TAMARA PICO

REVISITING MEGAFLOODS: INSIGHTS FROM GLACIAL ISOSTATIC ADJUSTMENT ON FLOOD SIZE, FLOW ROUTES, AND CLIMATE RESPONSE

Proposal basis

During the last ice age, 22,000 to 14,000 years ago, dozens of catastrophic megafloods from an ice-dammed Glacial Lake Missoula scoured the landscapes of Idaho and eastern Washington, forming what are known as the Channeled Scablands (Waitt 1985). These glacial lake outbursts are the largest known floods on Earth, and reconstructing the magnitude of these events informs our understanding of how floods shape Earth's landscapes and relate to abrupt changes in climate (Matero et al. 2017; Keigwin et al. 2018). Over the period of flooding, ice unloading during deglaciation caused crustal deformation with rates of ~10 mm/yr, orders of magnitude above regional uplift rates (Payne et al. 2012), resulting in a substantially altered regional topography relative to today. Glacial isostatic adjustment is a major process that has been neglected in prior estimates of flood volumes or discharge, introducing a potentially large error, which has not yet been quantified.

In this proposal, I seek to investigate the influence of glacial isostatic adjustment on late Pleistocene catastrophic flooding. The **intellectual merit** of the proposed research includes (1) understanding the timing and routing of megafloods, (2) improving estimates of total discharge during flood events, and (3) quantifying the response of the ocean and broader climate system to megafloods. The **broader impact** of this research includes (1) informing government planning by studying the nature of past catastrophic flooding and the stability of ice sheets in response to climate change, and (2) strong leadership, mentoring, and academic scholarship directed at improving the recruitment and retention of underrepresented minorities in geoscience.

Motivation

The Glacial Lake Missoula outbursts are the largest known floods on Earth (O'Connor & Baker 1992), and reconstructing the magnitude of these events informs our understanding of how floods shape Earth's landscapes (Baker 2009) and precipitate abrupt climate changes (Murton et al. 2010; Keigwin et al. 2018). From 22,000 to 14,000 years ago, dozens of catastrophic megafloods from an ice-dammed Glacial Lake Missoula scoured the landscapes of Idaho and eastern Washington, forming what are known as the Channeled Scablands (Bretz 1928; Baker 2009; Balbas et al. 2017; Clague & James 2002; Hanson et al. 2012). While the landscape, which incorporates deeply-carved canyons, wide boulder beds, and giant current ripples, contains clues for reconstructing these events (Larsen & Lamb 2016; Baker 2009), outstanding questions remain regarding the volume and discharge of meltwater associated with each flood event, and the routing of floodwater over time (Balbas et al. 2017; Hanson et al. 2012; Benito & O'Connor 2003). For example, depositional features can be used to calculate the energy required to carry a given size of debris (Benito & O'Connor 2003; Baker 2009) and high water marks allow estimation of the power and speed of water flow (O'Connor & Baker 1992). Yet these estimates can only be linked to total flood discharge through assumptions about the shape of carved canyons and the mechanism involved in bedrock incision or sediment transport (Larsen & Lamb 2016).

A particularly important assumption made in prior calculations of flood discharge is that topography, or slopes within the channel, have remained unchanged over time (Alho et al. 2010; Larsen & Lamb 2016). Local topographic slopes are a prerequisite for predicting flood routes and total floodwater (O'Connor & Baker 1992; Lamb et al. 2013; Larsen & Lamb 2016). Hydraulic models use slope to determine water speeds, erosion rates, and likely flow paths (Denlinger & Connell 2010; O'Connor & Baker 1992). However, to-date the topography of this region has not been reconstructed during the period of Missoula flooding.

Crustal deformation resulting from the solid Earth's response to variations in ice loading, known as glacial isostatic adjustment (GIA), caused ~100 meters of uplift or subsidence relative to today in the Channeled Scablands, and therefore slopes during the time of Missoula floods were significantly altered relative to today (Figure 1). In the Channeled Scablands, preliminary calculations show GIA-corrected slopes at 22 ka were ~30% smaller relative to today. Previous studies of the event assume that slopes are unchanged over time, and model flood dynamics using modern elevation (Denlinger & Connell 2010; O'Connor & Baker 1992; Larsen & Lamb 2016). Thus prior estimates of flood volumes include a potentially large error, which has not yet been quantified.

