Benthic foraminiferal faunas reveal transport dynamics and no-analog environments on a glaciated margin (Gulf of Alaska)

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Abstract

Paleoecological and faunal-based paleoenvironmental studies rely on fossil assemblages that have high fidelity to the once-living faunas and to the target environment. However, many sedimentary records contain multiple depositional facies, transported sediments with their associated fossils, and varying degrees of taphonomic alteration, which can confound interpretations. Here we combine measures of compositional fidelity, modern analog faunal methods, sedimentary analyses, and taphonomic scoring to examine the history of sediment transport and environmental change in a ~60,000 year continental slope record from the Gulf of Alaska using benthic foraminiferal assemblages. These assemblages generally have good compositional fidelity to modern faunas in the Gulf of Alaska, but are not necessarily faithful to the modern continental slope. Fossil benthic foraminiferal assemblages with modern analogs from shelf and slope environments are intercalated downcore suggesting episodes of sedimentary transport to the slope site. Fossil assemblages without modern analogs in this record appear ecologically, rather than taphonomically, derived and thus suggest that the range of past environmental variation in the Gulf of Alaska is not captured by modern spatial variation. These no-analog fossil assemblages are allied with analog assemblages using similarity in taxonomic and sedimentary characteristics, permitting analysis of environmental change in shelf and slope settings from a single core. The faunal composition of the no-analog assemblages suggests the Gulf of Alaska slope experienced lower oxygen conditions in the past than observed in the modern gulf. Lower productivity is also suggested for some shelf samples, however geochemical proxy data are necessary to fully interpret the no-analog assemblages.

Keywords: modern analog; live-dead; transport; glaciomarine; low-oxygen; benthic foraminifera

1. Introduction

Paleoecological and faunal-based paleoenvironmental analyses rely on identifying fossil assemblages with high compositional and spatial fidelity to the communities once living in the environment of interest. Live-dead studies test this fidelity by comparing death assemblages to the local living community and are often focused on providing a quantitative estimate of the reliability of the fossil record (Kidwell and Flessa, 1996; Murray and Alve, 1999; Zuschin et al., 2000; Kidwell, 2002). However decadal to millennial changes in environmental conditions can drive dissimilarities between the live and dead assemblages such that low fidelity does not necessarily equate to an unreliable fossil record (Kidwell 2008, Kowalewski, 2009; Terry 2010; Kidwell, 2013; Kidwell and Tomasovych, 2013; Webber and Zuschin, 2013). Instead, these ecologically relevant assemblages are simply not analogous to the living community.

Low fidelity to modern assemblages due to environmental change is recognized in paleoenvironmental studies using modern-analog techniques where some fossil assemblages differ in their faunal composition so much that they are termed no-analog assemblages (Overpeck et al., 1985; Mix et al., 1999; Jackson and Williams, 2004; Williams and Jackson, 2007; Williams et al., 2013). These fossil faunas with no modern analog may indicate either no-analog environmental conditions or no-analog faunal responses to environmental change, if their composition is faithful to their once-living counterparts. Alternatively, these no-analog faunas could be generated by taphonomic processes such as winnowing, dissolution, and temporal or spatial mixing of assemblages just as poor-live dead agreement can be interpreted as an altered fossil record.

Live-dead and modern analog analyses thus converge on a similar issue: low fidelity can be driven by both ecological and taphonomic processes. Paleoecological and paleoenvironmental analyses require separation of these processes such that assemblages with significant taphonomic bias are cautiously interpreted while not discriminating against faunas indicative of environmental conditions

not captured by modern spatial variation. In the context of a stratigraphic record that may contain allochthonous sediments, separation of autochthonous assemblages from allochthonous assemblages is also critical to reconstructing coherent records of paleoecological and paleoenvironmental change that are faithful to the locality of interest and capture the full range of variation, even when samples lack modern faunal analogs.

The Gulf of Alaska has high tectonic activity and a narrow shelf, which together can promote downslope transport of sediments and the fossil remains therein (Dobson et al., 1998; Eyles and Lagoe, 1998). During past glacial advances, sediment flows generated from the base of a grounded glacier potentially transported sediments from above the shelf break downslope (Molnia, 1983; Dobson et al., 1998). Downslope sediment transport could also be driven by earthquake liquefaction, oversteepening of depositional slopes or tectonic tilting in this setting (Eyles and Lagoe, 1998). Mobilization could range from detachment of coherent masses of sediment in slump deposits or completely disaggregated sediments deposited in debris flows (Molnia 1983; Eyles et al., 1991; Dobson et al., 1998). In addition, ice-rafting could contribute significant sediments to the slope during glacial intervals (Molnia 1983; Jaeger et al., 2014). Thus, sedimentary records from the Gulf of Alaska slope are likely to contain autochthonous, allochthonous and mixed fossil assemblages within various lithologies, complicating reconstruction of its paleoenvironmental history.

IODP Expedition 341 drilled a transect of sites across the Bering-Malaspina shelf and slope in the Gulf of Alaska aimed at understanding the relationships and feedbacks between climate, tectonics, and the development of a temperate glacial system (Jaeger et al., 2014). Site U1419, located on the continental slope, has the potential to yield high resolution paleoclimate records (Jaeger et al., 2014), however paleoecological and paleoenvironmental interpretation of this complex depositional setting first requires separation of sediment packages from disparate sources and recognition of fossil assemblages altered by mixing and other taphonomic processes. In addition, the record may contain

fossil faunas with no modern analogs due to distinctly different environmental conditions during glacial and deglacial modes than are experienced in our modern interglacial.

Here we build upon live-dead and modern analog faunal methods combined with sedimentary and taphonomic analyses to quantitatively define no-analog benthic foraminifera assemblages at IODP Expedition 341 Site U1419 on the continental slope in the Gulf of Alaska, assign analog and no-analog faunal assemblages to shelf and slope environments and assess sedimentary transport. Further, we evaluate the influence of faunal mixing, taphonomic alteration, and no-analog environmental conditions on the composition of fossil faunas without modern analogs. This approach permits the complex stratigraphy of this glacially influenced record to be interpreted in terms of sediment transport from the continental shelf and intensification of the oxygen minimum zone on the continental slope.

2. Study site and Geological Setting

The Gulf of Alaska has a narrow continental shelf (~ 25 km) with the shelf break located at ~220 m water depth (Molnia, 1983; Dobson et al., 1998). Today, no glaciers terminate on the shelf in the study region and the extent of past glaciation on the continental shelf is poorly constrained (Molnia, 1986; Kaufmann et al., 2011). Sediment accumulation in the modern is negligible on the continental slope in this region (Jaeger et al., 1998). Low rates of sediment accumulation began ~14,790 years ago and may be caused by glacial retreat behind fjord sills or onto land (Davies et al., 2011).

