Journal of Coastal Research	20	4	958–969	West Palm Beach, Florida	Fall 2004

Direct Sediment Dispersal from Mountain to Shore, with Bypassing via Three Human-Modified Channel Systems to Lake Annecy, SE France

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ABSTRACT

STANLEY, J.-D. and JORSTAD, T.F., 2004. Direct sediment dispersal from mountain to shore, with bypassing via three human-modified channel systems to Lake Annecy, SE France. *Journal of Coastal Research*, 20(4), 958–969. West Palm Beach (Florida). ISSN 0749-0208.

Lake Annecy in Haute Savoie, France, receives about two-thirds of its fluvial input from three rivers that flow to its southern end-point. The channels of the Eau Morte, Ire, and Bornette rivers are almost completely channelized in their lower reaches as a result of human activity, with flow contained along parallel, but separate, paths from headlands in the proximal drainage basin directly to the lake. Petrographic data from river samples collected in this study serve to differentiate sand-size material carried by each fluvial system. Proportions of the dominant (limestone) and five additional (dolomite, quartz, gypsum, rock fragments, and 'other') components in the 3 rivers are more closely related to source supply than to fluvial transport effects or sampling strategy. Of the 7 components, mica best records the influence of depositional mechanisms. Much of the carbonate sand and coarser material at the lake shore is derived from widespread Mesozoic outcrops. Non-carbonate sand input, partially resulting from erosion of glacial till deposits and pedogenic horizons in the southern drainage basin, provides key compositional markers to differentiate between sediment carried to the lake by each river.

Until several centuries ago, deposits of the Eau Morte, Ire, and Bornette flowed to the Bou du Lac, and formed a merged, multifluvial lacustrine delta. As drainage and channel containment projects related to agricultural development intensified in lake margin lowlands, the 3 channels were separated on the delta surface, allowing bypass of river material directly onto subaqueous deltas in the lake. Specific mineral assemblages, especially quartz, mica and rock fragments, may prove useful as key tracers of human-altered sediment between the margin and deeper lake sectors.

ADDITIONAL INDEX WORDS: *Bou du Lac delta, bypassing, carbonates, channelization, fan delta, glacial till, Holocene, human effects, lacustrine, mineral assemblages, perialpine setting, provenance, scree, wetland drainage.*

INTRODUCTION

Most of the nearly 300 lakes in the western Alps of Europe are elongate and fed by one or two primary rivers flowing to one of the lake end-points. Lacustrine deltas of various size, shape, and configuration have developed at many of these end-of-lake margins, a response to natural processes influenced by paleoclimatic events and, subsequently, by anthropogenic factors. Human activity during the past millennium has emphasized increased control of river channel flow to and across many such lacustrine deltas. In particular, channelization projects helped minimize the risk of flooding as agricultural activity increased and population centers developed in lake margin lowlands. To date, surprisingly few investigations have been made of the effects of such endeavors on fluvial alpine and perialpine lacustrine delta sedimentation.

This study presents an example of unusual modern sediment dispersal, one altered by human intervention at the major sediment feeder end-point of Lac d'Annecy (Lake Annecy, abbreviated herein as L.A.). This perialpine lake is located in the Haute Savoie department of southeastern France (Figure 1A). The southern lake setting receives sediment from three rivers that head in the proximal mountains and are of high gradient, yet are subparallel and closely spaced. During the mid- to late Holocene, and until several centuries ago, the Eau Morte, Ire, and Bornette rivers flowed from high-relief terrains to L.A., releasing a considerable portion of sediment load along their lower sectors, *i.e.* on fan deltas and beyond, on lacustrine deltas and the lake margin (Figures 1B, 2). Fan deltas developed at the base-of-slope (Figure 3A, B) and, beyond these, channels from the 3 rivers joined to form a single merged lacustrine delta, the Bou du Lac complex at the lake (Figures 2A–C, 3C, D, 4A). Currently, this is no longer the case. As a result of human modification, especially during the past few centuries (CHAVOUTIER, 1977; EVIN *et al.*, 1994; BUILLIT *et al.*, 1997; NEGREL *et al.*, 1997; DEARING, 2000), the rivers are almost completely confined along their lower stretches (Figure 5F), and flow from 3 separate, but proximal, source areas directly to the delta and lake shore (Figure 2). Sediment remains confined in each channel as it crosses the Bou du Lac, with records of only minor overbank deposition and flooding between the base of deeply incised river valleys and southern lake margin (Figures 1B, 2A, B). Consequently, there is only

03508A received and accepted in revision 12 May 2003.