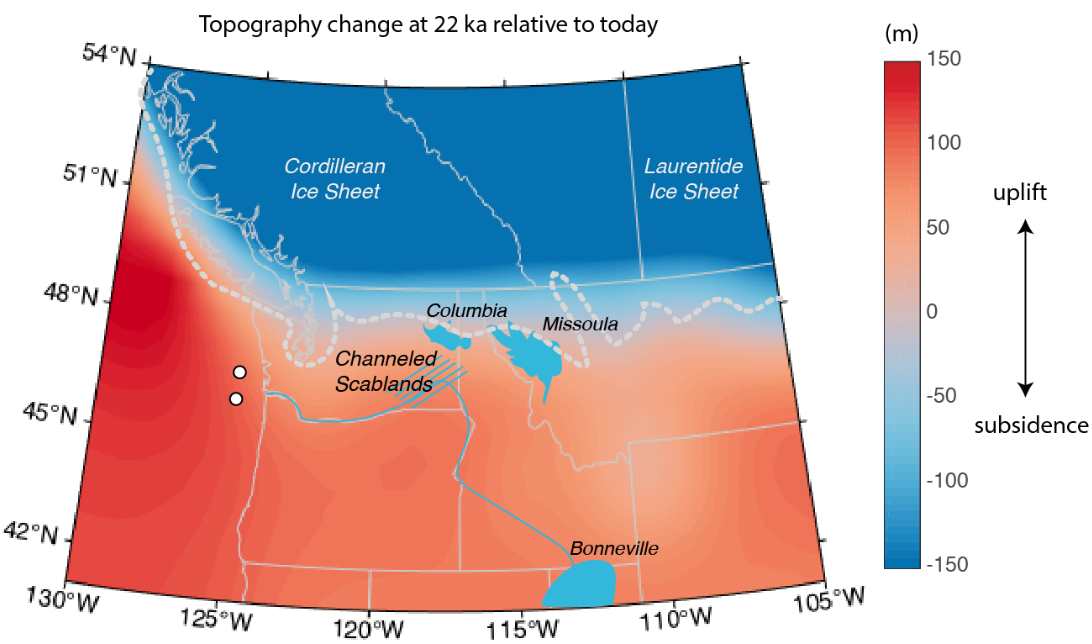

Figure 1 | Modeled topographic change due to GIA at 22 ka (start of flooding) relative to modern. Red regions are areas of predicted uplift and blue regions subsidence relative to today. Schematic locations of Glacial Lake Missoula, Glacial Lake Columbia, and Lake Bonneville are shown in blue. Channeled Scablands are labeled. Blue lines show schematic flood routes. Dashed white line indicates ice extent at Last Glacial Maximum (26 ka). White circles show location of collected sediment cores to analyze.

Furthermore, over the interval of Missoula flooding (22-14 ka), patterns of uplift and subsidence due to GIA evolved significantly, and these changes in topographic highs and lows may have been responsible for drainage patterns shifts that cannot be linked to ice damming (Figure 2). The long-wavelength (greater than ~100 km scale) reshaping of topography due to GIA may be key to understanding a number of other Pleistocene megafloods sourced from western North America, including Lake Bonneville and Glacial Lake Columbia.

