DATA PAPER

Post-Glacial Radiocarbon Ages for the Southern Cordilleran Ice Sheet
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The Pleistocene Cordilleran Ice Sheet (CIS) formed over mountainous terrain in northwestern North America, and last reached a maximum extent around 15 to 17 ka BP. Following this maximum, the ice sheet began to diminish in size. Retreat was rapid in some sectors, but was punctuated by still-stands and readvances in other sectors. Geochronology of CIS retreat is key for understanding the pace and style of this deglaciation, and for testing hypothesized feedbacks between the changing ice sheet and the ocean, atmosphere, and solid earth. One method of reconstructing ice sheet retreat relies on radiocarbon ages of immediate post-glacial organic material. Such ages are minima for deglaciation and are often utilized to infer the timing of ice sheet retreat. This paper describes a database of post-glacial radiocarbon dates on non-marine carbon for the region from 47° to 52° N that was once covered by the southern CIS. The data were collected from published literature. Each entry includes name, lab ID, location, elevation, the material dated, its stratigraphic context, the event dated, additional details, and a reference to the original data. This information is useful for validating numerical models of the CIS, for connecting CIS evolution to climate change, and for reconstructing late Pleistocene environments of the Pacific Northwest.

Keywords: Cordilleran Ice Sheet; Deglaciation; Post-glacial; Radiocarbon; Last Glacial Maximum; Continental Ice Sheets

Repository location
The data and references are stored in the Open Quaternary Dataverse (Gombiner, 2019). Age data is available as an excel spreadsheet (.xlsx), and as comma-separated values (.csv), and references are available as a Rich-Text file (.rtf) and as an Endnote file (.txt). This dataset will be updated as new data become available or known to the author, but past versions will remain accessible in the Dataverse. Note that to download the .xlsx file you must select the download button next to the file labeled “Southern_Cordilleran_Postglacial_Terrestrial_Radiocarbon.tab” and select “Original File Format”.

Introduction
The CIS once covered the mountain belts and interior plateaus of northwestern North America, with marine-terminating outlet glaciers extending into the Pacific Ocean (Clague, 2009). The CIS contained a volume of ice equivalent to 7–9 m of sea-level rise, which is similar to the volume of ice in the modern Greenland Ice Sheet (Seguinot et al. 2016). CIS growth seems to have lagged behind global glaciation, with maximum CIS extent at 15 to 17 ka BP (Darvill et al. 2018; Porter and Swanson, 1998), several thousand years after the maximum in global ice volume at 23 ka BP (Lisiecki and Raymo, 2005).

The topography of the CIS affected atmospheric circulation (Lora et al. 2016), and its advance onto the continental shelf diverted ocean currents (Taylor et al. 2014). Subglacial erosion created features including fjords (Shuster et al. 2005), drumlin swarms (Lesemann and Brennand, 2009), and deep linear troughs (Booth, 1994). Downstream of the ice sheet margin, glacial lake outburst floods from the southern CIS created the Channeled Scabland canyon system (Bretz et al. 1956) and transported vast amounts of sediment onto the Juan de Fuca and Pacific Plates (Normark and Reid, 2003). The timeline of these events is based on geomorphic relationships and geochronology, particularly radiocarbon dating, which has been one of the most commonly used geochronological methods for determining the glacial/deglacial chronology of the CIS in the last glacial cycle.

Many authors have compiled post-glacial or pre-glacial radiocarbon ages to infer CIS evolution during the last glaciation (e.g. Fulton, 1971; Clague, Armstrong, and Mathews, 1980; Porter and Swanson, 1998; Riedel, 2017; Menounos et al. 2017), some in combination with other age determinations such as surface exposure ages. Radiocarbon ages are also useful to understand connections between the CIS and ocean change (Taylor et al. 2014), to validate numerical ice sheet models (Seguinot et al. 2016), and to contextualize surface exposure ages (Balbas et al. 2017; Darvill et al. 2018) and luminescence ages (Smith et al. 2018). However, CIS studies that include radiocarbon dating do not typically utilize all existing
radiocarbon data. In addition, not all radiocarbon ages are open-access. Therefore there is need for an open-access database of radiocarbon ages for the CIS.

This paper presents an open-access compilation of post-glacial, terrestrial radiocarbon ages for the southern CIS (Figures 1 and 2). This compilation builds on previous work (Fulton, 1971; Porter and Swanson, 1998, Czajkowski, 2016; Menounos et al. 2017; Riedel, 2017) by adding ages for the Puget Lowland, Olympic Peninsula, Okanogan Trench, and Columbia River (Figure 3). The compilation presented here will be particularly useful to those investigating the deglacial chronology of the CIS during the last glacial cycle.