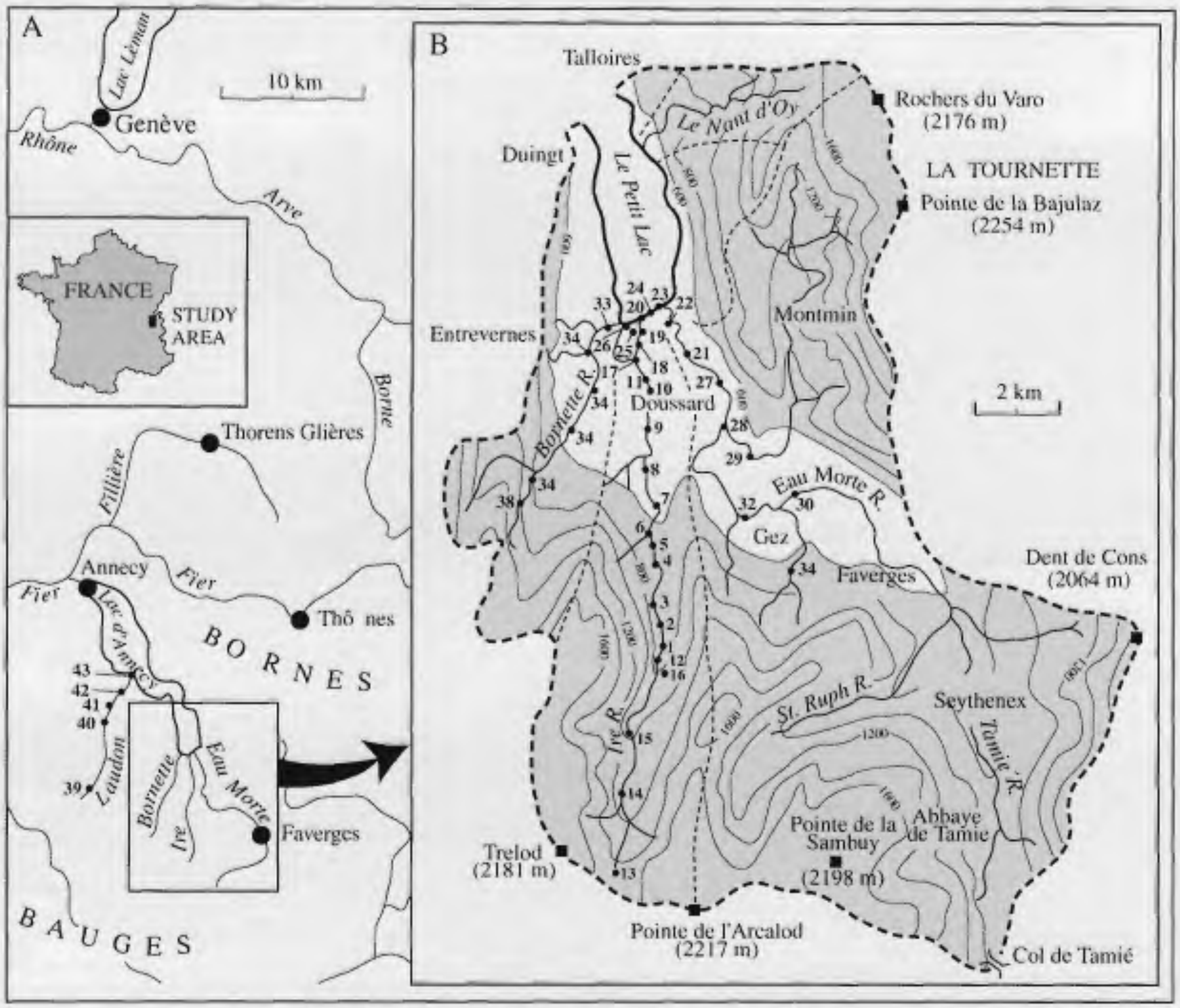

Figure 1. A, General map of Lake Annecy study area in Haute Savoie, SE France. B, Topographic map showing drainage basin and sample localities along the Eau Morte, Ire, and Bornette rivers that flow to the Petit Lac sector of the lake. Drainage basin area higher than 600 m shown in gray (topographic base after DEARING *et al.*, 2001).

minor temporary storage and little progressive dilution of fluvial materials as they are transported from their headlands to three submerged delta sectors (Figure 2D–F).

The primary purpose of the present study is to determine whether the composition of sediments carried by the three rivers to their respective lake entry-points are sufficiently diverse to be differentiated at the southern lake (Petit Lac) margin. Distinguishing the specific fluvial sediment discharged from each of the 3 rivers would not, *a priori*, be obvious: the channels cross extensive, but lithologically similar, exposures of Mesozoic limestones and marls in the fluvial headlands and river valleys of the southern lake drainage basin (Figures 2A, 3A, B, 4A). The dominant influence of source area is highlighted by (1) high proportions of carbonate sand, pebbles, and cobbles in surficial sediments of the southern lake margin, as observed in the field (Figure 3C, D), and (2) the large carbonate overprint in finer-grained sediment of late Quaternary age in the lake (THORNDYCRAFT *et al.*, 1998; BRAUER and CASANOVA, 2001; LOIZEAU *et al.*, 2001).

A multi-disciplinary effort, involving clay mineral, geochemical, mineral magnetic and other investigations, has been made of Würm and Holocene deposits in, and adjacent to, L.A. to interpret paleoclimatic fluctuations in this region (summaries by DEARING, 2000, and OLDFIELD and BERTHIERS and others in the special issue of *Journal of Paleolimnology*, 2001, vol. 25, pp. 133–269). Currently, however, there is almost no data available on sand-size compositional components transported from adjacent mountains to the lake's major sediment entry-point. Information that identifies distinct marker mineral assemblages at the three fluvial input sites is needed to complement interpretations on provenance and dispersal of sediments into the lake. This investigation emphasizes readily identifiable minerals and compositional assemblages characteristic of sand carried to the lake margin by each of the 3 rivers.