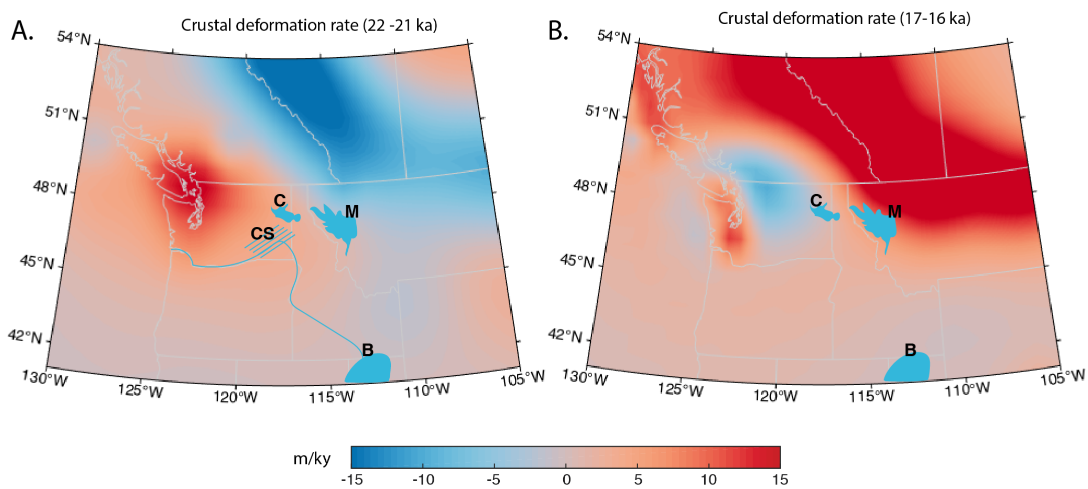

Figure 2 | Rates of crustal deformation due to GIA from 22 to 21 ka (A) and 17 to 16 ka (B). Across the interval of flooding (22-14 ka) rates of crustal deformation due to GIA vary in magnitude and sign. Glacial Lake Columbia (C), Glacial Lake Missoula (M), and Lake Bonneville (B) are labeled. Location of Channeled Scablands are noted as CS.

Today we are interested in how ice sheets respond to a warming climate, and ice melting in the past informs our understanding of the nature and resilience of the Earth's climate system (Dutton et al. 2015). The deglaciation of continental ice sheets, and the consequent influx of freshwater to the Pacific, impacts both ocean and atmospheric circulation, modulating global climate (Praetorius et al. 2014; Ivanovic et al. 2017). Without knowing how much meltwater entered the ocean during the Missoula floods, we cannot compare these events to available geological records, which is an imperative for understanding how past ice sheet melting was related to climate change (Lopes & Mix 2009).

The state of knowledge leaves these fundamental **research questions** unanswered:

1. Did glacial isostatic adjustment control routing of Missoula floodwaters?
2. How are estimates of total floodwater affected by channel slope changes due to glacial isostatic adjustment?
3. With refined estimates of freshwater flux, what is the response of the ocean, and broader climate system, to flood events in terms of geochemistry, biological productivity, and circulation?

I propose three interconnected goals for this project: **(1)** reconstruct *drainage path evolution* across the interval of flood events in response to glacial isostatic adjustment; **(2)** accurately *estimate flood discharge* using slopes corrected for glacial isostatic adjustment; and **(3)** connect the *response of ocean, and broader climate system*, to newly-refined estimates of total freshwater flux.

My overarching **hypothesis** is that *glacial isostatic adjustment significantly affected the Channeled Scablands* landscape as it developed, including flood routing and discharge reconstructions. Through my Ph.D I gained expertise in modeling both glacial isostatic adjustment and landscape evolution. My interdisciplinary approach, the first to quantitatively measure the influence of ice-age surface deformation on river dynamics, is well suited to apply to these ancient flood events.

Objective 1: Reconstructing paleo- topography and flood routing during megaflood events

The growth and decay of continental ice sheets deform the solid Earth on glacial timescales, producing subsidence under ice-loaded regions and inducing uplift in the periphery of the ice sheet. This process of glacial isostatic adjustment (GIA) produces 1-10 mm/yr of vertical motion hundreds of kilometers away from Late Pleistocene North American ice cover (Mitrovica & Milne 2002), on the peripheral bulge of the ice sheet; these uplift rates exceed tectonic rock uplift rates in these regions (Payne et al. 2012). The Channeled Scablands sit on the edge of past ice cover, where the magnitude and gradient of GIA-induced uplift is greatest (Youse et al. 2018; Creveling et al. 2017). Previous studies show that this process of glacial isostatic adjustment (GIA) produces sufficient crustal deformation to control rates of river incision (Wickert et al., in review), river drainage patterns (Wickert 2016), river diversions (Pico et al. 2018), and delta accumulation rates (Whitehouse et al. 2007). Despite the location of the Channeled Scablands in a zone of maximum ice-age crustal deformation, reconstructions of the Missoula floods have not considered the impact of GIA on local slope and regional topography.