IODP Expedition 341 Site U1419 is located at 684 m water depth on a relatively flat bank above the Khitrov Basin and Ridge within the continental slope, which is informally referred to as the Khitrov Bank (Jaeger et al., 2014; Figure 1). The core of the oxygen minimum zone (OMZ) in the Gulf of Alaska is ~670-1060 m (Paulmier and Ruiz-Pino, 2009), placing site U1419 near its uppermost modern reach where changes in the extent and intensity of the OMZ are likely to be recorded by *in situ* benthic faunas. In addition, the site is located in a region of high seasonal surface productivity (Ladd et al., 2007), thus

responses of the OMZ and of benthic communities to changes in paleoproductivity may also be recorded.

Site U1419 was drilled to 177 m below the seafloor; benthic foraminiferal $\delta^{18}\text{O}$ data suggest all sediments recovered are younger than ~60,000 years (Jaeger et al., 2014; Gulick et al., 2015). Sedimentation rates range from an average of ~36 cm/kyr over the last 15,000 years (top ~8 m) to ~644 cm/kyr in the oldest part of the record below ~100 m core depth (Gulick et al., 2015). The low sedimentation rates correspond to an interval of diatom-rich hemipelagic mud in the top 5 m of lithological Unit I (Figure 2; Davies et al., 2011; Jaeger et al., 2014). Unit 1 continues to ~90 m core depth and is dominated by massive mud with lonestones previously interpreted as suspension settled muds with ice rafted debris (Davies et al., 2001; Jaeger et al., 2014). Within this mud, interbeds of sand and silt are present from 54-79 m and an interval of diamict occurs at 68-74 m, which may indicate fluctuations in sediment supply via sediment gravity flows, debris flows, or iceberg or sea ice-transported sediment (Jaeger et al., 2014; Figure 2B). Interbeds of diatom-rich massive muds without lonestones, each less than 0.25 m thick, occur at 70-90 m core depth and indicate decreases in coarse sediment supply. Unit 1 has a gradational contact with the underlying Unit 2, which is comprised primarily of diamict deposited by either debris flows or ice rafting (Jaeger et al., 2014). Within Unit 2, the number of clasts generally increases downcore and core recovery is poor below 114 m core depth. Decimeter-scale interbeds of diatom-rich muds without lonestones also occur in Unit 2 at 100-105 m and at 170 m core depth, suggesting intervals of reduced glacial sediment supply (Jaeger et al., 2014).

The complex lithostratigraphy of the U1419 core suggests a complex depositional history that may include sediments transported downslope. In order to use the downcore record from U1419 in paleoenvironmental reconstruction of the OMZ, episodes of sediment transport must be differentiated from the *in situ* record. Benthic foraminifera are often used for quantitative biofacies analysis, including in the Gulf of Alaska (Lagoe et al., 1989; Zellers, 1990; Eyles et al., 1991), and to determine the

provenance of sediments to infer sediment transport mechanisms in glacially influenced records (Jennings et al., 1996; Andrews et al., 1998). Previous studies in the Yakataga Formation, which underlies the Gulf of Alaska, have focused on faunas from continental shelf and upper slope settings shoreward of Site U1419 (Lagoe et al., 1989; Zellers, 1990; Eyles et al., 1991; Lagoe et al., 1994; Eyles and Lagoe, 1998). Some of these studies recognized sediment slumps in outcrops of the Yakataga and suggest downslope transport may be triggered by tectonic activity (Lagoe et al., 1989; Eyles and Lagoe, 1998); failure of outershelf to upper slope deposits also occur in the modern Gulf of Alaska (Hampton et al., 1993). Thus, multiple mechanisms of sediment transport from the shelf to the slope may contribute sediment, and potentially benthic foraminiferal faunas, to U1419. If distinct autochthonous and allochthonous foraminiferal assemblages can be segregated downcore, then timeseries of environmental change restricted to shelf and slope environments could be obtained from the U1419 record.

3. Methods

3.1 Modern Benthic Foraminiferal Faunal Analyses

To provide a modern context for paleoenvironmental interpretation of U1419 faunas, a modern array of 225 surface-sediment live+dead benthic foraminiferal assemblages from the Gulf of Alaska is compiled from published faunal counts in Bergen and O'Neil 1979 (95 samples) and Echols and Armentrout 1980 (103 samples) and from new faunal counts from 24 EW0480 multicore samples and mudline samples from Expedition 341 sites U1418 (Holes A-C pooled), U1419 (Hole A), and U1421 (Figure 1). The datasets vary in their sample preparation methods. Echols and Armentrout (1980) used the >62 μm size fraction and foraminifera were separated from sediment via flotation in some samples. EW0480 was processed at >125 μm and Expedition 341 mudline samples were processed at >63 μm ; coarse fractions were dry picked for foraminifera in each case. Bergen and O'Neil 1979 do not describe their methods, however taxa typically found in the 125-63 μm size fraction are common, suggesting they

also used >63 μm assemblages. The datasets are taxonomically standardized to the species-level by comparison to illustrations and references in the publications and to identified specimens from Echols and Armentrout 1980 provided by Exxon Mobil. Species whose abundances are not at least 1.5% of at least one sample are excluded from further analyses (Appendices A and B).

Faunal assemblages are grouped into similar biofacies using hierarchical cluster analyses with unweighted pair group mean averaging of the Bray-Curtis distances among samples calculated from the proportional abundances of taxa. Cluster analysis is performed using the “hclust” function of the R programming language.

Variation in the proportional abundances of taxa is further summarized using principal coordinates analysis (PCO) to evaluate faunal gradients in the context of environmental variation and to examine the potential effects of differences in sample preparation. PCO was chosen as the ordination method because it can accommodate dissimilarity matrixes, such as the Bray-Curtis dissimilarity used herein, that do not assume linear species abundance relationships and is thus more appropriate for ecological data than principal components analysis, which is constrained by the Euclidean dissimilarity matrix (Legendre and Legendre, 1998). The number of axes computed for the PCO (k) is selected as the axis number beyond which changes in eigenvalues are small, indicating that higher dimensions do not contribute greatly to the analyses (Legendre and Legendre, 1998). PCO analyses were conducted on both the full set of taxa and on a subset that includes only the calcareous taxa to test whether taphonomic loss of agglutinated taxa could affect paleoenvironmental interpretations. The similarity of these two PCO analyses is assessed using a mantel test based on the Euclidean distances between assemblages in PCO space and the Pearson correlation coefficient. PCO analyses and mantel tests are conducted using the vegan package (functions “cmdscale” and “mantel”, respectively) of the R programming language (Oksanen et al., 2015).

For comparison with faunal clusters and faunal gradients, temperature, salinity and oxygen concentration data are interpolated from World Ocean Atlas 13 (Locarnini et al., 2013; Zweng et al., 2013; Garcia et al., 2013), with flagged data excluded, using 3D estimation in Ocean Data View 4.7.0 (Schlitzer, 2015; Appendix C). Biofacies defined by the cluster analysis described above are examined for significant differences in environmental variables using Mann-Whitney tests. The relationship between faunal similarity and environmental similarity is further assessed using mantel correlations based on Euclidean dissimilarities between sample distances in PCO space and environmental variables.

