Schlesinger, 1995; Vitousek et al., 1997; Schlesinger et al., 1998), is presented in Fig. 2. On a newly exposed lithic surface, phosphorus typically is present in the form of the mineral apatite (termed here mineral phosphorus). Over time, and with soil development, phosphorus is increasingly transformed into fractions co-precipitated with and/or absorbed onto iron and manganese oxyhydroxides (occluded phosphorus, formed in soils), in soil organic matter (organic phosphorus), and incorporated into more readily bio-available (labile) forms in soil pore spaces and adsorbed onto soil particle surfaces (nonoccluded phosphorus). Concurrently, the total amount of phosphorus in the soil profile decreases as soil phosphorus
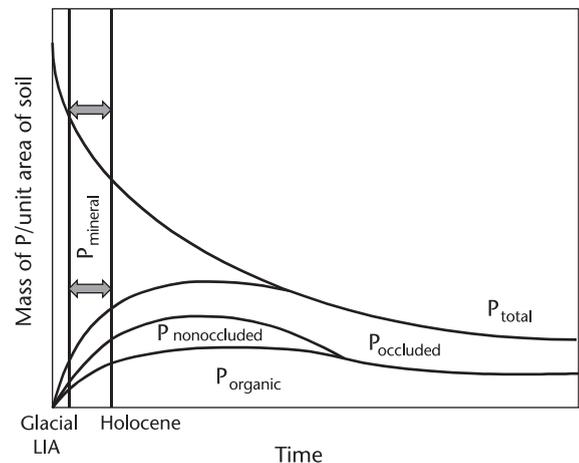

Fig. 2. Modeled changes in soil phosphorus geochemistry over time showing transformation of mineral phosphorus into nonoccluded and organic forms before eventual dominance of occluded (oxide-bound) and organic forms. Note the continual loss of total phosphorus from system. From Filippelli and Souch (1999) based on Walker and Syers (1976). The vertical lines indicate the extent of the development of the Kwoiek watershed system.

is lost through surface and subsurface runoff. Eventually, the soil reaches a steady state when soil phosphorus lost through runoff is replaced by new phosphorus weathered from apatites at the base of the soil column.

Headwater, oligotrophic alpine lake sediments that are dominated by terrestrial clastic inputs are best suited for recording the geochemical transformations of phosphorus of watershed soils over time. The dissolved inputs of phosphorus are so low that in situ organic production is at a minimum and low amounts of labile organic matter in the sediments limit the degree of diagenetic overprinting of the original sediment record. The advantages of looking at alpine lake sediments in this way, rather than relying on soil chronosequences, relate to the facts that (i) the lake sediment records provide an integrated record of watershed scale processes and (ii) discrete temporal resolution allows interpretation of landscape development through time. The following complications must be acknowledged, however. Post-depositional diagenetic overprinting of phosphorus inputs; the leakiness of the lake sediment record; some phosphorus is lost from the system; and the calibration of the time scale with phosphorus form changes depends on the dated varve chronology and the net sediment accumulation over time.

5. Description of study sites: Kokwaskey, Green, and Duffey Lake basins

Geochemical analyses of phosphorus were conducted on the sediments of Kokwaskey Lake, located within the Kwoiek Creek watershed, Coast Mountains of British Columbia (50°N, 122.8°W; elevation 1050 m) (Filippelli and Souch, 1999). Approximately 40% of the contributing watershed (total area ~ 42 km^2) currently is above tree line and 10% is glacierised. The watershed has a high range of relief (150–2944 m), with most summits and ridge crests above 2000 m. Valley slopes are steep (average slope 31°), with vertical rock faces common. The watershed is underlain by coarse-grained granodiorite of the Coast Plutonic complex, or low-grade metamorphosed stratified rocks. Beyond recent extensive logging, the watershed is unaffected by anthropogenic activity.

