Carbon Dynamics Along a Temperate Fjord-Head Delta: Linkages With Carbon Burial in Fjords

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Abstract We used seven 210Pb-dated sediment cores from the Gaer Arm in the Doubtful Sound fjord complex, Fiordland, New Zealand to evaluate organic carbon (OC) dynamics in a temperate fjord-head delta. The highly dynamic spatial features of this delta were clearly evident in the observed sediment properties such as mass accumulation rates that varied by a factor of 14, sediment grain size by a factor 5, and sedimentary OC content by a factor 6. Low lignin concentrations (e.g., 2.95 mg (100 mg OC)−1) and syringic/vanillic ratios of lignin phenols (S/V; e.g., 0.44) at the upper deltaic stations were representative of substantial autochthonous OC contributions to delta sediments. Significantly higher acid/aldehyde ratios of vanillic phenols ([Ad/Al]v) at the deltaic stations (0.45–0.82) than the surface grabs (0.26–0.30) indicated rapid degradation of OC within the delta. Despite being a “hot spot” for OC oxidation, the delta likely improves OC preservation in the adjacent fjord by filtering out coarse-grained particles and exporting fine-grained particles to fjord sediments. Our results showed that fjord-head deltas can influence sedimentation and OC dynamics in select regions of fjords and thus warrant more examination of fjord-head processes, particularly in areas where they are expanding. In particular, as Earth warms and glaciers retreat, the newly exposed fjord-head platforms in high-latitude environments may evolve into similar “hot spots” of OC oxidation, thereby altering the dynamics of OC burial in these systems.

1. Introduction

One of the primary goals of Earth sciences is to investigate the past to better predict Earth’s future. Consequently, many studies focus on studying carbon cycling on Earth through geological time scales (Berner, 1989, 2004; Hedges, 1992; Hedges & Keil, 1995). More recently, scientists sought to better constrain carbon burial in the ocean, as this is closely linked with climate change through the Anthropocene (Burdige, 2005; Hedges & Keil, 1995). Recent work on fjords, a type of estuary formed by glacial carving in high-mid latitudes, showed that fjords have disproportionally high burial rates of OC and efficient CO2 sequestration over interglacial time scales (Smith et al., 2015). In fact, recent estimates suggest that fjord area-normalized OC burial rates are at least 5 times higher than other coastal systems and 100 times greater than the entire ocean average (Cui, Bianchi, Savage et al., 2015; Smith et al., 2015). Moreover, fjords were estimated to bury 17 to 21 ± 16 Tg OC yr−1, accounting for as much as 12% of the total OC burial in the ocean (Smith et al., 2015) despite accounting for <1% of coastal ocean surface area. A latitudinal trend in the role of fjords in processing OC was proposed, where high-latitude fjords rebury mostly petrogenic OC, while temperate fjords sequester CO2 from the atmosphere by burying modern OC (Cui, Bianchi, Jaeger et al., 2016).

Minideltas are commonly found along fjord heads, and their sedimentology aspects have been studied for decades (Barnes, Pickrill, & Bostock, 2016; Barnes, Pickrill, Bostock, Dlabola et al., 2016; Gutsell et al., 2004; Syvitski & Farrow, 1989, 1983). These deltas, usually classified as Gilbert-type (i.e., formed from coarse sediment deposition on a steep slope), contain three depositional regimes (e.g., topset, foreset, and bottomset) and are largely dominated by a subaerial topset (Barnes, Pickrill, & Bostock, 2016; Barnes, Pickrill, Bostock, Dlabola et al., 2016; Gobo et al., 2015). In many cases, these subaerial regions of the deltas, based on morphology, are more narrowly regarded as fjord-head deltas (Syvitski et al., 1987; Syvitski & Farrow, 1983, 1989). A
growing body of evidence shows that minideltas along small mountainous rivers may have been underesti-
mated in their ability to impact sediment and carbon dynamics in fjords (Barnes, Pickrill, Bostock, Diabola et al., 2016; Syvitski et al., 1987). The classic work on fjord-head deltas dates back to the 1980s, when
Syvitski and coworkers studied the sedimentology and stratigraphy of this unique geological setting
(Syvitski et al., 1987; Syvitski & Farrow, 1983, 1989). In the case of fjords in Fiordland, New Zealand, the role
of these smaller fjord-head deltas is largely understudied in terms of carbon burial along the Fiordland sys-
tem (Cui, Bianchi, Savage et al., 2016; Hinojosa et al., 2014; Smith et al., 2015). For example, fjord-head deltas
are primarily colonized by vegetation that represents a signi ficant input of OC to deltaic sediments (Barnes,
Pickrill, Bostock, Diabola et al., 2016). Recent work in Fiordland, New Zealand, examined the sediment accu-
mulation in these fjord-head deltas over the Holocene (Barnes, Pickrill, & Bostock, 2016; Barnes, Pickrill,
Bostock, Diabola et al., 2016). Nevertheless, we posit that more work is still needed to better understand
the role of these fjord-head deltas, in temperate climates, where seasonal changes in river flow have signifi-
cant impacts on the hydrodynamic sorting and transport of organic carbon to adjacent fjord sediments, and
in polar regions where glacier retreat is increasing the spatial extent of these deltas.