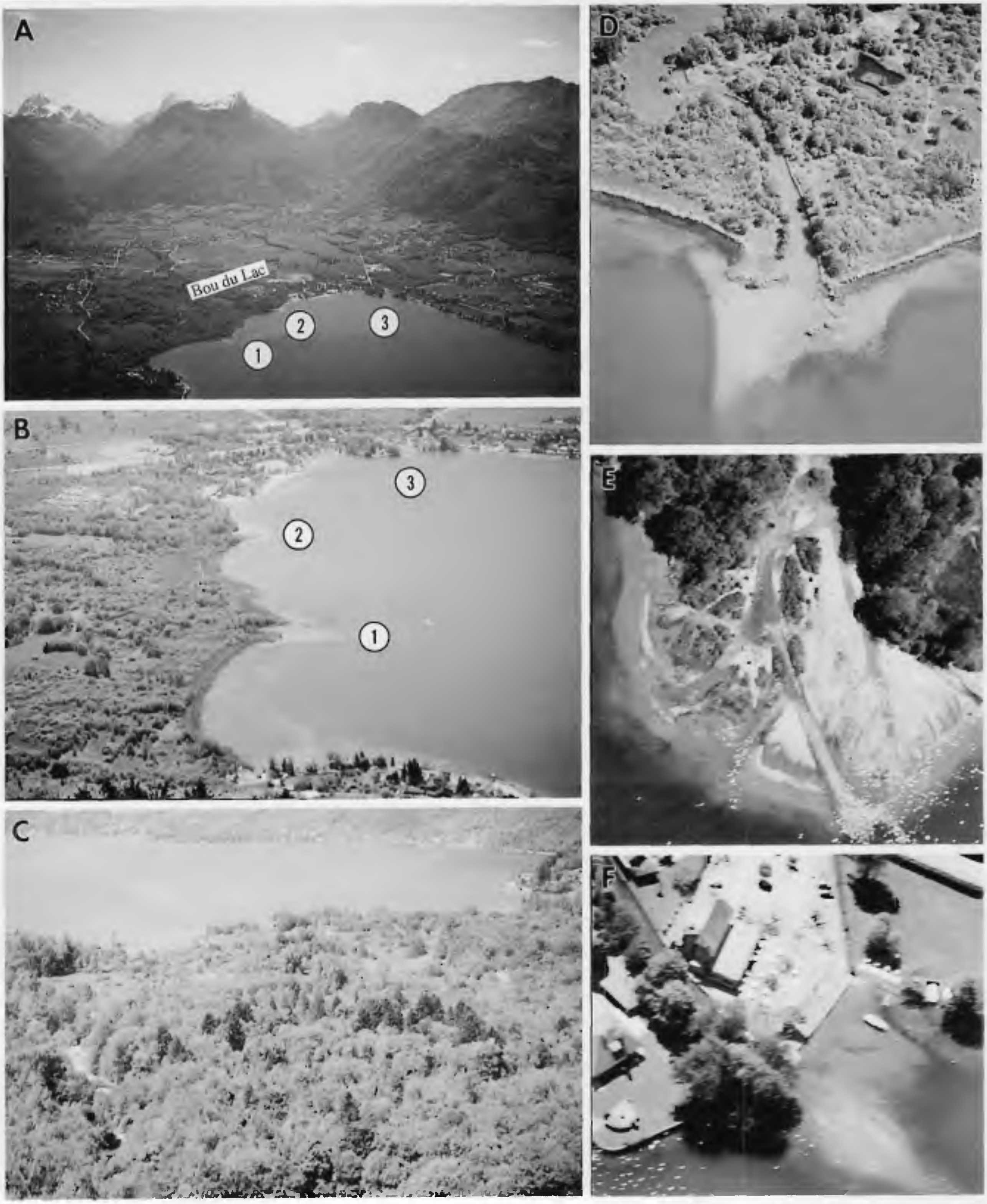

Figure 2. Photographs of the southern Lake Annecy study area. A, base-of-slope and Bou du Lac delta sectors, including three river outlets at southern lake margin: (1) Eau Morte; (2) Ire; and (3) Bornette. Mountains in background are formed largely of Mesozoic carbonate. B, Bou du Lac delta and southern L.A. margin showing outflow of the (1) Eau Morte, (2) Ire, and (3) Bornette. C, view from above the Bou du Lac delta toward the north. D, above the Eau Morte river outlet and subaqueous delta, showing sediment plume. E, Ire river outlet and subaqueous delta, with several distributaries and small sediment plume. F, jet flow into the lake, derived from the mouth of the Bornette river. Aerial (parachute) photos taken on 16 May, 2002.

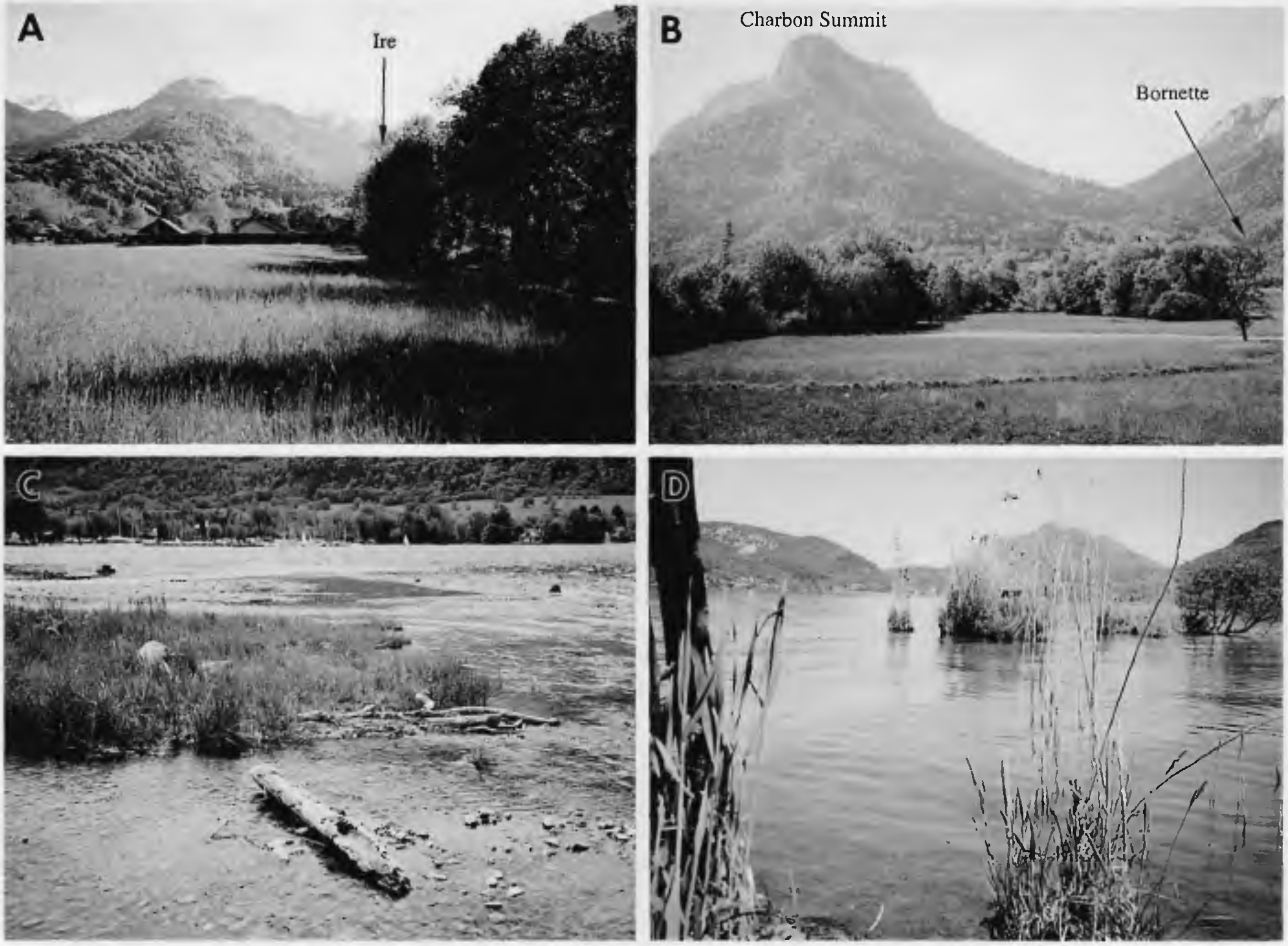

Figure 3. Photographs of base-of-slope (fan delta, delta) environments below carbonate terrains. A, near Ire river sample site no. 8 on fan delta, below the Bossonnet-Ugeret chain. B, near Bornette river sample site no. 36, on fan delta below the Charbon summit. C, along one of the Ire delta distributaries, near sample no. 20. D, mouth of the Eau Morte, near sample site no. 23; view toward north. Carbonate sand, pebbles and cobbles extend to subaqueous delta platforms in the lake.

GEOLOGICAL AND GEOGRAPHIC CONSIDERATIONS

The lake depression extends along the NW-SE oriented Vuache fault (Figure 4A), and occupies a region that has been subject to tectonic activity until recently (JOUANNE *et al.*, 1994). The distribution and configuration of geological formations in the Bornes and Bauges mountain chains around L.A. is shown in a series of detailed maps (CHAROLLAIS *et al.*, 1988; DOUDOUX *et al.*, 1992). Exposures crossed by the 3 rivers include primarily limestone, dolomitic limestone, and marl of Jurassic and Cretaceous age (Figure 4A). Late Pleistocene (primarily Würmian) tills (EVIN *et al.*, 1994; NICOUD and MANALT, 2001), fluvio-glacial and lacustrine deposits, and slope scree are also locally important in the southern drainage basin and lake margin (Figures 4A, 5A–C).