Glacial isostatic adjustment modeling and ice history

Over the ice age, the wax and wane of continental ice sheets drive a complex pattern of sea-level (or equivalently topographic) change. In the proposed simulations, I will model paleotopography during the interval of Missoula flooding by performing GIA calculations based on the theory and pseudo-spectral algorithm described by Kendall et al. (2005) These calculations include the impact of load-induced Earth rotation changes on sea level (Milne & Mitrovica 1996) as well as evolving shorelines and the migration of grounded, marine-based ice (Johnston 1993; Milne et al. 1999; Lambeck et al. 2003; Kendall et al. 2005). By correcting modern topography for crustal deformation over the ice age, I can predict paleoelevation, and thus paleoslopes along the channels. GIA predictions require models for Earth's viscoelastic structure and the history of global ice cover. I will use an Earth model characterized by an upper and lower mantle viscosity of 0.1×10^{21} and 5×10^{21} Pa s, respectively, and a lithospheric thickness of 95 km, in agreement with a recent GIA-analysis of sea-level markers in the western United States (Creveling et al. 2017).

Accurately modeling North American deglaciation is key to reconstructing paleotopography in the Channeled Scablands as this region sits on the edge of ice loading, where GIA-induced crustal deformation gradients are large. Because this region is particularly sensitive to the history of ice loading, it is critical to reconstruct an accurate model of Cordilleran deglaciation. While there remains considerable debate about the timing of ice decay in the Cordilleran and Western Laurentide region (Gregoire et al. 2012; Gowan 2013; Munyikwa et al. 2011; Menounos et al. 2017), I have worked towards resolving these arguments by constructing a new ice history designed to fit a large database (n=818) of radiocarbon, luminescence, and cosmogenic ages constraining the deglaciation history of the Cordilleran and western Laurentide Ice Sheets (Gowan 2013; Munyikwa et al. 2011; Munyikwa et al. 2017; Menounos et al. 2017), as well as constraints imposed by observations of the Bering Strait flooding (Pico et al., in revision). I will use this ice loading history, and refine details by accurately reconstructing ice lobes in the Channeled Scabland region.

The geometry of ice lobes is an important consideration for calculating GIA in regions proximal to ice sheets. In the case of the U.S east coast, for example, the resolution of ice lobes is critical for reconstructing GIA-drive topography changes. In particular the Erie lobe causes an east to west gradient and I have demonstrated, by driving a landscape evolution model with GIA-driven uplift, that it is possible to explain the geologically-inferred eastward diversion of Hudson river at 30 ka (Pico et al. 2018, Pico et al, submitted). GIA predictions are sensitive to two input parameters, ice history and Earth model, thus I will run simulations that vary the ice loading history and Earth viscosity structure, comparing to geologic constraints imposed by glacially-transported sediment and regional shorelines. I will include a realistic ice thickness for the Okanagan lobe (~500-800 m) in my constructed ice history following regional constraints (Kovanen & Slaymaker 2004; Porter & Swanson 1998), which is crucial for predicting accurate uplift gradients. Testing the accuracy of the ice and Earth model will be possible by comparing to local GIA constraints, including rebounded glacial lake shorelines in Puget Sound (Porter & Swanson 1998; Clague & James 2002) and tilted uplifted lake sediments near Steamboat Rock, Washington (Atwater 1987).