In this study, we use a fjord-head delta, located at the Gaer Arm head in the Doubtful Sound fjord complex,
Fiordland, New Zealand (Figure 1), to examine (1) sources and dynamics of OC along this fjord-head delta, (2)
degradation status of OC along this fjord-head delta in comparison with OC in fjords, and (3) burial rates of
OC in this fjord-head delta relative to regional fjords in Fiordland. Results from this work will provide new
information on fjord-head deltas that will help to compare and contrast OC burial mechanisms in New
Zealand fjords and improve future estimation of OC burial in the coastal zone, especially in places where
these fjord deltaic systems are expanding. Specifically, we will (1) measure sedimentation rates and mass
accumulation rates by using dry bulk density and 210Pb radionuclide profiles, (2) measure sediment grain size,
and (3) analyze bulk OC contents, stable isotope composition, and lignin phenol biomarker concentrations.

2. Methods

2.1. Local Settings and Sampling

The Camelot River, New Zealand, forms at the confluence of the Elaine Stream and Cozette Burn and flows
west into the Shoal Cove of Gaer Arm (Figure 1). The Camelot River is small with an average flow rate of
16.0 m3 s−1 (Rutger & Wing, 2006), with the majority of water being discharged during strong events. The
highest elevation in the river catchment is 1,760 m. The Camelot River, including the upper stream Cozette
Burn, is about 20 km in length, of which the last 5 km stretch is relatively flat with an elevation of <1 m
(Figure S1 in the supporting information). Gaer Arm delta is the largest fjord-head delta found in Fiordland
(Figure S2) and is expected to be representative of this type of delta in Fiordland.

A total of seven sediment cores were collected from the Gaer Arm Delta in March 2016. Samples were
retrieved by hand with 10 cm ID PVC push-core liners, which minimized potential compaction and sediment
disturbance artifacts (Figure 1). Four cores were collected near the bank of the main channel (C1, C3, C6, and
C7), one core near the bank of the relict-channel (I4), and two cores inland of the delta (I2 and I5). The letters
C, I, and F were associated with the station names channel, inland, and fjord, respectively. These seven deltaic
cores covered an upper-to-lower delta transect. All sediment cores were taken at high tide (~2 m) when sta-
tions I5 and C7 were submerged. In addition, five surface-grab samples were collected near the head of Gaer
Arm (F8–F12) that is characterized by steep bathymetry. From the delta channel to station F8, bed deposition
is dominated by pebbles and coarse grain particles. The lengths of the seven cores ranged between 15 and
25 cm and were subsampled every 1 cm upon arrival at the Deep Cove Field Station. The samples were trans-
ported to the University of Otago, New Zealand, on ice where they were stored frozen at −20°C, before being
freeze-dried and homogenized. Water content was calculated as the fraction of sample weight-loss after
freeze drying.

2.2. Geochronology

Sediment cores were dated using the naturally occurring radioisotope 210Pb (22.3 year half-life). Briefly,
homogenized dry sediment aliquots were packed and sealed in vials and stored for ≥21 days to allow
226Ra to reach equilibrium with its gamma-emitting daughters (214Bi and 214 Pb). Radiometric measurements
(210Pb, 226Ra, and 137Cs) were made using low-background gamma counting with well-type intrinsic
germanium detectors (Schelske et al., 1994). Sediment ages were calculated using the constant rate of supply model (Oldfield & Appleby, 1984). Ages of sediment layers below the $^{210}$Pb-datable sections of the cores were extrapolated using the best fit, age-depth relationship for the $^{210}$Pb-datable section of the core (Figure 2). However, given the large uncertainties generated for these older ages, this method was only used for plotting downcore profiles and was not used to calculate accumulation rates of sediments and organic carbon.