The detailed history of L.A. and surrounding region has been summarized in a series of articles that focus on the multi-proxy late Pleistocene and Holocene record of sediments in the lake. Glacial activity and erosion sculpted the valleys in this region. The oldest identified glacial and fluvioglacial deposits are attributed to 'Riss' glaciation; most are buried by the younger basal Würmian till that once covered large segments of the paleolake. Following late Pleistocene glacial erosion of the major valley, glaciolacustrine and lacustrine deposits accumulated in the depression now occupied by L.A. (Figure 4B). The subglacial lake began to develop ~16,600 years before present (yrs BP), and its subsequent evolution is determined on the basis of radiocarbon dates and varve stratigraphy (BRAUER and CASANOVA, 2001). A major glacial stream from the SE flooded the southern end of L.A., and overflowed into the northwestern part of the valley from 16,350 to 15,900 yrs B.P. (Figure 4C). Important flows were also derived from ice-masses to the northwest and along the valley margins (Figure 4D). The lake gradually evolved from a glacial to a biologically productive system by ~14,500 to 14,000 yrs BP (BRAUER and CASANOVA, 2001).

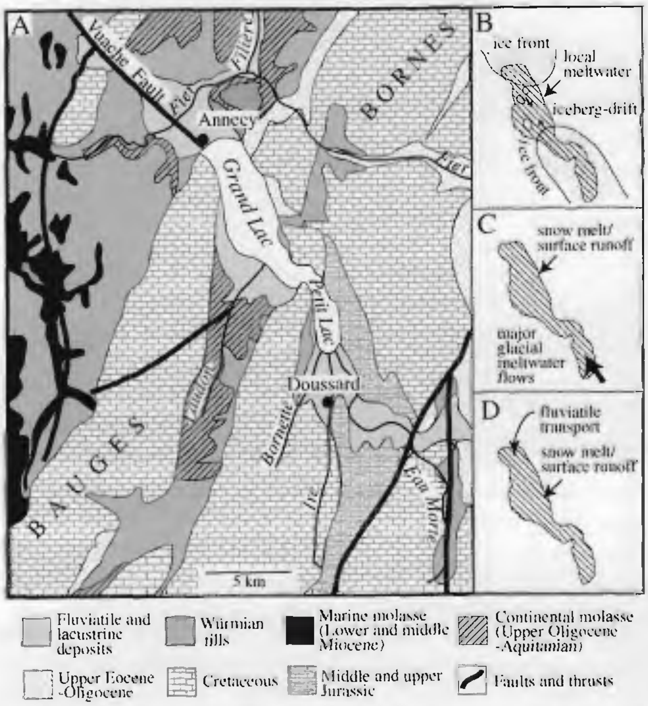

Figure 4. A, simplified geological map of the L.A. region (modified from NICOUD and MANALT, 2001). B, C, D, sketch maps, showing lake evolution during the late Quaternary (after BRAUER and CASANOVA, 2001), discussed in text.

Following Würmian glacial retreat, fill in the ice-carved depression resulted in a longer lake than the present one, extending from ~8 km SE of present L.A., to about 7 km NW of the city of Annecy (Figure 6A). This sinuous late glacial lake had a length of ~28 km, or almost double its present length of 14.6 km. Its elevation of ~460 m above mean sea level (m.s.l.) was well above the present artificially maintained elevation of 446.5 m m.s.l. (NICOUD and MANALT, 2001). Lake levels continued to fluctuate during the Holocene, including a lowering of 3 m during the late Neolithic period (MAGNY *et al.*, 2001; NICOUD and MANALT, 2001).

The modern L.A. drainage basin area is 251 km², and comprises high-relief topography (to 2351 m at La Tournette). The lake surface area is 27 km² and is little more than 3 km at its widest. A submerged ridge divides L.A. into a smaller southern N-S oriented sub-basin (Petit Lac), and a larger NW-SE sector (Grand Lac) (Figure 4A). The basin depth of the Grand Lac is 67 m, and that of the Petit Lac is ~55 m. Over time, seven rivers have flowed into L.A. The major ones at present are in the following declining order of discharge importance: Eau Morte and the Ire, with 40% and 15% of the total lake inflow, respectively, discharged to the Bou du Lac delta (Figures 2A, B); and Laudon (Figure 1A), with 12% of L.A. inflow, on the western margin of the Grand Lac (Figure 1B). The Bornette (also flows to the Bou du Lac delta) and other smaller streams, together, contribute 33% of total inflow (NICOUD and MANALT, 2001).

The Eau Morte, Ire, and Bornette, of major interest here, thus account for nearly ⅔ of the lake's total fluvial input. River lengths are: Eau Morte ~19 km (river valley = 9, fan delta and delta = 10), Ire ~14 km (river valley = 9, fan delta and delta = 5), and Bornette ~6 km (river valley = 3, fan delta and delta = 3). Most of the catchment area (170.4 km²) drains into the Petit Lac (area 6.25 km²), providing a catchment-to-Petit Lac basin ratio of ~27, compared with catchment to the Grand Lac ratio of ~4 (DEARING *et al.*, 2001). The gently inclined Bou du Lac delta complex formed by the 3 rivers covers an area of ~2 km². The NE-SW oriented southern lake shore is just under 1.5 km in length (Figures 1B, 2A–C), and distance from the delta apex, near the village of Doussard, northward to the lake shore is ~4 km.

The three rivers in the southern area presently flow from proximal high-relief source terrains that reach more than 2200 m (Point de l'Arcalod, Figures 1B, 5B), and carry very poorly sorted material (clay to cobble size) to the lake margin. The river beds confined in the incised valleys are steeply inclined (Figures 2A, 3A, B, 5): (1) Eau Morte river valley (1:13) and its fan delta to delta surface (1:67); (2) Ire valley (1:9) and fan delta to delta surface (1:33); and (3) Bornette valley (1:5) and fan delta to delta surface (1:13). High flows and floods recorded during the past 300 years have resulted from winter-spring snow melt and summer-autumn storms (THORNDYCRAFT *et al.*, 1998). The rivers now flow in 3 topographically separate sub-basins (Figure 1B): from their upper reaches, to an elevation of ~600 m, their flow is naturally confined largely by steep-walled carbonate and marl exposures (Figures 3A, B, 5E) and scree (Figure 5C). As the valleys open, their channels on the fan deltas and Bou du Lac delta are artificially maintained (Figure 5F) and remain separate to the lake shore (Figure 2). Channel distances between the base-of-slope and lake shore range from 3 (Bornette) to 10 (Eau Morte) km.

METHODS

A total of 38 surficial sediment samples were collected in the uppermost 2–3 cm of river bed deposits along the three channels flowing to the Bou du Lac delta and southern lake margin (Figure 1B). Samples were taken in the naturally confined narrow valleys (n = 16), and in the artificially channelized sectors on the fan deltas and merged delta (n = 22). Sediment samples include, from east to west: Eau Morte valley (n = 3) and fan delta to delta (= 6); Ire valley (= 11) and fan delta to delta (= 11); and Bornette valley (= 2) and fan delta to delta (= 5). For comparison purposes, five samples in the Laudon river valley (= 2) and its fan delta to delta (= 3), west of the Grand Lac, were also collected (Figure 1A).