However, compilations are subjective, reflecting i) where and how field investigators worked, ii) selection criteria (Arnold, 2002), iii) access to and awareness of data by the compiler, and iv) spatial constraints. Gajewksi et al. (2011) discuss how compilation subjectivity may introduce sampling biases, and thus recommend comparing independent databases and multiple dating techniques to produce robust conclusions. Following this advice, the compilation of radiocarbon ages for the southern CIS described here should be a starting point for understanding the glacial and deglacial chronology of the southern CIS during the last glacial cycle.

**Context**

**Spatial coverage**

Description: Southern region of the Cordilleran Ice Sheet including Washington, Idaho, British Columbia, and Alberta.

- Northern boundary: 51.97°N
- Southern boundary: 47°N
- Eastern boundary: –114.96°W
- Western boundary: –125.03°W

**Temporal coverage**

8,900 to 14,480 14C years ago.

**Methods**

A list of post-glacial radiocarbon ages for the southern Cordilleran Ice Sheet was compiled from previously published scientific literature. All radiocarbon ages in the database are interpreted to represent a minimum age for

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**Figure 1:** Locations of radiocarbon age sampling sites, grouped into eight geographic regions. Base map shows regional topography and the maximum extent of glaciation during the last glacial cycle (black line).

**Figure 2:** Temporal coverage of the dataset, plotted as probability distribution functions of radiocarbon ages for each geographic group, with individual radiocarbon ages as open squares. Color-coding in Figure 2 corresponds to colors in Figure 1.
The majority of radiocarbon ages in the database are from sediment cores taken from bogs, ponds, or lakes. A typical core stratigraphy is organic-rich sediment overlying organic-poor sediment such as glacial till or glacial clay. The organic-poor sediment is interpreted to represent a period of subglacial sediment deposition, and the organic-rich sediment is thought to represent post-glacial sedimentation in a vegetated landscape. The lowermost organic material (i.e. the organic-rich sediment overlying organic-poor glacial sediment) in such a stratigraphy indicates the age when the site became ice free, when vegetation returned to the landscape, and when organic material began to accumulate. By radiocarbon dating the organic material within the organic-rich sediment that overlies glacial sediment, it is possible to determine a minimum age for when glacial ice last occupied the site.

Sixteen of the 66 ages in the database are from depositional environments that are not bog or lake bottoms. Fourteen of the 66 total ages are from wood or other organic material within deltaic or nearshore deposits, and thus provide a minimum age for the formation of the host deposit. Four radiocarbon ages are from deltas that were deposited in a proglacial lake environment that was previously covered by glacial ice. Radiocarbon ages for these glaciolacustrine deltas represent the minimum age of deglaciation at the sample site, and also represent the time when a downstream glacier was sufficiently advanced to pond the proglacial lake. Ten of the radiocarbon ages in the database are on terrestrial organic material, typically wood, within uplifted marine deposits that formed when marine water flooded the landscape following deglaciation of an isostatically-depressed crust. Radiocarbon ages for these marine deposits also represent a minimum age for deglaciation of the sample sites. One age is from loess that overlies outwash gravel at a formerly glaciated site, and one age is from a nonmarine deposit interbedded with marine deposits at a formerly glaciated site. These ages both represent minima for deglaciation of the sample sites.

The following steps were carried out to obtain and document radiocarbon ages for the southern CIS.

**Steps**

1. The radiocarbon age compilation was begun from previous radiocarbon age lists of Fulton (1971), Porter and Swanson (1998), Czajkowski (2016), Menounos et al. (2017), and Riedel (2017). Original journal articles containing primary age data were obtained, and radiocarbon age data transcribed into a spreadsheet directly from the original sources. Only ages that relate to the deglaciation of the Cordilleran Ice Sheet were included.

2. References within the aforementioned journal articles were used to find additional journal articles...
that contain radiocarbon age data for deglaciation of the CIS.

3) Google, Google Scholar, and Web of Science were searched with terms such as “Cordilleran Ice Sheet radiocarbon”, “Okanagan Lobe”, etc. to locate additional sources of age data.