### 2.3. Bulk OC, Isotope, and Grain Size Analyses

All bulk sediments were analyzed for OC and total nitrogen (N) concentrations and stable isotopes except station F8 due to minimal OC and coarse grain size. The samples were fumigated in silver capsules with 12 N HCl to remove carbonates and analyzed on an elemental analyzer coupled to an isotope ratio mass spectrometer.
Figure 2. Downcore profile of excess $^{210}$Pb activities and the calculated calendar year. Calendar years were only calculated for the post-1900 layers to ensure accurate chronology.

(Harris et al., 2001). The precisions for $\delta^{13}$C and $\delta^{15}$N were better than 0.1‰ and 0.2‰, respectively. C/N ratios were reported as molar ratios: $C/N = (% \text{ OC}/12)/(% \text{ TN}/14)$.

Surface-grab samples and every 3 cm of the sediment cores (e.g., 0–1 and 3–4 cm) were analyzed for sediment grain size. The samples were pretreated with $\text{H}_2\text{O}_2$ at 60°C and centrifuged to remove organic matter before being measured on the LS 13320 Beckman Coulter Laser Diffraction Particle Size Analyzer (0.04–2,000 μm) (Wang et al., 2015; Xu et al., 2014). Due to the coarse grain size of the surface-grab sediments at F8 and F9, dry samples at these two stations were measured using sieve separation (Konert & Vandenberghe, 1997). Grain size is reported in μm with higher values representing coarser grain sizes.

2.4. Lignin-Phenol Analysis

The same samples for grain size analysis were measured for lignin phenols, according to the method of Goñi and Hedges (1992). Briefly, sediment containing 5 mg OC was oxidized with 2 N NaOH, neutralized with 12 N HCl, extracted with ethyl acetate, derivatized using bis-(trimethylsilyl)-trifluoroacetamide, and analyzed on a gas chromatography mass spectrometer. Phenols were quantified based on internal standards (ethyl vanillin and methyl 3,4-dimethoxy-benzoate) and a mixed standard. The average recovery rate of lignin phenols, based on internal standards, was 78 ± 5%. Lignin phenols, including vanillyl, syringyl, and cinnamyl, were calculated for the sediment mass ($\sum_{i=1}^{n} \text{mg g sediment}^{-1}$) and carbon-normalized concentrations ($\Lambda_{\text{phy}}$, mg (100 mg OC)$^{-1}$). Generally, greater values represent more vascular plant contributions (Goñi & Hedges, 1995). 3,5-Dihydroxybenzoic acid was also reported as carbon-normalized value ($\Lambda_{3,5-\text{Bd}}$, mg (100 mg OC)$^{-1}$), while 3,5-Bd/V is the mass ratio of 3,5-Bd to total vanillyl phenols and is representative of relative soil inputs (Houel et al., 2006). S/V was defined as the mass ratio of syringyl and vanillyl phenols, and smaller values represent either more gymnosperm inputs or greater lignin decay (Jex et al., 2014). Acid to aldehyde ratio of vanillyl [(Ad/Al)$_V$] was indicative of lignin degradation, with higher values representing greater decay (Hedges et al., 1988; Jex et al., 2014).

2.5. Statistical Analysis and Data Calculation

For statistical analysis, t tests were performed to determine any significant differences among groups of variables (e.g., channel versus inland stations). Statistical significance was considered at the level of $p < 0.05$, while 0.05 < $p < 0.1$ were considered only weakly significant.

To compare the spatial differences in sediment and OC accumulation rates over same time scales and to ensure accurate geochronology generated using $^{210}$Pb method, post-1900 sediment layers were used to calculate the average sedimentation rates (SRs), mass accumulation rates (MARs), OC accumulation rates (OCARs), and lignin accumulation rates (LARs). These values were further compared with values from New Zealand fjords (Cui, Bianchi, Savage et al., 2016; Hinojosa et al., 2014; Ramirez et al., 2016).

3. Results

3.1. Density, SR, MAR, and Grain Size

Dry sediment densities ranged from $0.18 \pm 0.02$ g cm$^{-3}$ at station I5 to $0.98 \pm 0.04$ g cm$^{-3}$ at station C1. The inland and relict-channel stations (I2, I5, and I4) were significantly lower than stations along the main channel ($p < 0.01$) (Figure S4). Stations I2, I4, and I5 showed a consistent increase in density downcore. Sedimentation rates (SRs), as calculated based on depth-age relationship, ranged from $0.063$ cm yr$^{-1}$ at station I5 to $0.197$ cm yr$^{-1}$ at station C6, with lower delta stations C6 and C7 significantly lower than upper delta stations ($p < 0.02$) (Figure 3). Mass accumulation rates (MARs) had a 14-factor variation and varied largely from $11.26$ mg cm$^{-2}$ yr$^{-1}$ at station I5 to $158.04$ mg cm$^{-2}$ yr$^{-1}$ at station C6. The inland and relict-channel stations (I2, I4, and I5) had significantly lower MAR than main channel stations ($p < 0.02$) (Figure 3).