3.2. Downcore Benthic Foraminiferal Faunal Analyses

Thirty-six samples from the U1419 core were wet-sieved over a 63 μm sieve and picked for benthic foraminifera >63 μm . Samples were ~30 cc (~50 grams dry weight) and each spanned a 3 cm core interval. All samples included in downcore faunal analyses (34) have at least 100 individuals in the >63 μm fraction. All individuals were identified using the same references used to taxonomically standardize the modern array. Major downcore variation in faunal assemblages are summarized using PCO as for the modern samples. Species scores in PCO space are calculated as the expanded weighted averages for each PCO axis using the function “wascores” in vegan (Oksanen et al., 2015). Community evenness is calculated for each assemblage as the probability of interspecific encounter (PIE), which is insensitive to differences in sample size (Hurlbert, 1971).

To test for taphonomic effects on downcore assemblage composition, specimens >125 μm were taphonomically scored using a semi-quantitative damage scale (0=pristine, 1=opaque and pitted, 2=only aperture chamber broken, 3= many chambers broken, 4=broken across sutures) following Belanger (2011). The preservation quality of *Epistominella pacifica*, which is found in 34 of 36 downcore samples in the >125 μm fraction, is also compared among samples to control for taxonomic variation in preservation. The Spearman correlation is used assess preservation trends with core depth.

3.3 Defining Modern Analogs and Assemblage Types

The similarity among modern assemblages is calculated to establish a baseline for differentiating fossil faunas with and without modern analogs. This is necessary because the ability to identify modern analogs is dependent on the breadth of faunal variation in the modern array (Overpeck et al., 1985; Jackson and Williams, 2004). The Spearman correlation of the rank-order abundances of species was calculated between all pair-wise modern samples. Taxa that do not appear in at least one sample in the pair are removed before the Spearman rho is calculated. Spearman rho, which only considers the similarity in the rank abundance of taxa, was chosen to minimize the influence of differences in proportional abundances of species and is commonly used as a similarity metric in live-dead studies (eg. Kidwell, 2008). Agglutinated foraminifera are less likely to preserve in fossil records, thus similarities among modern assemblages were calculated with and without agglutinated foraminifera to test whether the loss of agglutinated taxa affects the ability to identify modern analogs. A fossil assemblage has a modern analog if its correlation to a modern assemblage is greater than 95% of the modern-modern nearest-neighbor correlations. The nearest modern analog to a fossil assemblage is the modern assemblage with the highest Spearman correlation.

Given the modern environment of Site U1419 is a continental slope setting with low sedimentation near the OMZ, fossil benthic foraminiferal assemblages analogous to the modern Khitrov Bank should most closely resemble modern assemblages from similar slope settings. However, downcore assemblages could be transported from upslope environments and would thus be more analogous to modern assemblages from the continental shelf. In addition, no-analog environmental conditions and taphonomic process could result in fossil assemblages that are analogous to neither slope or shelf modern assemblages. Given these possibilities, we define potential five types of downcore fossil assemblages to guide our interpretations:

Type 1: Assemblages with modern analogs from the modern low-oxygen slope.

Type 2: Assemblages without modern analogs, but from similar slope environments. These samples will have sedimentary and faunal similarities to samples with Type 1 assemblages.

Type 3: Assemblages with modern analogs from environments other than the low-oxygen slope. These samples may have sedimentary characteristics that differ from Type 1 and Type 2 assemblages.

Type 4: Assemblages without modern analogs that have sedimentary characteristics and faunal compositions more similar to Type 3 assemblages than Type 1 assemblages.

Type 5: Assemblages without modern analogs due to extensive mixing of originally distinct faunas or significant taphonomic alteration.

After assignment, Type 1 and Type 3 fossil assemblages are tested for significant differences in their faunal composition using an Analysis of Similarity (ANOSIM) on the rank-order Bray-Curtis dissimilarity matrix. If these sample groups are indeed faunally distinct, within group dissimilarity will be significantly less than among group dissimilarity (Legendre and Legendre, 1998). ANOSIM analyses are performed using the “anosim” function in vegan (Oksanen et al., 2015). Differences in sedimentary grain size (% grains <63 μ m), foraminiferal test size, and taphonomic score are compared using Mann-Whitney tests to test for lithological and taphonomic differences that could explain the compositional differences between Type 1 and Type 3 faunas.

No-analog fossil assemblages are assigned to Type 2 or Type 4 based on similarities in grain size and faunal composition to Type 1 and Type 3 assemblages, respectively. To test whether no-analog assemblages in each group are produced by taphonomic processes, and should thus be assigned to Type 5, the faunal composition of no-analog assemblages is tested for significant differences from their corresponding analog group (Type 1 or Type 3) using ANOSIM as above. Substantially mixed assemblages should exceed the range of assemblage variation within endmember assemblages (Tomasovych, 2006). Higher community evenness may also occur in mixed assemblages due to the

amalgamation of previously distinct random abundance distributions (Cummins et al., 1986). Winnowing creates size biases in foraminiferal assemblages (Murray, 1991), thus if no-analog faunas are created via winnowing then there should be significant differences in the size distribution of foraminifer tests between analog and no-analog assemblages. Dissolution also leads to greater fragmentation of shells (Murray, 2006; Berkeley et al., 2009), thus no-analog faunas should have significantly higher damage scores than analog faunas if dissolution was prominent. Mann-Whitney tests are used to compare sedimentary grain size, foraminiferal test size, and taphonomic scores between sample groups as above. In the absence of evidence for mixing or other taphonomic alterations, no-analog assemblages are assigned to Type 2 or Type 4. Mixed or otherwise taphonomically altered assemblages are assigned to Type 5.

4. Results

4.1 Modern Benthic Foraminiferal Spatial Variation

After taxonomic standardization, 149 taxa are included in the modern assemblage array, 112 of which are calcareous taxa. Modern samples span 0 to 3667 m water depth and encompass both open-ocean and inland basin environments with mean annual salinities of 30.4-34.69 and mean annual oxygen concentrations of 0.36-7.64 ml/l.

PCO analyses of the full modern benthic foraminiferal data set reveal faunal gradients that reflect oceanographic variation (Figure 3). Assemblages from each study are distributed throughout PCO space and do not appear segregated (Figure 3A). Assemblage position in PCO space is primarily related to salinity (Mantel $r=0.3888$, $p=0.001$; Figure 3B) and oxygenation (Mantel $r=0.3329$, $p=0.001$; Figure 3C), with weaker correlations to temperature (Mantel $r=0.2351$, $p=0.001$) and water depth (Mantel $r=0.1266$, $p=0.001$). The position of modern samples in PCO space is strongly correlated between analyses of the total assemblage and of the calcareous-only subset (Mantel $r=0.99$, $p=0.001$).

Hierarchical clustering analysis (cophenetic correlation =0.789) using only the calcareous component of the modern data set reveals four primary benthic foraminiferal assemblages separated by a dissimilarity >0.9 (Figure 4). The first division includes only the deepest sample (U1418, 3667 m water depth) and is the sole representative of a deep bathyal fauna (Figure 4). Unlike other assemblages in the modern array, the U1418 assemblage is dominated by *Chilostomellina fimbriata* with high abundances of *Bolivina pacifica*, *Bolivina pseudobeyrichi*, and *Pullenia salisburyi*.