The 4.2-m lake sediment core analysed is described by Souch (1994); chronology is provided by two radiocarbon dates (11,485 + 185 S-2935; 4900 + 325 S-2988) and two tephra layers (Mazama and Bridge Rivers) (Souch, 1994). The lake sediments (mean grain size 7.2 Φ) are composed almost exclusively of terrigenous material from the upstream Chochiwa glacier and surrounding slopes, with little material contributed by lake productivity. Trap efficiency is not 100%, but a significant fraction of inflowing sediment has accumulated throughout the lake's history. Because the main goal of this study is to examine relative phosphorus geochemical fractions, it does not matter if a significant amount of material is flowing through the system without being deposited, as long as the relative proportion of phosphorus geochemical fractions in the lake sediments reflects that coming off the slopes. Eolian input is limited and primarily derived from local sources (Souch, 1994).

The Duffey Lake basin (250 km^2) was heavily glaciated but, at present, is lightly glacierised (1.7%). Cayoosh and Van Horlick Creeks are the two main stream systems that drain the basin and 40% of the basin is above tree line. Duffey Lake itself, with a surface area of 3.8 km^2, is a 90-m-deep basin that is oriented parallel to the main valley axis of Cayoosh Creek. Van Horlick Creek is a sandbed river draining 118 km^2. Cayoosh Creek is largely a gravel bed river draining 98 km^2. Lateral instability and river incision are important sediment sources in Cayoosh Creek, whereas large-scale channel aggradation characterises the Van Horlick system. A large sandur extends 3 km downvalley from an active glacier in the east fork of Van Horlick Creek. Forestry activity and general land use began in 1970 in the Duffey basin when a logging road was constructed to link the towns of Pemberton and Lillooet. Approximately 8.6% of the basin has been logged. Total forest road length is 121.7 km, giving a density of 0.48 km/km^2. The geology is dominated by mid-Cretaceous to mid-Jurassic granodiorites, diorites, and quartz diorite.

The Green Lake basin drains ~ 180 km^2. Three creeks drain the lake basin, but only one (Fitzsimmons Creek) delivers the majority of sediment to Green Lake. Fitzsimmons Creek is a 19.5-km-long mountain creek draining rugged glacierised terrain (9% glacierised). The creek is steep and is incised

into thick valley fill. Green Lake has a surface area of 2 km^2 and typically has a hummocky, glaciated bottom with two main basins-one of which is 40 m and the other 30 m deep. Land use in the basin has increased dramatically since the formation of Blackcomb and Whistler ski resorts. The first expansion into the basin occurred at the beginning of the 20th century with the construction of the Pacific Great Eastern Railway, but general development of the region did not commence until the 1960s. The geology is complex with 50% granodiorite, diorite, and quartz diorite and roughly equal amounts of volcaniclastics and conglomerates.

6. Application of a hydroclimatological approach

Varve chronologies from two lake basins in the southern Coast Mountains were examined to interpret major flood events. Varve thickness is correlated with annual maximum discharge at the nearest stream gaging station (Fig. 3). The interpretation of flood events, however, is more subtle than this and a number of issues must be taken into account:

(i) the hydrologic seasons for preferred sediment transfer;
(ii) the spatial variations in impact, both internally to the basin and also regionally in mountain regions with highly variable meteorological conditions;
(iii) variable climatological controls during the period A.D. 1370–1998;
(iv) anomalously high sedimentation rates in the early part of the 20th century;
(v) post-1946 changes of sediment source.

6.1. The hydrologic seasons for preferred sediment transfer

Based on monitoring of water and suspended sediments (1997–2000), sediment transfers to the lake basins occurred primarily during three distinct seasons: nival runoff, glacial melt, and intermittent autumn cyclonic disturbance (Menounos and Slaymaker, 2000). The particle size and physical characteristics of the sediments reflect this seasonality. During snowmelt, channel sediment sources are dominant and normally graded; coarse silts to very fine

sands are characteristic of these lowermost units of varve couplets. Glacial melt produces finer sediments, which are delivered directly to lake basins, and, because of late summer lake stratification, they are effectively transported throughout the lake basin. Autumn cyclonic events, by contrast, are more intermittent and spatially discontinuous. Sediment is entrained from all basin sediment sources and larger volumes of sediment are produced.