Median grain size in the seven subaerial stations ranged from $32.05 \pm 0.07$ μm at station I5 to $154.32 \pm 33.66$ μm at station C1. There was a general trend of finer particles toward the inland (e.g., I4, I5) and lower delta (e.g., C7) stations (Figure S4). In contrast, the five subtidal surface-grab samples (F8–F12)
showed large variation in median grain size varying between 1250.41 and 45.36 μm, with a consistent decreasing trend in grain size from upper (F8) to lower (F12) stations (Figure S4). It is clear that fjord sediments in the deeper stations have a much finer grain size average (9.43 ± 5.09 μm) (Ramirez et al., 2016) than found in the Gaer Arm fjord-head delta.

3.2. Bulk OC, C/N Ratios, δ¹³C, δ¹⁵N, and OCAR

The seven fjord-head delta stations had OC concentrations (% mass) that ranged from 3.94 ± 1.58% (C6) to 24.13 ± 12.51% (I2) with inland and relict-channel stations significantly higher than stations along the main channel (p < 0.001) (Figures 4 and S4). Four out of seven cores showed decreasing OC concentrations downcore with the exception of I2, C7, and C6 that had the highest OC concentrations in the subsurface layers (Figure 4). OC contents in the four surface grab samples ranged from 0.22% to 4.27% and were significantly lower than along the subaerial stations (p = 0.03) and fjord surface sediment average (6.02%) (Figure S4).

Nitrogen concentrations followed a spatial pattern similar to OC. C/N ratios varied largely from 15.57 ± 1.74 to 27.76 ± 1.97 along the delta stations, with the highest and lowest values analogous to terrestrial vascular plant end-members and aquatic end-members (Figure S3). All stations showed consistently decreasing C/N ratios downcore, with the exception of C1 that showed the opposite trend (Figure 4). Underwater surface-grab samples varied between 20.20 and 25.67 for C/N ratios, which were higher off the delta at deeper water depths (Figure S4). All stations, including deltaic and underwater surface sediment samples, were lower in δ¹³C values than the average of fjord surface sediments (−27.19 ± 1.05‰); δ¹⁵N showed similar variations to δ¹³C. More specifically, the average δ¹⁵N values at deltaic stations ranged

Figure 3. The average (a) sedimentation rates (SR), (b) mass accumulation rates (MAR), (c) OC accumulation rates (OCAR), and (d) lignin accumulation rates (LAR) of each deltaic station and fjord average (Fj). The values are illustrated by the size of the dots on a schematic basemap with gray color indicative of land. The values at all deltaic stations shown in this figure are calculated from the post-1900 deposits to ensure same time scales (1900–2016) at each station.
between 0.44 ± 0.66‰ (C6) and 2.87 ± 1.59‰ (C1). In general, δ¹⁵N values increased downcore with some of the core surface intervals (I2, C3, and C6) having negative δ¹⁵N values (Figure 4). Surface-grab samples had similar values to fjord-head delta samples, with only station F10 having a negative δ¹⁵N value (Figure S4). At the same station, the odor of H₂S was clearly indicative of low oxygen levels.

Post-1900 OCAR, calculated based on cumulative OC and age-depth relationship, ranged between 2.08 (I5) and 5.83 (C6) mg cm⁻² yr⁻¹ and revealed that inland and relict-channel stations had slightly lower OCAR than stations along the main channel (p = 0.055). When calculating the arithmetic mean of the Gaer Arm fjord-head delta stations (4.39 mg cm⁻² yr⁻¹), OCAR along the fjord-head delta was comparable or slightly lower than in the deeper reaches (>50 m) of New Zealand fjords (4.62 mg cm⁻² yr⁻¹) (Cui, Bianchi, Savage et al., 2016; Hinojosa et al., 2014; Smith et al., 2015).