4) An entry was created for each individual radiocarbon measurement that includes sample name (usually referring to the location), lab ID (a unique identifier created by the radiocarbon lab), latitude, longitude, elevation, whether the elevation was derived (D) from Google Earth or reported (R) in the original study, whether the latitude and longitude was derived (D) from Google Earth or reported (R) in the original study, the material dated, radiocarbon age, analytical error, IntCal13 calibrated age, combined analytical and calibration error, stratigraphic context of the sample, additional details, and a reference to the original study.

5) When a sampling location lacked elevation data, the latitude-longitude coordinates and Google Earth were used to derive the elevation of the sampling site. The elevations of 27 out of 66 sample sites were derived from Google Earth, by entering the horizontal coordinates from the primary source and then determining the elevation at that location. Extra care was taken in the three cases where sample sites are in high-relief landscapes and where small horizontal displacements result in large vertical changes. The elevation of these sites was determined by checking that the location matched the sample site description provided in the primary source. It is important to note that modern elevations are not the same as immediate post-glacial elevations, as post-glacial isostatic adjustment and tectonic deformation has resulted in significant vertical displacements, on the order of 100 meters at many sites.

6) Certain authors located sample sites in the United States using the Public Land Survey System. For these samples, the centroids of Township and Range locations were converted to latitude-longitude coordinates using an online tool.

7) In two cases, authors did not include numerical location data. For one of these cases, a sample from Dailey Bog in Washington, the place name and associated map was used to locate the sample site. For the other case, a sample from Finney Lake in British Columbia, the place name was entered into Google Earth, and the latitude-longitude coordinates of Finney Lake were recorded into the database.

Constraints
This dataset has a variety of limitations and possible issues, some of which are described below:

1) Transcription errors are possible.

2) Stated analytical uncertainties do not include external errors such as the possible incorporation of non-atmospheric carbon into age data. Where authors suggested such possibilities, their comments are in the “Additional details” field within the excel spreadsheet.

3) Beta counting age determinations required larger samples than needed for Accelerator Mass Spectrometry (AMS). Therefore ages from earlier studies utilizing beta counting may represent a longer interval of carbon fixation and thus may trend younger than AMS determinations.

4) Elevation data varies in accuracy, as some authors report approximate elevations and many field collections predate widespread availability of Global Position System measurements.

5) The database includes ages from an uncertain stratigraphic context, such as where coring did not reach the base of a deposit, or where part of a section is not exposed. Additionally, authors may have unique interpretations of how the dated sections relate to ice sheet history.

6) The ages in the database limit the timing of the deglaciation, but deglaciation may have occurred hundreds or thousands of years earlier, with the exact offset between the age of deglaciation and the radiocarbon age depending on the rate and style of revegetation in the area, the type of organic remains dated, the thickness of bulk samples, the stratigraphic height of the sample above the deglacial horizon, sedimentary processes near the sample location, and other factors.

7) Age interpretation is complicated in areas that experienced an initial deglaciation, glacier readvance, and a final deglaciation, such as occurred in the Fraser Lowland (Friele and Clague, 2002). Two ages, TO-6838 and GSC-6140, specifically date the first deglaciation of the sample sites. Most other ages in the radiocarbon age compilation likely date the final deglaciation of the sample sites.

8) In the database the lab ID for CAMS-57590 Squamish has the same 14C age as the CAMS-95970 Squamish sample listed by Menounos et al. (2017). This age is presented in Friele and Clague (2002) as CAMS-57590. Since this is the first reference to this sample in the literature, this is the ID retained in this database. It is not clear from the literature if CAMS-95970 of Menounos et al. (2017) is the same sample with a transcription error or a different sample.

Dataset description
Object name

Data type
Previously published data with references to published sources.

Format names and versions
Excel and CSV.

Creation dates
The original data was collected between 1957 to 2007, and the data was compiled in 2018 and 2019.
**Dataset Creators**
Compiled by Joel Gombiner.

**Language**
English.

**License**
CC0 – “Public Domain Dedication”.

**Reuse potential**
This radiocarbon age database will be useful to other researchers who study the evolution of the CIS. For example, Seguinot et al. (2016) compare their numerical model of the CIS with post-glacial radiocarbon dates to see if the model produced a similar pattern of retreat to that shown by age data. In addition, Balbas et al. (2017), Menounos et al. (2017), and Darvill et al. (2018) combine post-glacial radiocarbon ages with surface exposure dating of glacially-transported boulders to reconstruct CIS retreat. The compilation described here provides a useful radiocarbon framework for future data-model comparisons, and for comparisons between radiocarbon dating and other geochronological methods such as surface exposure dating and optically stimulated luminescence dating. This will be increasingly useful as more researchers apply numerical modeling, surface exposure dating, and luminescence dating to the study of the CIS. Illustrating the utility of collecting age data on a regional scale, the DATED-I project used an age compilation to reconstruct margins of the Eurasian Ice Sheet through time, highlighting areas for future work and generating a useful data product for modelers (Hughes et al. 2016).