Reconstructing drainage path evolution over flooding interval

Preliminary calculations using the ice loading history developed in Pico et al. (in revision), estimate that slopes at 22 ka in the Columbia Plateau region of the Channeled Scablands were 30% lower than today (calculated at 47.1°N, 118.5°W; as shown in Figure 1). I will perform GIA simulations using the refined ice history and Earth model described above to produce maps of paleotopography and paleoslope across the interval of Missoula flooding. I will use existing Matlab code I developed during my Ph.D to solve the so-called sea-level equation (Farrell & Clark 1976) using a pseudo-spectral algorithm. Next, I will use predictions of GIA-induced change to topography to calculate drainage patterns along the channels draining these floods. In prior work I performed similar calculations by using steepest descent routing to connect GIA-induced slope changes to evidence of sudden changes in river evolution along the U.S. east coast (Pico et al., submitted). Because the Missoula floods were of sufficiently large magnitude to surpass small drainage divides, in the proposed work I will use a 2D hydraulic model to calculate flood routing (see *Objective 2*). I will specify the location of the lake outlet and the total associated water volume. To model drainage blockage by ice lobes, I will impose ice margin boundaries based on terminal moraine limits (Kovanen & Slaymaker 2004; Waitt 2017). Given uncertainties surrounding the nature and timing of these flood events, I will conduct a series of numerical experiments to test the plausible range of variables that control flood routing, including: the timing and location of ice lobes, the location of the lake outlet, the lake volume drained, and the depth of canyons at the time of drainage. I will calculate drainage paths at 1 ky time steps throughout the 22-14 ka period of glacial lake Missoula outburst floods. These drainage flow predictions allow a rigorous assessment of whether GIA-induced crustal deformation was sufficiently large to explain the observed change in routing of the Missoula floods over this interval. In particular, current 2D hydraulic modeling of Missoula floods do not predict sufficient flood routing to Moses Coulee (Liu & Baker 2018), despite evidence of flood routing through the channel (Baker et al. 2016). By correcting topography for GIA, it may be possible to explain this routing.

The proposed research fills a crucial gap in understanding the role of GIA in Missoula flood route evolution. The reshaping of topography by GIA, and consequent perturbations to drainage directions during megafloods, are key to reconstructing paleoclimate over western North America over the last glacial cycle since the formation and drainage of pluvial and glacial lakes reflects information about regional precipitation and freshwater influx to the ocean.

Objective 2: Improve estimates of flow rates and total water volume during megaflood events

The Channeled Scablands, with landforms of scoured bedrock, expansive gravel beds, and deeply carved canyons, contain evidence for megafloods (Bretz 1928). Geologic features such as canyon geometry and size of transported sediment, provide valuable insight into the shear stress imposed on the bed and water flow rates at the time of flooding (O'Connor & Baker 1992; Baker 2009). Because flow velocity depends on channel slope and width, reconstructing flood discharge requires knowledge of local topography. Previous approaches relied on local modern-day slopes to model lake dam failure (Denlinger & Connell 2010) or flow speeds (O'Connor & Baker 1992) through the channel. In this proposed work, flow estimates will be improved by using slopes corrected for topographic deformation associated with GIA, described in *Objective 1*.

One approach to determine flood volumes involves modeling lake size and dam failure (Denlinger & Connell 2010). Local slopes determine whether flow rates were rapid or slow, resulting in either a sudden or progressive flood. Therefore accurate reconstructions of paleo-topography are necessary to constrain the flood volume, flow paths, and discharge of the floods. To illustrate that errors in bed slope would affect discharge reconstructions, I use the Manning equation here to derive simple scaling relationships between discharge and slope. In Manning's equation (Costa 1983), the flow velocity (u) varies as the square root of slope (S), such that a steeper slope produces more rapid and shallower floods for the same discharge: $u = \frac{1}{n} h^{2/3} S^{1/2}$ (1)
where h is water depth and n is the Manning roughness coefficient. The flood discharge (Q) can be estimated from conservation of mass as a function of flow velocity (u), water depth (h), and width (W) within the channel (Costa 1983): $Q = uhW$ (2)