Initially, all samples were allowed to soak overnight in a dilute solution of sodium hexametaphosphate (Calgon and distilled water) for sediment deflocculation. The particle size distribution and textural characteristics (percentage sand, silt and clay; mean and modal size) were determined from a cut of each sample using a Coulter Counter LS 200, which measures particles from 0.4 to 2000 μm. A second cut of each sample was wet sieved to separate the *complete sand* (63 to 2000 μm) fraction for compositional analysis. After this examination had been made, the complete sand fraction was

Figure 5. Photographs showing different sectors of the Ire river system. A, thick wedge of glacial deposit (arrow) abutting bedrock above the source of the Ire (near sample site no. 13). B, stream source and uppermost stretch of the Ire near Pointe de l'Arcalod pass (sample site no. 13). C, scree (rock fall) on the steep eastern flank of the Ire (sample site no. 16). D, torrent flow diverted by enormous blocks of Mesozoic limestone, near sample site no. 3. E, Mesozoic strata of alternating limestone and shale at sample site no. 2. F, artificially channelized river at base-of-slope, near sample site no. 9.

again wet sieved to separate and analyze the composition of the *medium sand* (250 to 500 μm) fraction.

To identify limestone particles, both complete and medium sand fractions were stained using Alizarin Red S (0.1 g/100 ml of 0.2% HCl) for 4 to 6 minutes (DICKSON, 1965; FRIEDMAN, 1971). The sediment was then washed and allowed to air dry. Subsequently, the sample was additionally stained to identify dolomite, using Potassium Ferricyanide (0.5 g/50 ml of 1.5% HCl) for 20 minutes, then washed and allowed to air dry (EVAMY, 1963; TUCKER, 1988). The stained sample counts were made using loose granular sample material, as opposed to more commonly used methods (examination of polished thin sections or of cut and polished bulk material in an epoxy stub).

In each sample, 300 or more grains were identified in the wet sample concentrates of both stained complete and medium sand-size fractions, using a Leitz binocular microscope. The counts, made on both size fractions, record relative percentages of 7 components: limestone, dolomite, quartz, mica, gypsum, rock fragment and 'other' (heavy minerals, volcanic grains, micro-fossils). Most concentrates of the complete sand fraction are characterized by a wide range of particle size, with carbonate grains prevailing. One sample (no. 26) had insufficient sand-size material for counts.

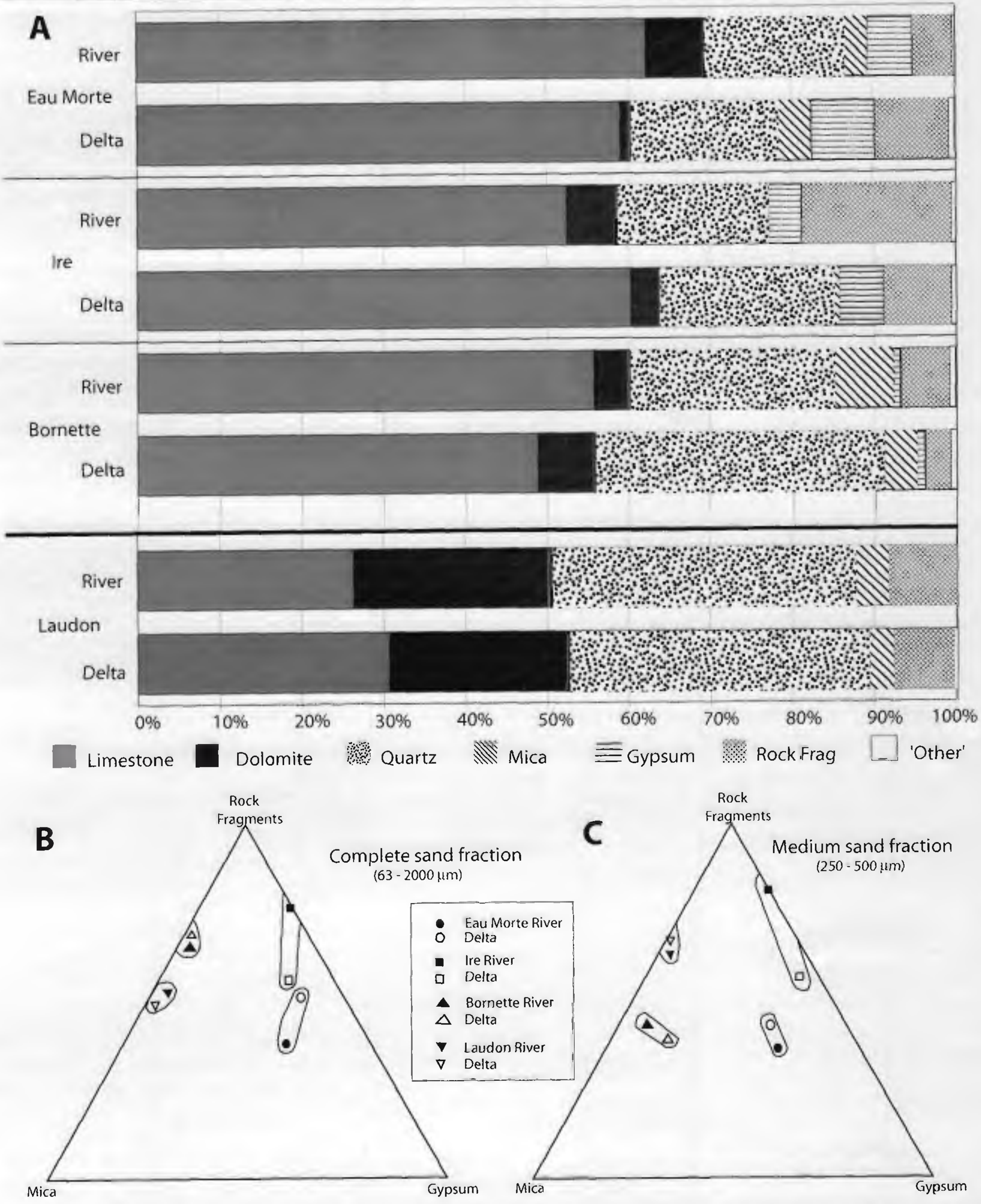

Figure 6. Graphs summarizing averaged compositional data for the three river systems (n = 37) flowing to the Petit Lac and, for comparison, the Laudon river (n = 5) flowing to the Grand Lac (Figure 1A): A, relative percentages of major compositional components in the medium sand fraction (250–500 μm); data listed in Table 1B. B, distribution of rock fragments, mica, and gypsum (recalculated to 100%) in the complete sand fraction (63–2000 μm). C, distribution of rock fragments, mica, and gypsum (recalculated to 100%) in the medium sand fraction.