Cluster 1 contains assemblages from the shallow continental shelf (median water depth = 66 m, IQR=58-81 m) characterized by *Islandiella californica*, *Cassidulina limbata*, *Cassidulina tortuosa*, *Lobatula labatula*, and *Cibicides fletcheri*. These taxa are typically associated with sediment-starved or gravel-rich areas of the shelf (Echols and Armentrout 1980; Lagoe et al., 1989).

Cluster 2 contains the U1419A mudline sample, which represents modern conditions at the core site, as well as other samples from the low-oxygen slope (median oxygen concentration= 0.627 ml/l, IQR=0.488-0.971; median water depth = 1159 m, IQR=712-1740 m). Cluster 2 assemblages frequently have high abundances of *Uvigerina peregrina*, *Trifarina angulosa*, *Cassidulina minuta*, *Epistominella pacifica*, *Eilohedra vitrea* and *Islandiella norcrossi*. *E. pacifica* is associated with suboxic conditions and taxa associated with strongly dysoxic conditions, such as *Buliminella tenuata* and *Bulimina striata*, also occur in Cluster 2 samples with abundances as high as 20% each in some samples (Murray, 2006; Ohkushi et al., 2013). *E. vitrea* and *I. norcrossi* both respond to seasonal primary productivity and influx of phytodetritus (Knudson et al., 2012, Murray, 2006). *C. minuta* may also indicate high phytodetritus if it is ecologically similar to the morphologically similar *Cassidulina reniforme* (Knudsen et al, 2012; Murray 2006). Both *C. reniforme* and *I. norcrossi* are also typical of glacial distal settings of normal marine salinity (Knudsen et al., 2012).

Within Cluster 3, three subclusters contain 10 or more samples; these are designated 3.1, 3.2, and 3.3 (Figure 4). *Nonionellina labradorica* is present in all Cluster 3.1 samples with a median

abundance of 47% (IQR = 21-61%); where *N. labradorica* is not dominant, *Globobulimina auriculata* comprises up to 84% of the assemblage. *N. labradorica* is associated with weakly hypoxic to oxic settings (Ohkushi et al., 2013) and with high seasonal productivity and fresh phytodetritus (Knudsen et al., 2012); both *N. labradorica* and *G. auriculata* are found in fine-grained sediments (Murray 2006). *E. pacifica*, *Elphidium excavatum*, and *I. norcrossi* also frequently occur in Cluster 3.1 samples, but at relative abundances less than 16% each. *E. excavatum* is common in high latitude fjords, in inner neritic sandy substrates, and in clay-rich sediments proximal to glacial melt (Bergen and O'Neil, 1979; Osterman and Andrews, 1983; Hald, 1994; Lagoe et al, 1994; Murray, 2006). These ecological characteristics are consistent with the inland waterways and Yakutat Sea Valley where many Cluster 3.1 assemblages were collected (Appendix C, Echols and Armentrout, 1989; Eyles et al., 1991; Walinsky et al., 2009).

E. excavatum comprises at least 10% of the assemblages in all Cluster 3.2 samples with a median proportional abundance of 35% (IQR=22-47%). Other taxa that occur in >58% of Cluster 3.2 assemblages, and occasionally dominate those assemblages, include *I. norcrossi*, *Buliminella elegantissima*, *Elphidiella hannai*, *Buccella frigida*, and *Nonionella stella*, which are typical of sandy inner neritic environments (Bergen and O'Neil, 1979). This faunal composition is consistent with the water depth of the Cluster 3.2 samples (median = 77 m, IQR=49-140).

Cluster 3.3 assemblages are from significantly deeper water depths than Cluster 3.2 assemblages, but are still above the shelf break (median water depth = 142 m, IQR = 119-171.5; MW=1015, $p < 0.001$). *I. norcrossi* occurs in all but one Cluster 3.3 assemblage and has a median abundance of 25% (IQR = 11-38%) in this faunal group. *Islandiella californica*, *Uvigerina junacea*, *Cassidulina limbata*, *Trifarina angulosa* and *Nonionella auricula* occur in >75% of these samples and each occasionally dominate the assemblage. *E. excavatum* occurs in only 74% of Cluster 3.3 assemblages and at lower proportional abundances (median = 2%, IQR = 0-8%) than in Cluster 3.2. Cluster 3.3 assemblages are from areas with significantly higher salinity (median salinity = 32.6, IQR = 32.3-32.9)

than Cluster 3.2 assemblages (median salinity = 31.9, IQR = 31.7-32.1; MW=496, $p < 0.001$); this is consistent with the higher abundances of *I. norcrossi*, which prefers normal salinity waters (Knudsen et al., 2012), in Cluster 3.3 assemblages than *E. excavatum* in Cluster 3.2 assemblages, which can tolerate lower salinities (Korsen and Hald, 1998; Polyak et al., 2003).

Cluster 4 assemblages are all from samples collected in less than 35 m water depth and are dominated by either *Trichohyalus ornatissimus* or *Criboelphidium oregonense*, which are common in beach sediments and the inner sublittoral zone (Bergen and O'Neil, 1979; Echols and Armentrout, 1980). *E. excavatum*, *E. hannai*, and *B. frigida* are also common in Cluster 4 assemblages.

4.2. U1419 downcore benthic foraminiferal record

All 40 taxa included in downcore U1419 analyses are also found in the modern Gulf of Alaska assemblages (Appendix B). *Eilohedra vitrea*, *Elphidium excavatum*, *Epistominella pacifica*, and *Cassidulina minuta* each occur in at least 35 of the 36 samples studied, sometimes as the dominant taxon. *Islandiella norcrossi*, *Elphidium bartletti*, *Fursenkoina complanata*, *Buliminella tenuata*, *Epistominella exigua*, and *Nonionellina labradorica* are each present in >75% of the down core samples. The number of foraminifera per gram of sediment varies greatly among samples with generally higher abundances in Unit 1 than in Unit 2 (Figure 2A).

Principal coordinates analysis (PCO, $k=4$) of the U1419 downcore record summarizes 40.3% of the variation in the proportional abundances of taxa among samples on the first axis. Abundant taxa with strong positive PCO axis 1 scores include *N. labradorica* and *I. norcrossi* (Appendix D). Less common taxa such as *Cibicides* sp. and *Islandiella californica* also contribute strongly to positive sample scores and are typical of the continental shelf, however taxa with modern slope distributions, such as *Trifarina angulosa*, *Triloculina trihedra*, and *Valvulineria glabra*, also have strong positive scores. Taxa with the most negative PCO axis 1 scores include *E. pacifica* and *Chilostomellina fimbriata*, both of which occur in oxygen-depleted environments and are most abundant in slope settings (Bergen and O'Neil,

1979; Ohkushi et al., 2013; Fontanier et al., 2014). Sample scores on PCO axis 1 decline from the youngest sample to ~22 m core depth below which values fluctuate (Figure 2C).