The radiocarbon age data presented in this study may also be useful for modeling the impact of ice sheets on climate. For example, the surface topography of the CIS influenced atmospheric circulation, causing precipitation to shift southward (Lora et al. 2016). The changing ice sheet in the climate model of Lora et al. (2016) is based on geodetic and sea-level data, but incorporation of geochronology would improve the accuracy of ice sheet reconstructions and of deglacial climate simulations (Abe-Ouchi et al. 2015). This radiocarbon database might be helpful in developing more accurate ice sheet reconstructions.

The radiocarbon data presented here suggest that deglaciation along the southern CIS propagated from west to east, with the Puget Lowland and Olympic Peninsula becoming ice free first, followed by the Strait of Georgia and the lower Fraser River basin, and culminating with retreat in the Okanogan Trench and Columbia River (Figures 1 and 2). Balbas et al. (2017) also found that the Puget Lobe retreated before the Okanogan Lobe, and suggest that this was due to the Puget Lobe’s interaction with warming sea water. Rising eustatic sea level also played a role in earlier coastal retreat, as marine-terminating outlet glaciers destabilized through rapid iceberg calving (Clague, 1985). Future work could utilize this radiocarbon database to more quantitatively examine the regional pattern of deglaciation and its causes.

In addition, the database highlights areas for future work. The Purcell Trench and Rocky Mountain Trench regions are clearly undersampled relative to the Puget Lowland, Strait of Georgia, and Fraser River (Figure 1), as noted previously by Booth et al. (2003).

Finally, the database may be useful to educators as the basis of teaching exercises or public outreach materials.

**Additional File**
The additional file for this article can be found as follows:

- **Post-Glacial Radiocarbon Ages for the Southern Cordilleran Ice Sheet.** Spreadsheet of radiocarbon ages and sample site information. DOI: https://doi.org/10.5334/oq.55.s1

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**Competing Interests**
The author has no competing interests to declare.

**References**

Arnold, TG. 2002. ‘Radiocarbon dates from the ice-free corridor’. *Radiocarbon*, 44(2): 437–454. DOI: https://doi.org/10.1017/S0033822200031829

Balbas, AM, Barth, AM, Clark, PU, Clark, J, Caffee, M, O’Connor, J, Baker, VR, Konrad, K and Bjornstad, B. 2017. ‘10Be dating of late Pleistocene megafloods and Cordilleran Ice Sheet retreat in the northwestern United States’. *Geology*, pp. G38956.1. DOI: https://doi.org/10.1130/G38956.1

Booth, DB. 1994. ‘Glaciofluvial infilling and scour of the Puget Lowland, Washington, during ice-sheet glaciation’. *Geology*, 22(8): 695–698. DOI: https://doi.org/10.1130/0091-7613(1994)022<0695:GFIASC>2.3.CO;2

Booth, DB, Troost, KG, Clague, JJ and Waitt, RB. 2003. ‘The Cordilleran Ice Sheet’. *Developments in Quaternary Sciences*, 1: 17–43. DOI: https://doi.org/10.1016/S1571-0866(03)01002-9

Bretz, JH, Smith, HTU and Neff, GE. 1956. ‘Channeled Scabland of Washington – New Data and Interpretations’. *Geological Society of America Bulletin*, 67(8): 957–1049. DOI: https://doi.org/10.1130/0016-7606(1956)67(957:CSOWND)2.0.CO;2

Clague, JJ. 1985. ‘Delaciation of the Prince Rupert Kitimat area, British Columbia’. *Canadian Journal of Earth Sciences*, 22(2): 256–265. DOI: https://doi.org/10.1139/e85-022

Clague, JJ. 2009. ‘Cordilleran Ice Sheet’. *Encyclopedia of Paleoclimatology and Ancient Environments*. Springer, 206–211. DOI: https://doi.org/10.1007/978-1-4020-4411-3_49

Clague, JJ, Armstrong, J and Mathews, W. 1980. ‘Advance of the late Wisconsin Cordilleran Ice Sheet
in southern British Columbia since 22,000 yr BP'. *Quaternary Research*, 13(3): 322–326. DOI: https://doi.org/10.1016/0033-5894(80)90060-5

Czajkowski, JL. 2016. Washington State geochronology database—GIS data. 1.1 ed.: Washington Division of Geology and Earth Resources.