The database includes the following information for the complete and the medium sand fractions for each of 37 Eau Morte, Ire, and Bornette river samples and, for comparison, 5 Laudon river samples: percent sand, silt and clay; mean and modal sizes, and relative percentages of the 7 major compositional components. These data are available from the authors. Averaged textural and compositional component data for samples in the three river valleys and three channelized base-of-slope and delta sectors are listed in Table 1A and B, and depicted graphically in Figure 6.

COMPOSITIONAL VARIATIONS IN SAND FRACTIONS

The poorly sorted characteristic of sediment samples collected in the three rivers is recorded by the wide range of mean (87 to 1278 μm) and modal (140 to 1909 μm) grain sizes and also by the highly variable percentages of sand (24–99%), silt (0.1–67.5%) and clay (0.1–8.3%). Averaged data indicate that, overall, the Ire samples are coarsest, the Bornette intermediate, and the Eau Morte finest (Table 1A). Moreover, the mean size of base-of-slope to delta samples is, for the most part, finer-grained than of those collected in their incised valley sectors.

The mineral composition of the two sand-size fractions in each of the 3 rivers flowing to the Bou du Lac delta was calculated separately, *i.e.* for the river valley samples and for base-of-slope (fan delta) to delta channel samples in the three rivers. The averaged proportions of compositional components of the complete (63–2000 μm) and medium (250–500 μm) sand fractions were tabulated (Table 1B), and are depicted graphically (Figure 6).

The complete sand fraction in the three rivers flowing to L.A. comprises a major limestone grain component that exceeds 65%. Although carbonate particles dominate mineral assemblages, each of the three rivers can nevertheless be distinguished on the basis of averaged compositional data (Table 1B) as follows:

- the Eau Morte includes the highest proportions of limestone (range, 76.1–87%) and gypsum (to 3.8%) grains;
- the Ire records the highest dolomite content (range, 4.9–10.2%); and
- the Bornette comprises highest relative percentages of quartz (range, 15.6–23.9%), mica (range, 3.1–6.1%), and rock fragments (range, 7.2–13.1%).

In the medium sand fraction, averaged grain count data from samples collected in the 3 rivers also record compositional differences (Table 1, Figure 6A):

- the Eau Morte records the largest percentage of carbonate (limestone plus dolomite; range 60.3–69.4%) and gypsum (range, 5.6–7.9%);
- the Ire comprises the highest proportions of rock fragments (range, 8.3–18.3%); and
- the Bornette is characterized by the highest proportions of quartz (24.9–35.2%) and mica (range, 4.0–7.2%).

Although generally comparable, there are some size-related compositional differences between the two size fractions examined (Table 1B). The medium sand fraction, for example, shows the following:

- markedly decreased relative percentages of limestone in all 3 rivers;
- increased proportions of dolomite in the Bornette and Eau Morte (decreased in Ire);
- increased proportions of quartz and gypsum in the 3 rivers;
- increased percentages of mica in the Bornette and Eau Morte; and
- increased proportions of rock fragments in the Ire and Eau Morte.

The above averaged compositional values in both complete and medium sand fractions serve to readily distinguish the Bornette sediments from those of the Ire and Eau Morte (Figure 6A).

Compositional differences between the Ire and Eau Morte are less obvious. Nevertheless, sand from the Ire can be differentiated from that of the Eau Morte on the basis of higher proportions of mica, gypsum and rock fragments; these three components, together, account for <23% of the total proportion of compositional components in the two sand fractions in the 3 rivers. The percentages of these three components, when normalized to 100% and plotted on triangular diagrams, serve to distinguish sand of the Eau Morte and Ire rivers (Figure 6B, C). Still further differentiation is made on the basis of higher ratios of limestone to quartz values for the Eau Morte (range of 5.9–10.5) than for the Ire (range of 3.7–4.2). The Fisher's exact test was selected to test for the significance of differences between two percentages of the sample characteristics (Sokal and Rohlf, 1969). In an examination of the percent mica, gypsum and rock fragments in the Ire and Eau Morte rivers, it was found that the percentage of mica, gypsum and rock fragments were very highly significantly different ($p<.00001$). These observations are graphically visible in the ternary diagrams in Figure 6C.

DISCUSSION

Petrographic data obtained for both the complete and medium sand-sized fractions, as summarized above, differentiate the sediment carried by the 3 rivers to the southern Petit Lac shore. Differences in sediment composition in the three fluvial systems are due largely to variations in the composition of bedrock and sedimentary deposits (till, scree) across which the rivers flow. To a lesser extent, it is recognized that some compositional variation is a function of grain size selected for analysis and sampling procedure. These observations are not unexpected in view of the major attributes of all 3 rivers that include: high channel gradient; short total sediment transport distance; high flow velocity, stream power and turbulence; and direct dispersal from mountain source to lakeshore without progressive dilution of the sediment load. This analysis indicates that the near-complete containment in the anthropogenically-altered lower channel stretches of the three rivers is a major controlling factor in fluvial sediment displacement to the lake shore.

An example of the prevailing influence of provenance is most clearly demonstrated by limestone particles that domi-

Table 1. *Averaged textural (A) and compositional (B) data from 37 samples collected in the 3 Bou du Lac rivers and 5 samples in the Laudon river (see Figure 1). Complete data base for each sample available from authors.*

A

	TEXTURAL PARAMETERS (AVERAGED VALUES)				
FLUVIAL SYSTEM	MEAN (µm)	MODE (µm)	SAND	SILT	CLAY
EAU MORTE RIVER	522	809	95.45%	4.03%	0.52%
EAU MORTE DELTA	545	536	96.84%	2.89%	0.28%
IRE RIVER	924	1513	93.26%	5.68%	1.06%
IRE DELTA	781	1021	95.87%	3.52%	0.61%
BORNETTE RIVER	683	1025	94.50%	4.85%	0.65%
BORNETTE DELTA	568	1209	81.51%	16.48%	2.01%
LAUDON RIVER	473	283	96.32%	3.24%	0.44%
LAUDON DELTA	343	263	95.89%	3.79%	0.33%