PCO axis 2 summarizes 27.1% of the variation with sample scores most affected by the strongly negative species scores of *Pullenia salisburyi*, *Gyroidina gemma*, *Valvulineria araucana*, *L. elongata*, *Bolivina decussata*, *Bolivina pacifica*, *Bolivina pseudobeyrichi*, *Bulimina striata* and *B. tenuata*. These taxa are most common in slope environments in the Gulf of Alaska (Bergen and O'Neil, 1979) and their occurrences in the modern dataset herein have a median water depth of 550 m (IQR = 180-1317 m). The most negative PCO 2 sample scores occur in the uppermost 4 m and at 80 m, 83 m, and 100 meters downcore (Figure 2D).

PCO axis 3 summarizes 19.7% of the variation with high positive species scores for *E. bartletti*, *E. excavatum*, *Buccella tenerrima*, *Buliminella elegantissima* and *I. californica*. All these taxa are most common in inner shelf environments in the Gulf of Alaska (Bergen and O'Neil, 1979) and their occurrences in the modern dataset herein have a median water depth of 107 m (IQR = 66-167 m). Samples with positive PCO axis 3 scores occur throughout the upper 100 meters of downcore record and suggest intervals with continental shelf faunal elements (Figure 2E).

PCO axis 4 explains only 12% of the faunal variation and positive sample scores are most reflective of high abundances of *B. tenuata*, *B. pacifica*, and *B. pseudobeyrichi*. Samples with the most positive PCO axis 4 scores occur at 80 and 83 m core depth near the transition between lithological Units 1 and 2 (Figure 2F).

4.3 Fidelity of U1419 fossil assemblages to modern assemblages

While the relative abundances of fossil taxa can be used to interpret faunal changes in the context of the downcore record, the similarity of downcore assemblages to modern assemblages places the fossil record in the context of faunal variation in the modern Gulf of Alaska. On average, the rank order correlation between a fossil assemblage and its nearest modern analog is positive (Figure 5A;

median Spearman $\rho=0.141$, IQR=0.056-0.269). The strength of the correlation varies downcore and appears to decline with increasing core depth, although this decline is not significant nor particularly strong (Spearman $\rho=-0.3149$, $p=0.070$). There is also no relationship between the maximum similarity to a modern assemblage and average taxonomic score (Figure 5; Spearman $\rho = 0.04$, $p=0.41$). Single taxon preservation scores (*E. pacifica*) parallel average preservation (Figure 5; Spearman $\rho = 0.707$, $p<0.001$). The similarity of fossil assemblages to the U1419A mudline is significantly lower and more variable than the similarity to their nearest modern analogs within the total Gulf of Alaska (Figure 5B; median Spearman $\rho = -0.076$, IQR = -0.215-0.0176; $U=998$, $p<0.001$).

4.4 Downcore Analog Faunas

In the calcareous-only data set, Spearman correlation coefficients are greater than $\rho=0.1285$ in 95% of the modern-modern nearest-neighbors, thus a fossil assemblage is considered to have a modern analog if the correlation between it and its most similar modern assemblage is greater than 0.1285. The nearest-neighbor similarities among modern assemblages are significantly lower when agglutinated taxa are included (mean $\rho=0.50$, $sd=0.22$) than when restricted to the calcareous component (mean $\rho = 0.54$, $sd=0.22$; $U=22602$, $p=0.049$).

Fossil assemblages with modern analogs, by definition, all have a positive rank-order correlations with their most similar modern assemblages (median $\rho=0.233$, IQR=0.167=0.307). Modern assemblages that serve as analogs occur throughout PCO space and are drawn from all included studies (Figure 3A).

Six U1419 fossil assemblages have analogs within Cluster 2 of the modern array, which contains the U1419A mudline assemblage, and are assigned to Type 1 (Figure 4; Figure 5F). All Type 1 analogs occur in the upper ~80 m of the core. The five youngest of these are most analogous to either the U1419A mudline sample or the multicore sample collected in 2008 with site survey core EW0408-85JC

(EW040884MC7). The oldest Type 1 assemblage is most analogous to a sample from 564 m water depth ~39 km from the U1419 core site (74B-047-5).

Fourteen fossil assemblages are most similar to modern assemblages within Cluster 3 and are assigned to Type 3 (Figure 5F). Two of the modern analogs are from Cluster 3.1, two are from Cluster 3.2, and two are from Cluster 3.3 (Figure 4). The modern water depth of these analogs ranges from 18 m to 401 m. None of the down core assemblages are analogous with modern assemblages assigned to Cluster 1 or 4 or to the U1418 mudline (Figure 4).

The compositional differences between Type 1 and Type 3 faunas are significant (ANOSIM $R=0.333$, $p=0.01$) and mirror the compositional differences between modern assemblages in Clusters 2 and 3. Type 1 assemblages correspond to diatom-rich intervals and have a significantly greater percentage of mud than Type 3 assemblages ($U=92$, $p=0.004$), which correspond to intervals of diamict and alternating sand and silt beds (Figure 5).

Species typical of Cluster 3 samples are present in Type 1 assemblages in low abundances, however, they are represented by smaller individuals. *E. excavatum* has proportionally more individuals in the 63-125 μm size fraction of the Type 1 assemblages (86% of individuals) than of the Type 3 assemblages (44% of individuals; Chi square =42.25, $p<0.001$, $n=490$ total individuals across the four size fractions). Over the total assemblage, however, Type 1 and Type 3 assemblages do not differ in the percentage of foraminifera in the 63-125 μm size fraction ($U=49$, $p=0.6015$). Type 1 and Type 3 assemblages are also similar in community evenness ($U=29$, $p=0.3119$) and mean taphonomic score ($U=50$, $p=0.5466$).

4.4. Down Core No-Analog Faunas

Fossil assemblages with no modern analog have weakly positive to weakly negative rank order correlations with their closest modern assemblages (median $\rho=0.052$, $\text{IQR}=0.033\text{-}0.100$). All assemblages deeper than 100 m core depth have no modern analog, but no-analog fossil assemblages

are found throughout the core (Figure 5F). Among the no-analog faunas, there is a bimodal distribution in the proportion of grains < 63 μm , allowing these samples to be partitioned into two broad groups with respective ranges of 99-94.5% and 88.2-82.4% mud.

The finer-grained no-analogs (5 samples) are not significantly different in their grain size from Type 1 assemblages ($U=18$, $p=1$), but are significantly different from Type 3 ($U=1$, $p=0.000258$). There is also no support for significant compositional differences between Type 1 assemblages and the fine-grained no-analogs (ANOSIM $R=0.2113$, $p=0.09$). In addition, neither the percentage of foraminifera in the 63-125 μm size fraction ($U=26$, $p=0.052$) nor the average taphonomic scores of the assemblages ($U=15$, $p=1$) are significantly different between these groups. The fine-grained no-analog assemblages do, however, have significantly lower assemblage evenness than Type 1 faunas ($U=1$, $p=0.008658$). Dominant taxa in the lowest evenness no-analog assemblages include *E. pacifica* (3 samples), *B. tenuata* (1 sample) and *C. minuta* (1 sample).