3.3. Biomarkers and Lignin Accumulation Rates
Organic carbon-normalized lignin phenol concentrations (Λ₈, mg (100 mg OC)⁻¹) ranged between 2.95 ± 0.63 (C1) and 6.06 ± 0.38 (C7) mg (100 mg OC)⁻¹ along the deltaic stations (Figures 5 and S5). There was a significant increasing trend in lignin toward the lower delta with the highest Λ₈ (C7) comparable to Doubtful Sound average (5.73 mg (100 mg OC)⁻¹) (Cui, Bianchi, Savage et al., 2016). When examining the downcore trends of Λ₈ values, most of the cores showed a similar decreasing trend downcore, with the exception of station I5 (Figure 5). The four surface-grab samples ranged between 5.49 and 8.55 mg (100 mg OC)⁻¹, with the lower end comparable to the Doubtful Sound average (Figure S5). The surface grabs were also significantly higher than the fjord-head delta stations (p < 0.02). An indicator of soil inputs, 3,5-Bd/V ranged between 0.09 ± 0.03 (C1) and 0.03 ± 0.01 (C7) along the deltaic stations and showed no significant differences (p = 0.15) to the surface grabs (0.06 to 0.07) (Figure 5). The opposite of Λ₈ values, the deltaic stations showed a decreasing trend in 3,5-Bd/V ratios toward lower stations with the lower end comparable to Doubtful Sound average (0.04). In contrast to the Λ₈ patterns, 3,5-Bd/V ratios either had no variation or increased slightly downcore (Figure 5).

S/V ratios, representative of gymnosperm inputs and lignin decay, ranged between 0.44 ± 0.18 (C1) and 1.13 ± 0.14 (C7) with an increasing trend from the upper to the lower fjord-head delta (Figure 5).
contrast, the four surface-grab samples were relatively consistent in S/V ratios, ranging from 1.32 to 1.40, and were significantly higher than the values of the deltaic stations ($p < 0.002$) (Figure S5). Overall, the S/V ratios in fjord-head delta sediments and the surface grabs were comparable to the average value for surface sediments in Doubtful Sound ($1.18 \pm 0.11$). The downcore profiles of S/V ratios for the deltaic stations showed a consistently decreasing trend with the exception of I5 (Figure 5). (Ad/Al)$_V$ ratios of the fjord-head delta sediment cores ranged between 0.45 ± 0.03 (I5) and 0.82 ± 0.11 (C3), with most of the cores showing an increasing trend downcore (Figure 5). In contrast, core I5 had the lowest (Ad/Al)$_V$ ratios and showed no variation downcore. However, there was no specific spatial trend associated with the fjord-head delta samples. (Ad/Al)$_V$ values in surface grabs (0.26–0.30) were comparable to Doubtful Sound surface sediments (0.30 ± 0.08) but were significantly lower than all fjord-head delta surface samples and downcore averages ($p < 0.0001$) (Figure S5).

Lignin phenol accumulation rates ranged between 0.08 (I5) and 0.30 mg cm$^{-2}$ yr$^{-1}$ (C6) and showed no significant differences across locations, except the inland station I5, which had the lowest LAR. The average LAR of all deltaic stations (0.20 ± 0.07 mg cm$^{-2}$ yr$^{-1}$) was comparable to the Fiordland fjord average value (0.21 mg cm$^{-2}$ yr$^{-1}$).

4. Discussion

4.1. Carbon Dynamics Along the Fjord-Head Delta

Fjord-head deltas, like many other deltas, have long been proposed as traps for coarse particles due to reduced flow energy (Gibson & Hickin, 1997; Orton & Reading, 1993). The coarse-grained particles found at all deltaic stations in this study, in contrast with the fine-grained particles in fjord sediments (Ramírez et al., 2016), indicated that the Gaer Arm fjord-head delta is comparable to other fjord-head deltas in trapping the majority of coarse particles in a fjord system. The ability of fjord-head deltas to trap coarse-grained sediments has been more attributed to the presence of particle-trapping vegetation growth on the delta, rather than direct deltaic deposition (Walling et al., 1997). The growth of vegetation on the delta also complicates the carbon dynamics of this dynamic geological setting, which remains largely unknown and is the focus of this work.
Clear patterns of lower MAR, higher OC contents, and finer-grained sediment toward the inland and relict-channel stations in the Gaer Arm Delta were indicative of selective dispersal of particles during overbank flooding (Figures 3, 4, and S4), likely related to hydrodynamic sorting. Based on Stokes’s law (Lamb, 1994), denser and coarser particles preferentially settled near river channels, while finer and lighter particles were transported further distance off channels. Consistent with this hypothesis, we found much higher %OC in the three inland and relict channel stations on the delta. Similar distribution patterns of mineral particles and OC were found during overbank deposition along the Mississippi River and the Ouse River (Kesel et al., 1974; Walling et al., 1997). In contrast with inland stations I4 and I5—which had lower OCAR than other stations, inland station I2 had comparable OCAR to the stations along the bank (Figure 3), largely due to local vegetation inputs at station I2, which will be discussed later. Interestingly, the observed decreasing sediment grain size, from fjord-head delta to subtidal stations, and then the main fjord (Figure S4), was analogous to patterns found on the Gilbert-type delta in Englebright Lake, CA (Pondell & Canuel, 2017).