B

	COMPOSITIONAL COMPONENTS (AVERAGED VALUES)						
FLUVIAL SYSTEM	LIMESTONE	DOLOMITE	QUARTZ	MICA	GYPSUM	ROCK FRAG	OTHER
EAU MORTE RIVER							
(63–2000 µm)	86.96%	2.37%	5.92%	0.99%	1.84%	1.82%	0.10%
(250–500 µm)	62.38%	6.93%	17.01%	2.88%	5.60%	4.94%	0.27%
EAU MORTE DELTA							
(63–2000 µm)	76.12%	0.73%	12.19%	1.01%	3.83%	5.22%	0.90%
(250–500 µm)	59.21%	1.05%	17.92%	4.13%	7.85%	9.19%	0.66%
IRE RIVER							
(63–2000 µm)	67.55%	10.24%	8.26%	0.13%	2.92%	10.66%	0.22%
(250–500 µm)	52.65%	6.03%	18.36%	0.00%	4.10%	18.26%	0.59%
IRE DELTA							
(63–2000 µm)	72.95%	4.89%	12.46%	1.06%	3.00%	5.08%	0.63%
(250–500 µm)	60.48%	3.34%	21.07%	0.73%	5.57%	8.25%	0.54%
BORNETTE RIVER							
(63–2000 µm)	64.55%	0.00%	15.61%	6.08%	0.63%	13.13%	0.00%
(250–500 µm)	55.99%	4.11%	24.93%	7.20%	0.95%	6.15%	0.68%
BORNETTE DELTA							
(63–2000 µm)	64.96%	0.05%	23.91%	3.07%	0.10%	7.17%	0.74%
(250–500 µm)	49.11%	6.70%	35.20%	4.01%	1.15%	3.33%	0.52%
LAUDON RIVER							
(63–2000 µm)	41.44%	11.66%	32.36%	6.25%	0.44%	7.63%	0.24%
(250–500 µm)	26.55%	23.80%	37.03%	4.23%	0.21%	8.19%	0.00%
LAUDON DELTA							
(63–2000 µm)	35.18%	18.68%	35.41%	4.79%	0.15%	5.10%	0.55%
(250–500 µm)	30.86%	21.77%	36.28%	3.59%	0.00%	7.17%	0.32%

nate ('flood and mask') all grain counts in the 37 samples collected in the three river channels. In effect, graphic depictions of the data show the abundance of sand-size limestone particles in all samples regardless of sample mean grain size. This observation records major sediment input from carbonate terrains at upper and mid-reaches of the three river channels (Figure 4A). Limestone particle content of samples, exceeding 50% and ranging to 90%, is a function of weathering and erosional characteristics in river headlands. Limestone dominance also records the irregular introduction of carbonate material from steep lateral valley margins into the channels in large, but variable, amount and size along the three river valleys.

There is no relation between relative proportion of dolomite and mean grain size in the complete sand size fraction of river samples, especially in samples where mean size exceeds 1000 µm. Field observations confirm the laboratory finding that proportions of limestone and dolomite in samples are generally most closely related to proximity of carbonate outcrop exposures. This, for example, is illustrated by the relatively high dolomite-enriched grain counts (12.3–36.1% for the 63 to 2000 µm fraction) in Ire river valley sample sites

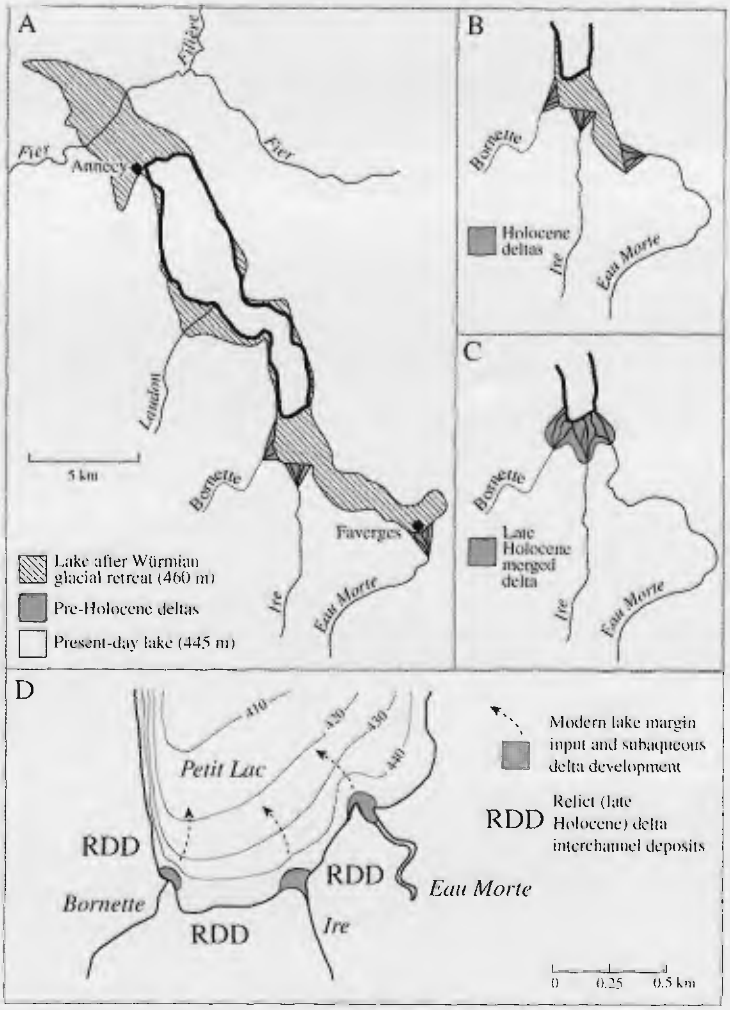

Figure 7. Schemes showing development and displacement of 3 lacustrine delta positions through time. A, three deltas fully separated along lake margin, late Pleistocene to early Holocene (base map modified after Nicoud and Manalt, 2001). B, deltas still separated but shifted closer to each other, Holocene. C, deltas merged at the Bou du Lac, late Holocene. D, human activity during the past several centuries has resulted in separation of channel outlets and subaqueous delta development at the Petit Lac margin. Discussion in text.

1, 3, 4, and 6 (Figure 1B) located close to exposures of dolomitic limestone. Moreover, the relation between grain size and relative percentages of quartz, gypsum, rock fragments, and 'other' components is not readily apparent in the down-river direction. As in the case of carbonates, proportions of these four components are more closely related to source supply than to fluvial transport effects or sampling strategy. Only in the Ire does quartz content tend to decrease slightly as mean grain size increases. This inverse relationship may be a function of original inherent size, where quartz grains generally tend to be smaller than the weathered and fresh carbonate particles with which they are displaced. Thus, some size-sorting effect associated with sediment transport is not discounted.

The influence of sediment displacement and depositional mechanisms on sand composition is best recorded by mica flakes that are present in both the complete and medium sand fractions in 27 of the 37 samples examined. In the two sand sizes, mica content shows a general decrease with increasing mean size of samples in the 3 rivers. This indicates that mica flakes are preferentially released with quartz, rock fragments, and other dense particles of smaller size. The size-sorting phenomenon is best shown by sediment in the Bornette river, the fluvial system where average grain size is smaller than in the Eau Morte and Ire (Table 1A).