The coarser-grained no-analog faunas (9 samples) do not differ from Type 3 assemblages in terms of the proportion of grains < 63 μm ($U=43$, $p=0.22$). There is also no support for compositional differences between this subset of no-analogs and Type 3 faunas (ANOSIM $R=-0.0373$, $p=0.65$). Further, there are no significant differences in foraminiferal test size ($U=66$, $p=0.88$) or in average taphonomic score ($U=53$, $p=0.56$) between coarse-grained no-analog assemblages and Type 3 faunas. Unlike Type 1 faunas and the fine-grained no-analog assemblages, the faunas from the coarse-grained no-analog assemblages do not have significantly different community evenness ($U=52$, $p=0.52$). There are, however, clear taxonomic differences between Type 3 faunas and the coarse-grained no-analog assemblages. For example, *N. labradorica* has significantly lower rank abundance in the coarse-grained no-analog assemblages than in the Type 3 faunas ($U=110.5$, $p=0.001187$).

5. Discussion

5.1 Modern benthic foraminiferal variation in the Gulf of Alaska

Assigning fossil assemblages to modern analogs requires a large array of modern assemblages from all possible environmental conditions (Overpeck et al., 1985; Jackson and Williams, 2004). Combining published benthic foraminiferal faunal counts from prior sampling in the Gulf of Alaska with new surface sediment assemblages gives the modern array herein a broader environmental representation than previous multivariate faunal studies in the region (Lagoe et al., 1989). Benthic foraminiferal assemblages from modern shelf and slope environments have high dissimilarity in the relative abundances of taxa (Figure 4); this strong separation is likely maintained by low downslope transport of foraminifera (Lagoe et al., 1994). Modern slope faunas are also distinct in their high abundances of low-oxygen taxa, such as *B. tenuata*, *B. striata*, and *E. pacifica*, which is consistent with the position of the modern oxygen minimum zone. Assemblages above the shelf break are clustered into environmentally coherent groups representing beach faunas, inner shelf faunas from gravel-rich sediments, low-salinity shelf faunas, normal-salinity shelf faunas, and fine-grained high-productivity settings. Thus, the modern array has a broad environmental range with distinct faunas, which can be used to place fossil assemblages in the context of modern environmental variation.

Differences in sample preparation, sieve size, and taxonomic identification among included studies could affect analyses of faunal similarity, however assemblages from each data set are distributed throughout faunal ordination space and among faunal clusters indicating that methodological differences do not drive assemblage patterns. In addition, modern assemblages that serve as analogs for U1419 fossil assemblages are drawn from all included studies. Thus, despite potential difficulties with integrating historical and original data, the modern array compiled here is well-suited for comparisons of modern and fossil faunas.

The position of modern assemblages in ordination space, and thus the environmental gradients it portrays, is also unaffected by the removal of agglutinated foraminifera. This indicates that agglutinated foraminifera do not provide unique information and their loss in the fossil assemblages will

not affect environmental interpretations. In addition, faunal similarity among modern assemblages is greater when restricted to the calcareous taxa, suggesting less stochastic variability in the calcareous fauna than in the agglutinated fauna. Thus, the loss of agglutinated foraminifera in the fossil record is unlikely to affect our ability to assign modern analogs and environmental interpretations to fossil assemblages.

5.1 Downcore benthic foraminiferal faunal variation at U1419

Variation in PCO scores with core depth at U1419 highlights frequent changes in faunal composition, which can be interpreted as changes in seasonal productivity, oxygenation, and depositional setting. Sample position on PCO axis 1 is heavily influenced by *N. labradorica* and *I. norcrossi*, both of which are broadly distributed across the shelf and slope in the modern and are associated with seasonal export of phytodetritus (Knudsen et al., 2012). This suggests that variation in seasonal productivity and phytodetritus availability are largely defining this faunal gradient. Thus, the increase in PCO axis 1 scores from ~22 m core depth to the core top suggests increasing seasonality of phytodetritus export toward the present, however variation deeper in the core is less systematic. Species typical of shelf and slope environments both have positive PCO axis 1 scores, indicating this axis does not reflect shelf to slope faunal gradients.

Changes in sample position on PCO axis 2 and 3 do, however, reflect differences in the relative abundances of shelf and slope taxa. Negative sample scores on PCO axis 2 indicate assemblages with high abundances of taxa that are most common below the shelf break in the modern Gulf of Alaska, suggesting preservation of slope faunas in the upper 4 m and between 80 and 100 m core depth. Some of these taxa, including *B. pacifica*, *B. pseudobeyrichi*, and *B. tenuata* are additionally associated with low-oxygen conditions (Ohkushi et al., 2013). In contrast, very positive PCO axis 3 sample scores are driven by high abundances of inner shelf taxa, which occur intermittently between ~8 and 90 m core depth. The intercalation of assemblages with characteristically inner shelf taxa among assemblages with

characteristically slope faunas suggests either frequent changes in depositional environment at U1419 or transport of sediments to the site.

Positive sample scores on PCO axis 4 have strong contributions from low-oxygen taxa, including *B. tenuata*, *B. pacifica*, and *B. pseudobeyrichi*, similar to the low-oxygen component on PCO axis 2, but without strong contributions from other slope taxa. Thus, PCO axis 4 more directly reflects variation in oxygenation with high sample scores reflecting the lowest oxygen assemblages. Assemblages with the most positive PCO axis 4 scores are a subset of samples with negative PCO axis 2 scores, suggesting these low-oxygen assemblages are only associated with slope faunas at U1419.

5.2 Fidelity of the U1419 fossil record to the modern Gulf of Alaska

To further understand the genesis of U1419 fossil assemblages, we examine the faunal similarity to modern Gulf of Alaska assemblages. The agreement in rank-order abundances between U1419 fossil assemblages and modern assemblages from across the Gulf of Alaska is similar to live-dead assemblage comparisons for benthic molluscs on the continental shelf (Kidwell, 2008), indicating that the fidelity of the analog fossil assemblages herein is on par with the fidelity of recently dead assemblages and their living counterparts. Live-dead analyses of benthic foraminifera tend to find lower agreement than seen here due to seasonal variations in the living assemblage, which are likely damped by time averaging in the live+dead modern assemblages used in this study (Murray, 1991; Jorissen and Wittling, 1999; Murray, 2006; Goineau et al., 2015). For the U1419 fossil assemblages, there is no relationship between fidelity and preservation quality, whether measured via the whole assemblage or on a single taxon, such that instances of low fidelity are not driven by poor preservation.