6.2. Spatial variability of impact

An exceptional rain storm in August 1991 illustrates the spatial variability of impact. Immediately west of the Coast Mountains topographic divide, within the Green Lake basin, significant channel change and hillslope and terrace material failure occurred. East of the divide, within the Duffey Lake basin, no perceptible change was visible on the air photos. The total mass (after correction for density and nonclastic component) of sediment delivered to Green Lake as a result of the rainstorm exceeded sediment yields to the lake basin for the previous decade while the event delivered only minor volumes of sediment to Duffey Lake. A large fraction of the sediments delivered to the lake basins occurred during the annual flood. Varve thickness is correlated with the magnitude of the annual flood. However, most of the truly exceptional floods for the basins west of the divide occurred during autumn, while the discharge maxima most important for sediment transfers east of the divide were snow melt and rain on snow events. Peak flows at Duffey Lake (1997–2000) occurred in May and June, and these floods transported fine-grained sediments stored within the channel originating from neoglacial and early Holocene paraglacial sediments. By contrast, the autumn floods, which dominated the more westerly basins, generated larger volumes of coarser sediments from all four sediment sources in the basin.

6.3. Variable climatological controls during the period A.D. 1370–1998

Without access to detailed air photo interpretation or climatological data, the inferring of sediment sources and sedimentation processes is difficult. Information for this region prior to the turn of the century
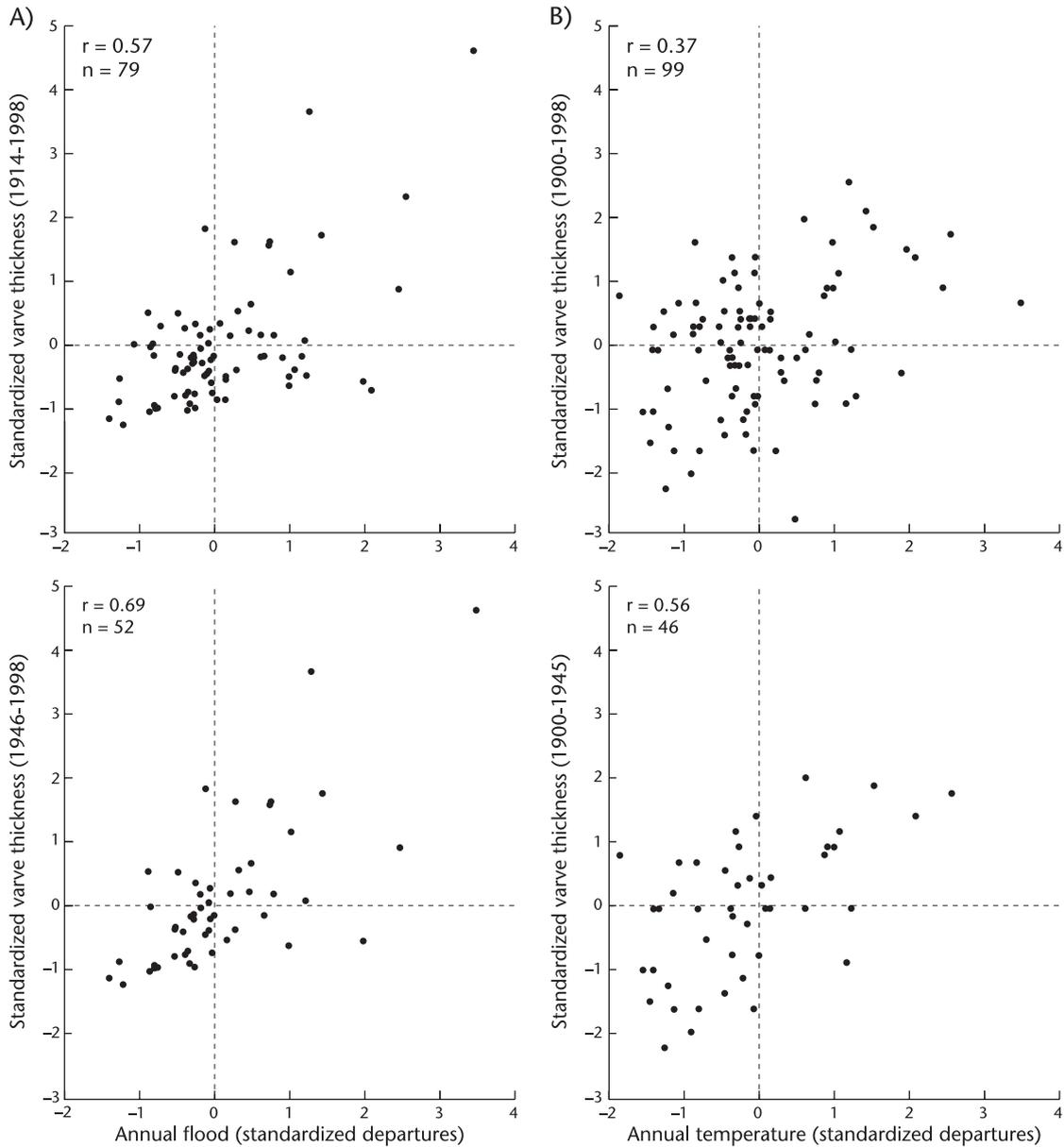
Fig. 3. Relation between varve thickness in Green Lake and (A) annual peak discharges (log transformed) in Lillooet River and (B) mean annual temperature departures from the mean at Agassiz. Note the improvement in correlation achieved from 1900 to 1945 with mean annual temperature departures and from 1946 to 1998 with annual peak discharge.