Darvill, CM, Menounos, B, Goehring, BM, Lian, OB and Caffee, MW. 2018. 'Retreat of the Western Cordilleran Ice Sheet Margin During the Last Deglaciation'. *Geophysical Research Letters*, 45(18): 9710–9720. DOI: https://doi.org/10.1029/2018GL079419

Fulton, RJ. 1971. Radiocarbon geochronology of southern British Columbia. *Department of Energy, Mines and Resources*. DOI: https://doi.org/10.4095/102467

Gajewski, K, Muñoz, S, Peros, M, Viau, A, Morlan, R and Betts, M. 2011. 'The Canadian archaeological radiocarbon database (CARD): Archaeological 14 C dates in North America and their palaeoenvironmental context'. *Radiocarbon*, 53(2): 371–394. DOI: https://doi.org/10.1017/S0033822200056630

Gombiner, J. 2019. 'Post-glacial radiocarbon ages for the southern Cordilleran Ice Sheet'. *Harvard Dataverse*. DOI: https://doi.org/10.7910/DVN/YGRESZ

Hughes, AL, Gyllencreutz, R, Lohne, ØS, Mangerud, J and Svendsen, JI. 2016. 'The last Eurasian ice sheets—a chronological database and time-slice reconstruction, DATED-1'. *Boreas*, 45(1): 1–45. DOI: https://doi.org/10.1111/bor.12142

Lesemann, JE and Brennand, TA. 2009. 'Regional reconstruction of subglacial hydrology and glaciodynamic behaviour along the southern margin of the Cordilleran Ice Sheet in British Columbia, Canada and northern Washington State, USA'. *Quaternary Science Reviews*, 28(23–24): 2420–2444. DOI: https://doi.org/10.1016/j.quascirev.2009.04.019

Menounos, B, Goehring, BM, Osborn, G, Margold, M, Ward, B, Bond, J, Clarke, GK, Clague, JJ, Lakeman, T and Koch, J. 2017. 'Cordilleran Ice Sheet mass loss preceded climate reversals near the Pleistocene Termination'. *Science*, 358(6364): 781–784. DOI: https://doi.org/10.1126/science.aan3001

Normark, WR and Reid, JA. 2003. 'Extensive deposits on the Pacific plate from Late Pleistocene North American glacial lake outbursts'. *Journal of Geology*, 111(6): 617–637. DOI: https://doi.org/10.1086/378334

Porter, SC and Swanson, TW. 1998. 'Radiocarbon age constraints on rates of advance and retreat of the Puget lobe of the Cordilleran Ice Sheet during the last glaciation'. *Quaternary Research*, 50(3): 205–213. DOI: https://doi.org/10.1006/qres.1998.2004

Riedel, JL. 2017. 'Deglaciation of the North Cascade Range, Washington and British Columbia, from the Last Glacial Maximum to the Holocene'. *Cuadernos De Investigacion Geografica*, 43(2): 467–496. DOI: https://doi.org/10.18172/cig.3236

Seguinot, J, Rogozhina, I, Stroeven, AP, Margold, M and Kleman, J. 2016. 'Numerical simulations of the Cordilleran Ice Sheet through the last glacial cycle'. *Cryosphere*, 10(2): 639–664. DOI: https://doi.org/10.5194/tc-10-639-2016

Shuster, DL, Ehlers, TA, Rusmore, ME and Farley, KA. 2005. 'Rapid glacial erosion at 1.8 Ma revealed by He-4/He-3 thermochronometry'. *Science*, 310(5754): 1668–1670. DOI: https://doi.org/10.1126/science.1118519

Smith, LN, Sohbati, R, Buylaert, JP, Lian, OB, Murray, A and Jain, M. 2018. 'Timing of lake-level changes for a deep last-glacial Lake Missoula: Optical dating of the Garden Gulch area, Montana, USA'. *Quaternary Science Reviews*, 183: 23–35. DOI: https://doi.org/10.1016/j.quascirev.2018.01.009

Taylor, M, Hendy, I and Pak, D. 2014. 'Deglacial ocean warming and marine margin retreat of the Cordilleran Ice Sheet in the North Pacific Ocean'. *Earth and Planetary Science Letters*, 403: 89–98. DOI: https://doi.org/10.1016/j.epsl.2014.06.026