A similar example of provenance-dominated composition, is recorded by the petrographic data of sediment collected in the Laudon river. This fluvial system, located northwest of the study area, has produced a somewhat larger (~15 km^2), more classically-shaped delta than the depocenter formed by the three rivers at the Petit Lac (Figure 7A). Analyses of Laudon material record smaller mean and modal grain sizes and a very different composition than those of the Bou du Lac rivers (Table 1, Figure 6A–C). Of note are the substantially higher proportions of dolomite and quartz, and lower relative percentages of limestone and mica. As in the case of material carried by the other three rivers to the lake's southern margin, the composition of Laudon fluvial sediment provides a strong record of source terrain provenance. Exposures in the Laudon drainage basin include not only Mesozoic dolomitic limestone, but also terrigenous molasse deposits of Tertiary age and glacial material (CHAROLLAIS *et al.*, 1988; DOUDOUX *et al.*, 1992). Moreover, little evidence of size-sorting (such as lower mica content in the delta than in river valley samples) may also be related, in part, to the relatively short distance between source (near Col de Leschaux) and lakeshore (<9 km), overall high average riverbed gradient (1:20), and some artificial channelization.

It would be expected that the important carbonate presence in sediment of the lake proper is a response to transport of material from Jurassic and Cretaceous limestone and dolomitic limestone units widely exposed in the surrounding drainage basin area (Figures 2A, 3A, B, 4A). In particular, results of the petrographic survey help account for the presence of exogenic carbonate material in late Holocene sediment recovered in cores of the lake proper (THORNDYCRAFT *et al.*, 1998; BRAUER and CASANOVA, 2001; LOIZEAU *et al.*, 2001). Currently, there have been limited lake sediment studies that focus on non-carbonate sediment input (DEARING *et al.*, 2001; HU and OLDENFIELD, 2001; MANALT *et al.*, 2001; NOËL *et al.*, 2001), especially derived from erosion of scattered glacial till deposits (Figure 5A) and from pedogenic horizons in the southern drainage basin. In fact, it is these non-carbonate materials that are among the most useful to differentiate between the sediment loads carried by each of the 3 fluvial systems to the lake shore and beyond.

It should be recognized that dispersal paths from the lake shore to the lake proper would have changed during the post-glacial evolution of L.A. At the time of the enlarged post-Würmian lake (Figure 7A), the three Bou du Lac rivers flowed to different coastal sectors than at present, and their deltas would have been separated from each other. As the lake decreased in size and as its southern margin contracted during the Holocene, the three deltas migrated northward (Figure 7B) and, by late Holocene time, had merged (Figure 7C). During this evolution, the effects of anthropogenic activity became progressively more important, and increasingly so during the past two millenia (CHAVOUTIER, 1977; HIGGIT *et al.*, 1991; BUILLIT *et al.*, 1997; NOËL *et al.*, 2001). By Roman time, deforestation had increased and, by the late Middle Ages, considerable lowland areas near the lake were cleared for agriculture. As agricultural activity expanded, drainage and channel containment projects in base-of-slope fan delta sectors and the Bou du Lac delta became increasingly necessary.

Human-induced modifications, and especially channel confinement during the last several centuries, would have induced an increase in sediment bypassing of the base-of-slope environments and the merged subaerial delta. By the mid-20th century, channel migration was almost completely restricted and the three rivers became separate on the delta surface. This modification is now causing fluvial sediment, including coarse grade material, to bypass the merged delta and, as in earlier Holocene time, accumulate directly on the submerged parts of the three separate delta platforms on the Petit Lac margin (Figure 7D). The artificial separation of the 3 channels has also resulted in preservation of older, pre-modern (late Holocene, but relict) sediment between channels on former Bou du Lac delta surfaces (Figure 7D, see RDD).

There continues to be some mixing and homogenizing of sediment discharged from the three rivers along the shallow southern lake margin (mostly by wave action) prior to further transport into the lake proper. However, as development of the three individualized river outlets and subaqueous deltas at L.A. margins becomes more pronounced, it follows that there would be more direct fluvial sediment dispersal from mountain to shore, and then by underflow displacement to deeper, more distal sectors of the lake.

CONCLUSIONS AND RAMIFICATIONS

During the past several centuries, a large number of modern deltas along Alpine and perialpine lake margins have been modified by human activity to such an extent that many are now in a destruction phase, that is, no longer functioning as normal deltaic depocenters (*cf.* STANLEY and WARNE, 1998). As a result of artificial embankments, river-bed straightening, and reduction of distributaries, many sediment-charged rivers flowing to lake margins can no longer freely migrate laterally across base-of-slope, including delta, surfaces. In this respect, sedimentation at the Lake Annecy margin is by no means unique. For example, modified lacustrine deltas formed by three or more human-modified rivers at lake end-points include those at Lago Maggiore and Lake Constance (Bodensee). As in the case of L.A., we suspect that a significant proportion of fluvial sediments in such altered settings presently bypass the fluvio-lacustrine delta plains and are deposited directly at the leading edge of prograding submerged delta sectors and farther into deeper lake environments. Remarkably few such modern settings, however, have as yet been detailed, and would be worthy of petrologic study.

To test the postulate that artificial channelization has induced more direct sediment dispersal between the southern Petit Lac shore and basin will require study of a series of closely-spaced cores, detailed bathymetry, and high-resolution subbottom profiles on the southern lake margin. Previous seismic surveys have been unable to detail late Pleistocene and Holocene stratification of glacial and post-glacial lacustrine sections in the Petit Lac. Poor subbottom resolution in this sector is attributed to weak acoustic penetration resulting from important accumulations of biogenic gas in the lake's upper sediment cover (VAN RENSBERGEN *et al.*, 1998; BECK *et al.*, 2001). Nevertheless, coupling detailed bathymetry and enhanced seismic profiling with a closely-spaced core survey on this lake sector is needed to define the configuration, petrology and age of late Holocene to modern strata. These would serve to identify sequences that have recently been deposited from underflows that carry sediment from the three submerged deltas to the Petit Lac basin.

From the petrologic findings obtained here, it is suggested that specific mineral assemblages, and especially distributions of quartz, mica, and rock fragments, can prove useful as key tracers of the present human-altered sediment displaced to deeper lake sectors. However, synergistic interactions between climate, human activities and hydrology in the Annecy catchment are complex (Dearing, 2000). It is important to recognize that modern, anthropogenically altered fluvial systems may have different characteristics than those that flowed in the past. Caution should thus be used in applying the petrology of present river discharge to calibrate past flood events and sediment delivery to lake margins.

ACKNOWLEDGMENTS

We thank Ms. Mary Parrish, National Museum of Natural History (NMNH), for help with illustrations and Ms. Christina Borg for technical assistance with manuscript preparation. Drs. L.-A. Hayek and M. Buzas, also at NMNH, advised us as to statistical testing. Prof. J. Dominik and Dr. J.-L. Loizeau, Institut Forel, University of Geneva, kindly reviewed the article. Financial support was provided by a Smithsonian Institution Research Opportunity Fund (FY-2002).

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