relies heavily on proxy data. We have reconstructed the varve chronology of Green Lake from A.D. 1370 to 1998 and compared this with estimates of northern hemispheric growing season temperature from a spatially distributed network of temperature sensitive

proxies (Mann et al., 1999). Decadally smoothed, standardised records reveal statistically significant correlation between the two records (JISOA, 2001). This indicates that enhanced sedimentation occurred during years that were warmer than average. Such

conditions and those where winter snow packs were light [commonly during the warm phase of the El Nino Southern Oscillation (ENSO)] produced prolonged periods of glacial runoff during the summer.

6.4. Anomalously high sedimentation in the early 20th century

Varve couplets deposited during this time period show low organic, fine-grained sediments uniformly distributed throughout the lake basins. Individual couplets deposited during this time have many sublaminae overlying the lowest, coarse-grained unit. These sublaminae are interpreted to reflect periods of sustained glacial melt as they are well distributed throughout the lake basins and are comprised of significant proportions of clay-sized material. This interpretation is partly supported by air photo evidence that documents dramatic glacial recession between 1931 and 1946. Indeed, meteorological data confirmed that this period of glacial retreat corresponded to the warmest and driest climate of the period 1900–1990. Evidence from strong correlation of varve thickness in Green Lake with annual regional air temperature (pre-1946) and stronger correlation with maximum daily discharge events (post-1946) is consistent with the importance of subglacial sediment sources during the earlier period (Fig. 3).

6.5. Post-1946 changes of sediment source

The secular trends within these records are also consistent with a sediment source change after 1946. Although northern hemispheric temperature estimates remained well above average following 1946, varve thickness declined appreciably. The suggestion then is that glaciers and glacial runoff played a larger role as a sediment source prior to 1946.

This hydroclimatological approach to sediment source and sediment budget assessments is greatly expanding our understanding of Holocene alpine landscape evolution. Periods of time when glacial sediment sources are dominant alternate with periods when basin-wide sources are dominant. Maritime and continental basins separated by only a few tens of kilometers, respond to different climatic signals. Such temporal and spatial variability of process is subtly reflected in varve thickness variation.

7. Application of a geochemical approach

The sequential extraction technique of Filippelli and Delaney (1996), similar to Tiessen and Moir (1993), was used to geochemically distinguish the mineral, occluded, and organic phosphorus fractions in multiple lake sediment samples from Kokwaskey Lake. The extraction technique involved (i) a citrate–dithionite–bicarbonate reducing agent and magnesium chloride (occluded fraction), (ii) dissolutions with sodium acetate and acetic acid solution and hydrochloric acid (mineral fraction), and (iii) ashing followed by dissolution with hydrochloric acid (organic fraction). Given accumulation rates in the lake and sample sizes used (depth increments ∼ 1 cm), each sample provides integrated results for time periods of decades to centuries.