4.2. Autochthonous Versus Allochthonous OC

The decreasing \( \Lambda_8 \) values toward the upper Gaer Arm delta indicated lower vascular plant inputs to the upper delta, possibly due to dilution of relatively low-lignin in situ autochthonous OC (Figures 5 and S5) (Aspetsberger et al., 2002). If we assume that the organic particles carried by the Camelot River were well homogenized before their delivery to the delta, then lower \( \Lambda_8 \) values represented in situ dilution by additional OC pools relatively depleted in lignin. Lower \( S/V \) ratios were also observed toward the upper delta and were strongly correlated with \( \Lambda_8 \) values (\( R^2 = 0.77 \); Figure 6). Previous work, which examined the lignin composition of several key plant end-members in this region (e.g., moss, fern, and epiphyte), showed that these plants were characterized by low lignin contents and low \( S/V \) ratios (Cui, Bianchi, Savage et al., 2016). The low \( S/V \) ratios in the upper deltaic sediments support the interpretation that inputs from these local plants are in fact accumulating in these sediments (Figure 5). Similarly, the Wax Lake Delta in Louisiana,
USA, an embryonic prograding delta, has much of its upper deltaic particulate lignin inputs ($\Lambda_B$) derived from plants growing on the upper delta and very little from upstream sources (Shields et al., 2016). Station C7 at the lower region of the Gaer Arm fjord-head delta had the highest $\Lambda_B$ values of all deltaic stations and was comparable to the surface-grab samples, indicative of exclusive allochthonous inputs from river transport with minimal in situ dilution (Figures 5 and S5). Consistent with the observation of large woody fragments underwater near the subaerial delta, we measured the highest $\Lambda_B$ value of all surface grabs at station F9. Similarly, deposition of coarse particles together with woody fragments has also been observed on the topset of the Gilbert-type delta associated with flooding events in Englebright Lake (Pondell & Canuel, 2017).

Finally, consistent with patterns of high $\Lambda_B$ and S/V, and low C/N ratios in the upper deltaic sediments, we also found higher 3,5-Bd/V ratios, indicative of better developed soils (Figures 4 and S4) (Ahearn et al., 2006; Aspetsberger et al., 2002). Once again, previous work on Wax Lake Delta, a similar sandy deltaic system albeit in a major floodplain displayed a subaerial chronosequence that signified different ages since becoming subaerial with older age and growth of plants in the upper delta (Shields et al., 2016). We propose that the changes in $\Lambda_B$ values, S/V, and 3,5-Bd/V ratios along the Gaer Arm Delta are all closely linked and are highly driven by the maturity of the upper deltaic setting.

4.3. Spatial and Temporal Degradations of OC

Significantly higher (Ad/Al)$_v$ ratios at the upper stations of Gaer Arm Delta compared to the underwater surface grabs in the upper reach of the Gaar Arm, and even to fjord surface sediments in the deeper waters of Fjordland, were indicative of significant lignin degradation in the Gaer Arm Delta (Figures 5 and S5). The low (Ad/Al)$_v$ ratios found in local plant end-members (<0.32) and soil end-members (avg. 0.42 ± 0.17) sampled in this region (Cui, Bianchi, Savage et al., 2016) further support the premise that the signature of high lignin decay was not from the plant tissue and upstream soil, but rather from decay of plant detrital material and soils occurring in situ. The strong negative correlation between (Ad/Al)$_v$ and S/V ratios ($R^2 = 0.81$; Figure 6) suggested that the dominant plants with lower S/V ratios growing in the upper delta (ferns, moss, and epiphytes) have a greater amount of nonwoody plant biomass and are thus likely to be more vulnerable to degradation than the large woody species found in the terrestrial areas of the watershed. The higher S/V ratios at stations I5 and C7, on the lower delta, were more indicative of woody angiosperm sources. Moreover, these samples had higher (Ad/Al)$_v$ ratios than the surface-grab samples and the surface sediments from the deeper basins of Fjordland (Figure 5 and S5), indicating high lignin decay in both upper and lower reaches of the Gaer Arm Delta. Finally, it should be noted that the use of S/V ratios as indices of plant sources in these sediments, where both decay and selective leaching are occurring (Hernes et al., 2007), makes it difficult to unequivocally link source inputs.