High water marks have classically been used to estimate water depth in order to model flood discharge. This method assumes that channel depth and width is known from the modern mapped canyon geometry, and has remained static over the duration of flooding (O'Connor & Baker 1992). Combining Manning equation and continuity under the assumption of known depth and width yields discharge proportional to the square root of slope ($Q \sim \sqrt{S}$). Nevertheless, because these canyons were carved during the flood event, the high water marks may overestimate paleo water depth. An alternative method assumes that bed stress is held constant for a given erosional threshold, allowing channel width and depth to vary over the flood duration (Larsen & Lamb 2016). Because values for channel width W and depth h are not constrained by field evidence, they are assumed to vary linearly with slope S. Using the bed-stress method, discharge becomes proportional to the square of slope ($Q \sim S^2$). Thus, both common paleo-hydraulic reconstruction techniques show that estimated discharge is sensitive to slope, and therefore GIA, and this is particularly true for the constant stress method (Larsen & Lamb 2016).

I include the above simplified equations, which assume steady and uniform flow, to illustrate that accounting for GIA will likely influence discharge calculations. Because crustal deformation resulting from the solid Earth's response to ice loading would have significantly altered slopes relative to today (by ~30% at 22 ka; *Objective 1*; Figure 1), I propose to calculate the GIA-induced perturbation to discharge through channels draining the floods sourced from Glacial Lake Missoula, Columbia and Lake Bonneville. I will extract the known locations of channels draining these floods (including the Columbia River, Moses Coulee, and Grand Coulee), and use the predictions resulting from *Objective 1* to correct modern-day slopes for changes in topography due to GIA. To begin I will adopt a 1D step-backwater approach (O'Connor & Baker 1992), which accounts for unsteady and non-uniform flow, but only for flow accelerations in the downstream direction. To implement this approach, I will define a series of channel cross sections using the GIA-corrected paleotopography. To consider how the broader field of GIA-corrected paleotopography affects flow discharge, I will adopt a 2D hydraulic model that is depth averaged, yet fully models both temporal and spatial accelerations in the horizontal directions. To this end I will implement ANUGA 2.0 (Roberts et al. 2015), a Python-based code which solves the shallow-water equations in 2D on a triangular mesh. ANUGA requires a grid of initial topography, boundary conditions including the location of the lake source, and an estimate of the bed friction coefficient, in order to simulate how floodwater is routed it over topography, calculating high water marks and discharges. I will use a friction coefficient of 0.065 as in Larsen & Lamb (2016), and a modern topography DEM of 10 m resolution from USGS corrected for GIA-induced crustal deformation. I will test the sensitivity to these inputs by varying the initial topography field using a series of ice histories and Earth models in the GIA simulations performed, as well as the location and volume of the lake. These calculations should be performed over the course of flooding (22-14 ka), as GIA-induced slope changes vary substantially over this interval (Figure 2).

This approach offers improved estimates of flood discharge and the evolution of channel slope through sequential floods. Refining channel flow velocity provides insight into the mechanism of incision, with implications for predicting modern flood hazards.

Objective 3: Connecting to ocean response and broader climate system

Understanding the Missoula floods is critical to both reconstructing local ice histories and regional climate, as ice melting and the consequent influx of freshwater to the Pacific impact both ocean and atmospheric circulation (Balbas et al. 2017; Lopes &

Mix 2009). These pulses of freshwater are recorded in ocean sediment cores through geochemical and biological indicators (Lopes & Mix 2009; Praetorius et al. 2015; Gombiner et al. 2016). By dating freshwater intervals, these sediment cores can resolve flood timing and frequency. Further, perturbations to ocean geochemistry and biological productivity inform us on how the ocean responded to these events, granting insight into the sensitivity and resilience of the ocean system. Freshwater input is an important regulator of ocean salinity and therefore efficiency of convection, with implications for global climate (Ivanovic et al. 2017; Praetorius et al. 2014; Taylor et al. 2014).