Souch (1994) documented that variations in sedimentation rates in Kokwaskey Lake clearly reflected the deglacial and neoglacial history of the region (Fig. 4). Sedimentation rates immediately following deglaciation (the paraglacial period of Church and Ryder, 1972) were very high as large expanses of unvegetated surficial deposits were exposed by retreating ice and thus easily eroded. Greater meltwater discharges also increased the capacity and competence of proglacial rivers. Rates of sedimentation decreased and stabilized 10,000–7000 YBP as the landscape stabilised and soil development was initiated. Climatic deterioration in the mid-Holocene and renewed neoglacial activity subsequently (Ryder and Thompson, 1986) increased glacial sediment supply, resulting in greater sedimentation rates 6000–5000, 3500–2900, and post-750 YBP.

Temporal variations in the phosphorus geochemistry of the lake sediments provide further insight into rates of erosion, soil development, and landscape stability over the postglacial period. Continual erosion from steep slopes and glacial sources is evidenced by the dominance of mineral forms of phosphorus in the lake sediments over the last 12,500 years (mineral phosphorus constitutes >90–50%). Occluded phosphorus is of secondary importance with organic phosphorus present only in relatively low concentrations (Fig. 4).

Kokwaskey Lake was completely glacier covered ca. 12 ka, thus the initial starting point for this system was nearly completely mineral phosphorus (>90%)
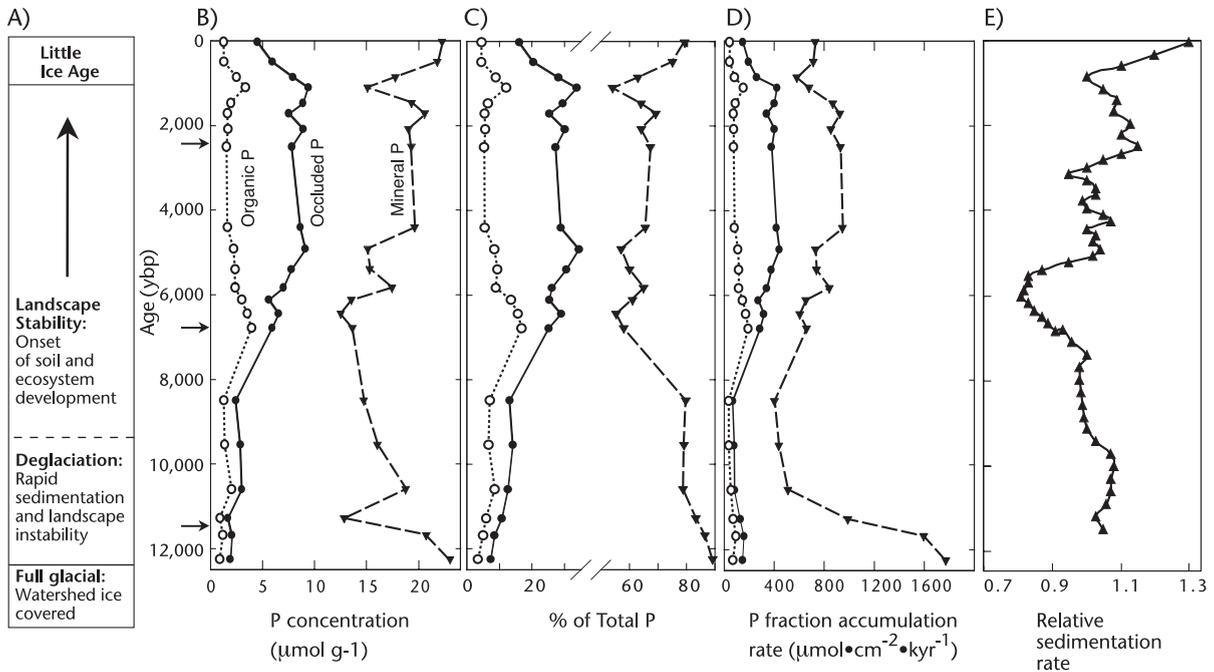
Fig. 4. (A) Environmental conditions in the basin; (B) phosphorus concentration for each P-bearing fraction in sediments from Kokwaskey Lake; (C) percent of total phosphorus; (D) accumulation rate of phosphorus fractions; (E) relative rates of sediment influx based on results and analyses in Souch (1994). Arrows on age axis are age control points (radiocarbon dates and Mazama and Bridge River tephras).