Despite variable OC contents with depth, we observed constant downcore increases in $\delta^{13}C$, $\delta^{15}N$, and (Ad/Al)$_v$ ratios and decreases in $\Lambda_B$ and S/V ratios at all deltaic stations, likely due to significant degradation of OC downcore (Figure 5). Previous work on forest soils showed that fresh litter inputs have $\delta^{15}N$ values of $-1.6\%$ to $-3.8\%$ and that organic matter decomposition by soil microbes elevated $\delta^{15}N$ values by 7% to 10% (Natelhoffer & Fry, 1988). While we can only speculate about the role of microbes based on inferential chemical proxy data, it does appear that OC degradation along this delta, both spatially and over variable time scales, is occurring more than in the deeper fjord sediments of Fjordland (Cui, Bianchi, Hutchings et al., 2016; Cui, Bianchi, Savage et al., 2016). For example, a previous study in Fjordland observed minimal variation in OC and $\delta^{13}C$ values over a century time scale (Cui, Bianchi, Savage et al., 2016), and this would be expected in these deeper waters that contain less oxygen (Hinojosa et al., 2016). More degradation of OC on Gaer Arm fjord-head delta is promoted by greater oxygen exposure in coarse sediment deposits (Rasheed et al., 2003), particularly in the subaerial reaches of the delta. This is analogous to OC degradation processes in salt marsh systems where the microbial-driven OC remineralization is oxygen-limited (Trevathan-Tackett et al., 2017). Because of elevated oxygen penetration and frequent tidal flushing, permeable coastal sediments efficiently decompose OC (Berg & Kostka, 2014). These factors work synergistically in the Gaer Arm fjord-head delta to efficiently decompose OC. On one hand, the exposure of the delta to the atmosphere during low water level can enhance the penetration of oxygen into the sediments and enhances aerobic degradation of OC (Langhans & Tockner, 2006; Rasheed et al., 2003). On the other hand, the frequent infiltration of flood waters into the permeable sediments promotes the leaching and flushing of degraded water-soluble OC (Precht et al., 2004; Rasheed et al., 2003; Rusch et al., 2006; Trevathan-Tackett et al., 2017). In fact, the water
just off Gaer Arm Delta appears to be particularly high in chromophoric dissolved organic matter (CDOM), which may be attributable to dissolved humics leached from the deltaic sediments (Gonsior et al., 2008). This is in contrast with the well-sorted and fine-grained particles exported into the deeper waters of Fiordland, where we see high burial efficiency of OC in sediments associated with the lower permeability of the sediment and the shorter oxygen-exposure times of the OC (Cui, Bianchi, Savage et al., 2016). In contrast, this OC high degradation signature found in Gaer Arm fjord-head delta was not observed in the Gilbert-type delta in Englebright Lake or the prograding Wax Lake Delta, most likely due to extremely high sedimentation rates and the relatively greater abundance of finer-grained sediments, respectively (Pondell & Canuel, 2017; Shields et al., 2016).