In June 2017 I joined the scientific team of R/V Oceanus, collecting sediment cores off the Oregon coast that sample these flood events (white circles, Figure 1). These cores will be analyzed at Oregon State for variability in freshwater diatoms, oxygen and carbon isotopes, and compositional elements, and I plan to use this data by working with Prof. Alan Mix to correlate the timing of pulses observed in sediment cores to observations of channel occupation on land. I will use the refined estimates of flood discharge, calculated in *Objective 2*, in order to understand how geochemical proxies, including oxygen isotope ratios and freshwater diatoms, vary with the magnitude of freshwater discharge. The presence of elements associated with sulfide formation can be used to infer past episodes of hypoxia. Thus I will compare the frequency and intensity of these events to estimates of flood discharge in order to understand how freshwater pulses impacted biological productivity.

Linking the ocean response to flooding on land helps resolve the timing and magnitude of freshwater flux. More importantly, the perturbations caused by massive floods to ocean geochemistry and biological productivity help connect our understanding of ice dynamics to climate forcing, painting a broader picture of the Earth's system.

Intellectual Merit

The proposed research will be the first to quantify the influence of glacial isostatic adjustment on the Missoula megafloods. I will model the routing of flood drainage, calculate new estimates of flood volumes, and quantify the response of ocean chemistry to these catastrophic events. Through interdisciplinary collaboration involving geodynamicists, geomorphologists, and paleooceanographers, these results will improve our knowledge of ice-sheet stability, the strength of water required to carve canyons, as well as the ocean's biological response to melting ice. This innovative approach uses glacial-isostatic adjustment modeling to connect geomorphic processes to both small and large wavelength features of the mantle's response to ice loading, ultimately linking local short-lived outburst flooding to longer global climate changes.

Work Plan

Institution choice: California Institute of Technology (Caltech) & Oregon State University (OSU)

At Caltech I will work closely with Prof. Michael Lamb, the host mentor and an expert in catastrophic floods, hydraulic modeling, and mechanisms of erosion during flood events. Prof. Lamb has extensive experience studying Missoula flood dynamics and has field expertise in the Channeled Scablands. At Caltech, I also will benefit from interactions with Prof. Ken Farley, who has expertise in dating megaflood channels and deposits. At OSU, I will work with Prof. Alan Mix, the co-mentor, who is an expert in paleooceanography and understanding geochemical proxies in the context of deglacial climate changes. I will also interact with Prof. Peter Clark, a renowned expert in North American ice histories, with extensive knowledge of geologic constraints on Cordilleran deglaciation.

Year 1: I will begin my appointment on September 1, 2019, spending three quarters of my time at Caltech and one quarter at OSU. Prior to the appointment, I will have attended an intensive, three-day *Friends of the Pleistocene* field trip in eastern Washington (September 2018) led by experts on the geologic record of the Scablands, including Jim O'Connor, Victor Baker, Isaac Larsen, and Andrea Balbas. At Caltech I will complete *Objective 1* (GIA modeling and calculating drainage path evolution over flooding) and prepare a manuscript reporting these findings. Results will be presented at the AGU Fall Meeting and the paleo sea level (PALSEA) workshop to gain feedback on the ice history being developed. I will begin researching *Objective 2*, learning techniques in the Lamb group for hydraulic reconstruction of Missoula flood events. At OSU, I will begin working with sediment core data, selecting which proxies will be most useful in comparison to freshwater fluxes estimated in *Objective 2*.

Year 2: I will spend 2 quarters at Caltech of my time and 2 quarters at OSU. I will submit a manuscript on *Objective 1* and begin preparing a manuscript on *Objective 2*. I will present results on *Objective 2* at the AGU Fall Meeting. I will work closely with the Mix group on *Objective 3* to link refined estimates of freshwater flux to geochemical proxies in sediment cores. At Caltech I will mentor an undergraduate student over the summer through the Waves or Mellon Mays Undergraduate Fellowship program.

Broader Impacts

Human Society & Natural Hazards

The scientific goals of this proposal, understanding past catastrophic flood events and the stability of ice sheets in response to climate change, are of interest to society as refining the hydraulic and erosional model during Pleistocence megafloods helps us understand modern flood hazards and plan for their impact on local inhabitants. Accurately estimating freshwater discharge, and its relation to deglacial climate change, will help us understand the resilience of ice sheets in response to climate warming.