from rock flour. Mineral phosphorus does exhibit a decrease, however, to ~ 50% during the latter part of the mid-Holocene warmer, drier interval indicative of landscape stabilisation and soil development (ca. 9–6 ka). The proportions of occluded P, and to a lesser extent organic P, increased during this interval. From the mid- to late-Holocene (6–1 ka), a period of cooler/wetter conditions (Pellatt and Mathewes, 1997), each fraction varied slightly, with mineral phosphorus 60–70% and occluded phosphorus 20–30%. The last 1000 years of this record, marked by the most extensive Holocene neoglacial activity (Ryder and Thompson, 1986), is characterized by a rapid return of phosphorus geochemistry to glacial/deglacial conditions—mineral phosphorus rises rapidly (to >80%), while the occluded and organic fractions fall.

Large changes in the accumulation rate of phosphorus over time are also recorded. These accumulation rate changes are driven partly by changes in bulk sedimentation rate, but several of the rapid shifts in phosphorus accumulation occur between age con-

trol points (indicated on Fig. 4) and are thus not just driven by rates of sedimentation. Rates of phosphorus accumulation in the early deglacial period, driven largely by paraglacial processes, exceed 1600 µmol P cm^{-2} ka^{-1}. Most of the material accumulating is mineral phosphorus (~ 1600 µmol P cm^{-2} ka^{-1}) derived directly from glacial rock flour (sediments are blue-gray glacial clays). From ~ 9 to 6 ka, landscape stabilisation began, although the landscape was still marked by high relief and rapid rates of erosion. In this period, total phosphorus accumulation rates in Kokwaskey Lake dropped by a factor of 3 to ~ 450 µmol P cm^{-2} ka^{-1}. Of this, most still remained mineral phosphorus (~ 400 µmol P cm^{-2} ka^{-1}). Total rates of accumulation rose in the mid-Holocene (8000–6000 YBP) to ~ 800 µmol P cm^{-2} ka^{-1}, driven both by increasing sedimentation rates and increased contributions of occluded phosphorus (up to ~ 400 µmol P cm^{-2} ka^{-1}). Phosphorus input rates rose again to ~ 1200 µmol P cm^{-2} ka^{-1} by 4 ka, decreasing slightly thereafter. Accumulation rates dropped in the last 1000 years, but the mineral

fraction increased again as the occluded and organic fractions dropped.

Throughout the Holocene, the high-relief Coast Mountains watershed led to constant loss of surface sediments with poorly developed soils and relatively little organic phosphorus. In this high-relief alpine setting, soil development is retarded by rapid denudation and thus the terrestrial phosphorus cycle is stuck in an "initial development stage" with high mineral phosphorus and high phosphorus release rates from the landscape. Vertical lines on Fig. 2 indicate the limited extent of the relative development of the soil P geochemistry of the Kwoiek watershed system over the Holocene. Detailed variation of lake sediment P geochemistry shows how the system is effectively reset (zeroed) back to initial conditions by neoglacial advances of the headwater glaciers (Fig. 4). By contrast, the transformation of mineral phosphorus is more complete and more rapid in relatively lower elevation and warmer sites (Jackson Pond, TN) (Filippelli and Souch, 1999). A chronosequence of Hawaiian soils revealed significant transitions in mineral phosphorus after about 1000 years of soil development (Crews et al., 1995; Vitousek et al., 1997), while significant transformations occurred in phosphorus biogeochemistry during soil development on a Krakatoa lava flow in just over 100 years (Schlesinger et al., 1998). In the Coast Mountain example presented here, this decrease occurred over time scales of 3000–5000 years. The alpine British Columbia site has never achieved the relative stabilisation observed in temperate and tropical settings elsewhere. Thus, phosphorus release remains relatively high and the phosphorus geochemistry of this system can be reset quickly. Readvance of alpine glaciers during the Little Ice Age was sufficient to move the phosphorus geochemical cycle back to near-glacial conditions (Fig. 2).