4.4. Importance of Fjord-Head Deltas in Fjord Carbon Dynamics

The OCAR on the delta is comparable to that in the fjord on a century time scale (Figure 3); however, the delta’s OCAR might be considerably less than that in fjords over longer time scales due to strong degradation of OC in the fjord-head delta as indicated by decreasing OC contents in the deeper sediment layers (Figure 4). The strong correlation between water content and OC content suggests that sediments with higher OC are more vulnerable to degradation through leaching (Figure 6). Comparatively, OCAR in Gaer Arm fjord-head delta is at least 80 times less than in the Gilbert delta in Englebright Lake, CA (Pondell & Canuel, 2017). Higher OCAR along the Englebright Lake Gilbert-type delta is particularly linked with underwater sedimentation and terrestrial inputs associated with mining operations in the drainage basin (Pondell & Canuel, 2017). Gaer Arm delta has a surface area of ~0.8 km². Within the Doubtful/Thompson fjord complex, there are at least 11 minideltas similar to Gaer Arm fjord-head delta, with a total surface area of ~3 km² (estimated using Google Earth) (Figure S6). By assuming similar OCAR in each delta, OC burial at these spots is equivalent to a maximum of 2.3% of total OC buried in the Doubtful/Thompson fjord complex. It suggests that when studying fjord carbon burial over short time scales, these systems may be important on a short-term regional basis in fjord systems, while overall, they only have a limited role as a long-term carbon sink. However, if more expansive than in Fiordland, these deltas may have many indirect effects on carbon dynamics in fjords. On one hand, these fjord-head deltas create platforms of permeable sediments that can intercept coarse particles from the steep slopes of the watershed. On this unique platform, the ability to decompose OC is much greater than can occur if the particles were directly injected into the deeper water with low oxygen, due in part to greater oxygen exposure and inherent high efficiency of OC associated with permeable sediments in deltas (Berg & Kostka, 2014). On the other hand, this type of delta intercepts coarse particles and exports well-sorted fine particles to fjords and thereby increasing carbon burial rates in the deeper reaches of fjords by reducing permeability of sediments and increasing coating of OC on fine particles (Cui, Bianchi, Hutchings et al., 2016; Ramirez et al., 2016).

Fjord-head deltas in Fiordland are also considered to be relict deltas, due to their much lower sedimentation rates than occurred during deglaciation times along with their much more limited efficiency of delta accretion in modern systems (Barnes, Pickrill, & Bostock, 2016; Barnes, Pickrill, Bostock, Dlabola et al., 2016). Based on seismic studies, these fjord-head deltas had tens to hundreds of times higher sedimentation rates back in the early Holocene (Barnes, Pickrill, & Bostock, 2016; Barnes, Pickrill, Bostock, Dlabola et al., 2016) that were likely associated with deglaciation processes. However, due to the short lengths of the cores in this study, we were unable to gather enough downcore information to evaluate millennial-scale OC burial in the Gaer Arm fjord-head delta. Although Fiordland is currently fully nonglaciated, the presence of such fjord-head deltas in high-latitude glaciated fjords (e.g., SE Alaska, South Patagonia) provides the opportunity to study the carbon dynamics of temperate fjord head deltas back in time (Carlson et al., 1992; Syvitski et al., 1987). Moreover, as global warming continues to enhance glacial retreat in these high-latitude fjord systems, we might also expect rapid OC decay rates in newly exposed fjord-head platforms composed of poorly sorted coarse cobbles and sediments that may also serve as trapping locations for OC being delivered from the thawing upstream glacial landscapes. In temperate regions, global warming and sea level rise may well inundate these fjord-head deltas changing their role as coarse-particle filters in fjords regions like Fiordland.

5. Conclusions and Implications

In this study, we used Gaer Arm Delta from a temperate fjord-head in New Zealand to investigate the role of fjord-head deltas in carbon dynamics in fjord systems. The pattern of grain size and OC contents
demonstrates the importance of hydrodynamic sorting in affecting particle and carbon distribution patterns along fjord-head regions. We observed lower vascular plant inputs moving from the upper to the lower delta due to dilution of in situ production, suggesting that in situ vegetation is a substantial source of OC to this fjord-head delta. Our bulk and biomarker data also demonstrated much stronger degradation of OC on the fjord-head delta than in fjords ascribing to coarse particle deposition. Finally, based on our data, we estimated that fjord-head deltas as a platform are likely a hot spot of carbon oxidation over century time scales; however, the more important roles of such deltas lie with their indirect effect on fjord carbon dynamics.

This is the first time that a temperate fjord-head delta was investigated using chronological, sedimentological, and organic geochemical methods. Although fjord-head deltas are commonly overlooked due to their scarcity in fjord systems, our results suggest that such fjord-head deltas may influence sedimentation and OC burial in fjords, so their inclusion in future studies on fjord sediment dynamics is justified, particularly in regions where they may be expanding (e.g., SE Alaska). In addition, we propose that similar deltas located in currently glaciated fjords need to be investigated for comparison to these nonglaciated, temperate fjord-head deltas.

Acknowledgments
The work was partially supported by University of Otago research grants to C. Savage and a scholarship from China Scholarship Council. We would like to thank Jon L. and Beverly A. Thompson Endowed Chair of Geological Science that Blanchi is the holder of in Geological Sciences at University of Florida. We thank Sean Hesseltine for field assistance. Many thanks to one anonymous reviewer, Craig Smeaton, and Editor Gorli for constructive comments that greatly improved the quality of this work. All original data are attached as supporting information to this manuscript.

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