Mentoring, Leadership in Service & Outreach, & Scholarship

As a Ph.D student I mentored three undergraduate students over the summer and academic year, guiding in research planning, teaching programming skills, and offering career advice. At Caltech, I will mentor a summer undergraduate student through the WAVE Fellows or Mellon Mays Undergraduate Fellowship program, initiatives designed to recruit and support URM undergraduates from a wide array of national institutions. The undergraduate will gain computational modeling skills and an understanding of ice-age sea level, and will be encouraged to present our findings as a poster presentation at the AGU Fall Meeting. Further, I will continue to mentor Ph.D students at both Caltech and OSU, in the Lamb and Mix research groups.

I have a strong history of commitment to equity and diversity in geoscience, inspired by my experience as a Hispanic woman in the natural sciences. As an executive board member of Harvard Graduate Women in Science & Engineering (HGWISE), I spearheaded initiatives in both professional development and community building, including an annual Title IX training. For five years, I served as a mentor for WiSTEM, the undergraduate women in science group. I was invited to join annual panels for the W.E.B du Bois Society, the graduate under-represented minority (URM) group, and Summer Research Opportunities at Harvard, a summer research program aimed at URM undergraduate students. I presented to visiting middle school student groups from underserved communities in the Boston area at the Harvard Natural History Museum and at the Harvard Foundation for Intercultural and Race Relations science conference.

I intend to continue my commitment to the recruitment and retention of URM's in the natural sciences. At Caltech, I will join the Women Mentoring Women program as a mentor, in addition to helping the Women's Engagement Board create professional development programs. Further, I will be a guest speaker at Caltech Latino Association of Student in Engineering and Sciences (CLASES), an organization that supports the Latinx community, whose members participate in outreach such as tutoring children of custodial staff. At OSU, I will be a guest speaker at a "Wake up Coffee" event, cohosted by OSU Women in Science and Women in Marine Sciences, and attend monthly social hours to support graduate women in science at OSU. I will also continue my commitment to scientific service as a journal reviewer and session convener. I plan to organize and co-chair a session at the AGU Fall Meeting each year.

I have academic training in studying issues facing minorities in science through a secondary Ph.D. field in Women, Gender, and Sexuality studies. To address an important step for academic advancement, I investigated the representation of women as first authors in leading geoscience journals over the last five years using web-scraping techniques to compile the names of first authors, and classifying them by gender. I found that first-author representation of female names is close to 20% in geology, geophysics, geomorphology, planetary, and atmospheric science journals. These results will be presented at the 2018 AGU Fall Meeting (Pico et al. 2018), and prepared for publication in a peer-reviewed geoscience journal. The additional research funding available through this fellowship will allow me to hire and advise summer students performing research on gender and race representation in geoscience.

Relevant preliminary work

Glacial isostatic adjustment modeling & regional ice histories:

Pico, T., Mitrovica, J.X., Mix, A.C., Two-phase flooding of the Bering Strait reflects the sea-level fingerprint of an expanding ice-free corridor, *Nature Geoscience*, in revision.

Pico, T., Birch, L., Weisenberg, J., Mitrovica, J.X., 2018. Refining the Laurentide Ice Sheet at Marine Isotope Stage 3 : A data-based approach combining glacial isostatic simulations with a dynamic ice model. *Quaternary Science Reviews*

Influence of glacial isostatic adjustment on landscapes:

Pico, T., Mitrovica, J.X., Perron, J.T., Ferrier, K.L., Braun, J., Influence of glacial isostatic adjustment on river evolution along the U.S. mid-Atlantic coast, *Earth and Planetary Science Letters*, submitted.

Pico, T., Mitrovica, J.X., Ferrier, K.L, Braun, J., 2018. Glacial isostatic adjustment deflects the path of the ancestral Hudson River. *Geology*, (7), pp.1–4.