Despite generally good fidelity of the U1419 fossil record to modern assemblages within the Gulf of Alaska, it is not necessarily faithful to the assemblages of the modern Khitrov Bank. The average rank order agreement between fossil assemblages and the U1419A mudline sample, which represents the modern assemblage at the U1419 core site, is significantly lower. Seventy-one percent of the fossil

assemblages have a negative rank-order correlation with U1419A, which indicates inverse dominance patterns – taxa that are most abundant in the fossil assemblage are least abundant in the U1419A mudline. The highest fidelity to the U1419A mudline occurs in the youngest fossil samples, suggesting the modern faunal composition is recently established. However, positive correlations with U1419A also occur deeper in the record suggesting that environmental conditions similar to those at the modern Khitrov Bank did occur in the past. Taken together, the high fidelity of U1419 fossil assemblages to faunas elsewhere in the Gulf of Alaska and the intermittent fidelity to the modern U1419 assemblages, suggests that either many of the U1419 fossil assemblages were transported to the site or environmental conditions at U1419 were often more similar to other modern Gulf of Alaska settings in the past.

5.3 Analog and no-analog fossil assemblages

The modern environments associated with benthic foraminiferal assemblages that are analogous to the fossil assemblages can be used to interpret the environment of deposition for U1419 sediments. Analog assemblages are quantitatively defined herein within the context of the similarity among modern foraminiferal assemblages so that the analog threshold reflects the distance metric and the modern assemblage array (Jackson and Williams, 2004). Only 20 of the 34 included U1419 fossil assemblages pass this analog threshold. These samples have nearest modern analogs from slope settings similar to the present day U1419 (modern assemblage Cluster 2) and from three distinct shelf settings (represented by Clusters 3.1, 3.2, and 3.3); these are categorized as Type 1 and Type 3 assemblages, respectively. The presence of both slope and shelf modern analogs is consistent with the ordination analysis described above, which indicates that differences in the relative proportion of slope and shelf taxa were major contributors to two faunal gradients. However, unlike the ordination analyses, direct comparison of the similarity of fossil and modern assemblages demonstrates that not

only do some samples have more continental shelf taxa than others, but that those samples have faunal compositions more similar to modern shelf assemblages than to assemblages from the modern slope.

Type 1 assemblages are also significantly finer-grained than Type 3 assemblages, which is consistent with a continental shelf origin for the Type 3 faunas. The relative abundance of foraminifera in the 63-125 μm size class are similar in Type 1 and Type 3 assemblages, suggesting that the coarser grain size in Type 3 is not indicative of hydrologic sorting of the assemblages, which would result in species and size sorting. Assemblages in both groups also have similar preservation quality, further suggesting taphonomic alteration is not responsible for the faunal differences. Thus, Type 1 and Type 3 samples are distinct both in faunal composition and sedimentology, but this is not the result of post-depositional processes.

Fourteen fossil assemblages have no modern analog, but similarities in sedimentary grain size suggest five of these are from a depositional environment similar to Type 1 assemblages and nine are most similar to Type 3 settings. Comparisons of Type 1 assemblages to fine-grained fossil assemblages with no modern analog demonstrate that these no-analog assemblages are not significantly outside the range of faunal variation of the Type 1 assemblages. In addition, they are taphonomically similar, thus they are assigned to assemblage Type 2 (continental slope assemblages with no modern analog). Similarly, coarse-grained fossil assemblages with no modern analog are similar in faunal composition and in preservation quality to Type 3 assemblages and are assigned to Type 4 (continental shelf assemblages with no modern analog).

5.4 Downslope transport dynamics using analog comparisons

Consistent with the modern Gulf of Alaska slope, which experiences very little downslope transport of foraminifera (Lagoe, 1994), Type 1 faunas received little influx of allochthonous specimens. *E. excavatum*, which in the modern Gulf of Alaska is characteristic of shelf settings grouped in Cluster 3, is significantly smaller when found in Type 1 assemblages than they are in Type 3 assemblages,

suggesting that transport of *E. excavatum* to the Khitrov Bank occurs largely via suspension within Type 1 assemblages. Transport of foraminifera < 200 µm in suspension have been observed elsewhere (Wang and Murray, 1983; Murray, 1987). Similarly, Type 2 assemblages do not contain high enough abundances of shelf-associated taxa that they are outside the range of faunal variation of the Type 1 faunas, thus these also do not have significant faunal contributions from the shelf.

In contrast, Type 3 and Type 4 assemblages suggest intervals of significant redistribution of shelf sediments to the slope. Sea level change is an unlikely explanation for the observed biofacies and lithofacies changes because Type 3 and Type 4 faunas occur intermittently throughout the record, thus, if we account for the environments of their closest modern analogs, they would suggest multiple water depth changes greater than 300 m within the last 60,000 years. This depth change exceeds the estimated 120 m lower sea level at the Last Glacial Maximum (Siddal et al., 2009). Instead, these faunas were likely redeposited at this site from upslope. Faunal mixing, test breakage and size sorting of foraminifera is expected during downslope transport via submarine channels or debris flows (Schroder-Adams et al., 2008), however these shelf faunas are not more poorly preserved than the slope faunas nor is there evidence of appreciable fauna mixing. This suggests that the faunas at U1419 were instead transported *en masse*.

Previous studies have observed large differences in sedimentation rates associated with changes in downcore lithology on the Khitrov Bank (Davies et al., 2011; Gulick et al., 2015). These changes in sedimentation rates were interpreted in relation to the advance and retreat of tidewater glaciers with ice damming of fjord sills as responsible for the decrease in sediment supply and the dominance of hemipelagic muds toward the present (Davies et al., 2011). Jaeger et al. (2014) hypothesized that high accumulation rates of coarse-grained glaciomarine sediments off the shelf were associated with times of ice rafting. An ice-rafting origin for coarse sediment on the continental slope can be supported by the lack of shelf foraminifera in coarse deposits (Andrews et al., 1998). However, the coarser samples at

U1419 are analogous to modern shelf faunas, thus it does not appear that ice rafted lithics were deposited among an *in situ* slope fauna. Alternatively, the foraminifera themselves could be ice rafted along with associated sediments, however greater mixing of allochthonous and autochthonous faunas would be expected than seen here. Thus, the faunal analyses herein do not support a purely ice-rafted origin for the high sedimentation rates at U1419.

Past glacial processes in the Gulf of Alaska could have also driven downslope transport. Shelf benthic foraminifera deposited in slope environments have been used as a proxy for ice advance across the Baffin Island shelf (Jennings et al., 1996) and transport of sediments can occur at the base of a grounded glacier (Dobson et al., 1998). Ice sheet advance may be similarly responsible for the transport of shelf sediments to U1419. However, alternations of benthic foraminiferal paleobathymetric indicators in older intervals of the Yakataga Formation have been interpreted as resedimentation of diamictites from shallower water (Eyles and Lagoe, 1998). These outer shelf to upper slope sediments and faunas may have been destabilized by depositional oversteepening of the slope, earthquake-shock induced liquefaction, or tectonic tilting (Eyles and Lagoe, 1998). Thus, the transport of continental shelf benthic foraminiferal assemblages to site U1419 may not necessarily indicate glacially driven processes even if the sediments are glacially derived.