These results are preliminary and work is currently underway to expand the geographic range of sites considered, increase temporal resolution to the decadal scale, and to examine downvalley lake sediment sequences as they integrate several watersheds. However, the results suggest that in alpine settings lake sediments allow us to document the effects of climate on soil and landscape development and on biogeochemical cycles.

8. Implications of findings for geomorphic interpretation at the landscape scale

8.1. Magnitude and frequency of geomorphic events

The lake phosphorus record illustrates the importance of glaciation in setting the initial stage of soil P geochemistry, effectively zeroing the system. This can be achieved by neoglaciation as well as by full glaciation. The slow rate of evolution of the phosphorus forms is a function of the hydroclimatological regime and inherent slope instability, reinforced by frequent glaciation/neoglaciation. This has implications for the geochemical form and total loss of phosphorus from these alpine systems. A high proportion of the phosphorus is mineral phosphorus and the bioavailability of phosphorus, a key to ecosystem development, is low.

The varved lake sediment record permits greater resolution of magnitude-frequency relations from A.D. 1370 to present, but we are unable to say much about events earlier in the Holocene. The lesson that is emphasised from these data is the necessity to combine a variety of proxy data to achieve understanding of the secular variations in varve thickness and the inadequacy of inferred temperature data to provide estimates of magnitude and frequency of sediment-producing events.

8.2. Time scale considerations

The resetting of the geological clock following neoglaciation and full glaciation is an important contribution provided by the phosphorus geochemistry. At this time, this provides a low resolution record for the Holocene, but in principle, higher resolution analyses can be anticipated.

The varve chronology provides decadal-scale resolution over the past 630 years. Positive residuals from the correlation between varve thickness and temperature indices are interpreted as times when glaciers are retreating most rapidly and negative residuals imply reduced glacier melt runoff.

8.3. Spatial scale considerations

From the phosphorus geochemistry, site and watershed scale interpretation is sought. An intermediate-

size headwater system (10^2–10^3 km^2) with strong glacial input, where dissolved nutrient inputs are minimal so as to limit the degree of diagenetic overprinting on the original sediment record, is the basic experimental unit. Sediment sources are relatively simple, incorporating direct glacial and proximal slope input.

The varve chronology from two lake basins provides an integrated account of clastic sedimentation for two intermediate-size headwater systems and makes inferences about the spatial variability of sediment sources within those watersheds, based on their response to hydroclimatological events (continental versus maritime location).

8.4. The paraglacial concept

Much of the work on sediment sources and sediment budgets in the Canadian Cordillera takes its inspiration from the work by Church and Ryder (1972), introducing the paraglacial concept. In the case of the phosphorus geochemistry study, glaciation (both neoglaciation and full glaciation) results in a pulse of sediment moving through the system. This is reflected in sediment accumulation rates as well as in the geochemical signature.

The varve chronology allows some increased resolution of the paraglacial effect from the Little Ice Age, namely the identification of a period of anomalously higher sedimentation rates during the early part of the 20th century. Sedimentation in the two lake basins is also recognized as greater at the base of the sediment cores retrieved, which correspond with the early Holocene paraglacial episode. Unfortunately, the varve records are incomplete, such that quantitative estimates are difficult to assess.

8.5. The sediment budget as an integrator of geomorphic information

Comprehensive quantitative sediment budgets for the three alpine lake basins studied for the whole of the Holocene epoch are not available. The advantage that the sediment budget approach affords, as illustrated by these two variants in three lake basins, is a conceptual framework that encourages new insights. The linking of sediment sources (glacial, paraglacial, and slope failures) to sediment sinks (the three lakes)

with hydroclimatology and weathering processes mediating the response provides a fruitful avenue for exploration of the evolution of these alpine landscapes.

Acknowledgements

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