5.4. No-analog fossil assemblages suggest no-analog environments in the Gulf of Alaska

While fossil assemblages with no modern analog were assigned to broad environmental settings on the basis of similarities in sedimentology and faunal composition, they are outside the range of modern faunal variation. No-analog fossil assemblages are often interpreted as the result of no-analog environmental conditions (Jackson and Williams, 2004; Williams and Jackson, 2007). Due to the multidimensional nature of environments and of the physiological requirements of taxa, different combinations of environmental states can create unique faunal compositions (Williams and Jackson, 2007). Thus, these no-analog assemblages can be important indicators of no-analog paleoenvironmental

conditions. All the species in U1419 fossil assemblages herein are found in the modern Gulf of Alaska, thus we can use the modern environmental preferences of these taxa to form hypothesis regarding the drivers of differences in the relative abundances of species between fossil assemblages with and without analogs.

Type 1 and Type 2 assemblages from U1419, which represent a slope environment similar to the modern Khitrov Bank, can be segregated from the total data set for analysis of environmental changes on the continental slope near the upper limit of the modern OMZ. High dominance in faunal assemblages, as seen in Type 2 assemblages, can indicate environmental extremes and is observed in foraminiferal assemblages from low-oxygen environments (Gooday et al., 2000; Levin, 2003). In addition, the taxa that dominate Type 2 assemblages, including *E. pacifica* and *B. tenuata*, are associated with low-oxygen environments. Thus, Type 2 faunas may represent lower oxygen conditions at the site than experienced on the modern Gulf of Alaska slope. The Santa Barbara Basin also records fossil benthic foraminiferal communities with no modern analog that are dominated by dysoxic taxa such as *Bolivina*, *Buliminella*, and *Globobulimina* (Cannariato et al., 1999). These dysoxic faunas are associated with Dansgaard-Oeschger cycles during the last 60,000 years (Cannariato et al., 1999) and the Type 2 assemblages identified here may represent similar events in the Gulf of Alaska. However, at least one Type 2 assemblage is dominated by *C. minuta*, which is most abundant on the modern low-oxygen slope, but may be more indicative of changes in phytodetritus availability. Furthermore, some taxa, such as *E. pacifica* while considered low-oxygen indicators in one region (eg. Ohkushi et al., 2013) are considered indicative of well-oxygenated conditions in others (eg. Cannariato et al., 1999). Thus, independent paleoenvironmental proxies, such as redox sensitive trace elements in sediments, are necessary to test whether each these assemblages actually represent low-oxygen conditions. In addition, the recognition of faunal transport at U1419 cautions that these paleoenvironmental events may only be recognizable when sediment redistribution from the shelf is low.

Type 3 and 4 assemblages can similarly be segregated to analyze environmental changes up slope from site U1419. For example, *N. labradorica* is associated with fine-grained substrates of low relief regardless of water depth (Bergen and O’Neil, 1979) and with high organic carbon fluxes (Jennings et al., 2004; Knudsen et al., 2012). Thus, the low abundance of *N. labradorica* in the no-analog fossil assemblages may indicate times of greater coarse sediment input or of lower productivity than experienced by the modern shelf. Thus, fully interpreting Type 4 assemblages will also require geochemical proxy data to differentiate among these environmental hypotheses and place the faunal assemblages within a paleoenvironmental context.

6. Conclusions

Benthic foraminiferal assemblages from the continental slope core at site U1419 have high compositional fidelities to modern assemblages in the Gulf of Alaska comparable to live-dead analyses, but are not necessarily faithful to the facies present at the site in the modern. Alternating autochthonous and allochthonous benthic foraminiferal assemblages are recognized downcore, indicating episodes of sedimentary transport from shelf facies. The high fidelity of these transported assemblages to modern shelf and upper slope assemblages and the taphonomic similarity of transported and autochthonous faunas suggest the assemblages were transported with negligible mixing and taphonomic damage.

Assemblages with no modern analogs can be interpreted as autochthonous or allochthonous by their similarity in sedimentary context and faunal composition to assemblages with clear analogs. No-analog faunas in this record represent primarily ecological rather than taphonomic processes, as evinced by their similarity in preservation quality and body size distribution to analog faunas. These assemblages contain potential information about the temporal variation in oxygenation and productivity in the Gulf of Alaska and highlight intervals which environmental variation are likely not encompassed by modern spatial variation. While this analytical approach is presented in terms of a core from continental slope

sediments, it is applicable to other types of fossiliferous sedimentary records and can improve paleoecological and paleoenvironmental interpretations by distinguishing among faunal assemblages with different depositional histories and allying no-analog assemblages with analog counterparts.

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Figure1, 2 column width

Figure2, 2 column width

Figure 3, 1 column

Figure 4, two column width
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Figure 5, two column width

Figure 1. Map with locations of all included modern benthic foraminiferal assemblages. Symbols indicate the study or sample set for each sample. U1419 is the location of the downcore record used herein. Base map is from the General Bathymetric Chart of the Oceans 2008 (www.gebco.net). Bathymetric contours in meters.

Figure 2. Stratigraphic column for Site U1419 with downcore sedimentary data and principal coordinate (PCO) analysis sample scores. Lithostratigraphic column is modified from Jaeger et al., 2014. Black = diatom-rich mud without lonestones; white = mud with lonestones; gray = diamict; broken lines = interbeds of sand and silt. Points adjacent to the lithostratigraphy indicate sample locations. Open circles indicate samples not included in foraminiferal faunal analyses due to low abundances. A. Foraminifera per gram of dry sediment. B. Percent dry weight of the mud fraction from sediment samples. C-F. PCO axis scores from ordination analysis of fossil benthic foraminiferal assemblages.

Figure 3. Principal coordinates analysis (k=3) of modern benthic foraminiferal assemblages. Axes labels indicate the proportion of variation summarized by each axis. A. Symbol shape indicates the study or sample set for each sample. Filled symbols are modern assemblages that are the nearest analog to a fossil assemblage from U1419. B. Shading indicates the modern oxygen content at the location of the sample. C. Shading indications to modern salinity at the location of the sample. Data for B and C are interpolated for World Ocean Atlas 13 using Ocean Data Viewer. X= samples flagged as poor estimates due to low data coverage.

Figure 4. Cluster analyses of modern benthic foraminiferal assemblages with cluster groups referred to in the text defined. Closed circles mark modern assemblies that serve as modern analogs for U1419 fossil assemblages. Samples referred to by name in the text are labeled.

Figure 5. Fidelity, measured as the Spearman rank order correlation, between U1419 fossil assemblages and (A) the closest modern analog and (B) the U1419A mudline sample. Dashed line in A and B indicate the no-analog threshold; samples with values lower than this line do not have a modern analog. Dotted line in B denotes a Spearman rho of zero. Mean taphonomic scores for (C) the whole assemblage (>125 μm) and for (D) *E. pacifica* follow Belanger (2011). E. Assemblage evenness measured as the probability of intraspecific encounter (PIE). F. Faunal type, as described in the text, assigned to each fossil sample. The three columns associated with Type 3 represent fossil assemblages with analogs in modern clusters 3.1, 3.2, and 3.3, ordered from left to right. Lithostratigraphic column as in Figure 2.