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Impacts of Resource Fluctuations and Recurrent Tsunamis on the Occupational History of Čḯxwicən, a Salishan Village on the Southern Shore of the Strait of Juan de Fuca, Washington State, U.S.A

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Impacts of resource fluctuations and recurrent tsunamis on the occupational history of Čı́xʷicən, a Salishan village on the southern shore of the Strait of Juan de Fuca, Washington State, U.S.A.

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ABSTRACT

A summed probability density function (spdf), generated from the catalog of 101 radiocarbon ages on wood and charcoal from the Čı́xʷicən archaeological site (Washington State, USA), serves as a proxy for the site's occupational history over the last 2500 years. Significant differences between spdfs derived from a null model of population growth (a bootstrapped logistic equation) and the observed index suggest relatively less cultural activity at Čı́xʷicən between about 1950–1750 cal BP, 1150–950 cal BP, and 650 to 550 cal BP; and increased activity between about 1350–1250 cal BP and 550–500 cal BP. Peaks in the Čı́xʷicən spdf are closely echoed by those derived from English Camp and Cama Beach, the other intensively dated archaeological sites in the region, from about 1600 to 650 cal BP. The fluctuations at all three sites in that period appear to be predominantly associated with the availability of marine resources, as shown by a statistically significant correlation between the Čı́xʷicən spdf and the abundance of fish remains in late Holocene sediments in Saanich Inlet, a fjord on the southeast coast of Vancouver Island. A dramatic fall in the Čı́xʷicən spdf after 1250 cal BP, and the presence of sandy deposits in the village midden may reflect the impact of a tsunami triggered by earthquake "U" at the neighboring Cascadia plate boundary. Other tsunamis from this source over the last 2500 years apparently had more modest effects on activity levels at Čı́xʷicən.

1. Introduction

More than 100 papers have been published in the last 30 years on the temporal and spatial dynamics of prehistoric populations. Most of this literature follows Rick (1987), and infers long-term demographic trends from the frequency distribution of radiocarbon ages from archaeological sites in a region. Several investigators have adopted a broader perspective, and analyzed prehistoric demographic trends on a continental scale (e.g., Shennan and Edinborough, 2007), but attempts to reconstruct the occupational dynamics of individual settlements, or village households, such as that by Prentiss et al. (2018), are rare.

The scarcity of site-specific studies is easily explained; few archaeological sites are sufficiently well-dated for this purpose. In North America, for example, the occupational histories of ~90% of the ~9000 archaeological sites listed in the CARD[1] database are constrained by fewer than 10 radiocarbon assays. Only five sites can boast catalogs of > 100 radiocarbon ages.[2] Čı́xʷicən is one of these.

The Čı́xʷicən village site, located on the northwest coast of Washington State (Fig. 1), was extensively excavated in 2004 as part of a large-scale mitigation effort on behalf of the Washington State Department of Transportation (Larson, 2006; Butler et al. *a*, this issue). The site lies on the south shore of the Strait of Juan de Fuca, approximately midway between the mouth of the strait and the archipelagos that separate the strait from Puget Sound and Georgia Strait, neighboring parts of the Salish Sea (Fig. 1). The village was located at the western end of a bay (now Port Angeles harbor) formed by Ediz Hook, a

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[1] card.anth.ubc.ca.
[2] Almost half of the North American sites listed in the CARD archaeological database (card.anth.ubc.ca), are dated by a single radiocarbon assay. The overall average is 3.5 ages per site (Andrew Martindale, personal communication, May 8, 2017).

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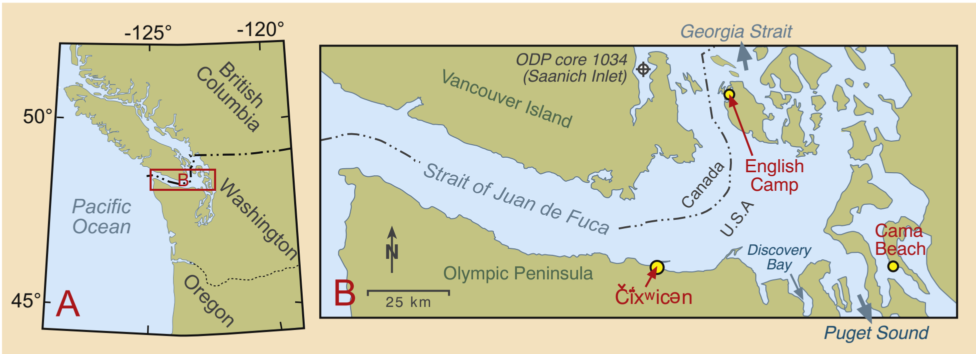

Fig. 1. A. Northwestern North America showing the location of the Strait of Juan de Fuca;
B. The Strait of Juan de Fuca, showing the location of Čḯxʷicən and other places mentioned in the text.

6-km long spit. The spit not only sheltered the village site and the shellfish beds in the bay from storm waves, but also allowed safe passage to the open waters of the strait, which are a migratory corridor for several species of fish (and their predators). In addition, the site was close to the mouth of the Elwha River, which, until it was dammed in 1911, was the largest salmon-bearing river on the Strait of Juan de Fuca.

Fifty-three radiocarbon ages obtained from Čḯxʷicən following the 2004 excavation (Sterling et al., 2006), joined with fifty additional samples dated as part of recent study (Campbell et al., in review) make it the most intensively dated site on the northwest coast of North America, and its rich register of radiocarbon ages offers an unrivalled opportunity to examine the occupational history of a late Holocene village in the Northwest Coast culture area.

Any analysis of radiocarbon age frequencies for this purpose, however, rests on a number of assumptions, which we discuss below. None of these assumptions appear to be invalidated in the case of Čḯxʷicən, and we proceed to generate a summed probability distribution function (spdf) from the calibrated radiocarbon ages as a proxy for occupational intensity. Abrupt changes that may represent environmental stressors are identified by comparing the observed spdf with simulated spdfs produced by a null model. We then assess whether these anomalous phases are restricted to Čḯxʷicən, or are more widespread, by comparing the Čḯxʷicən index with those from two other well-dated sites in the vicinity. Commonalities between these inferred occupational histories and the depositional sequence in a local marine sedimentary archive, along with palaeoclimatic records of glacial advance and retreat, allow us to assess the potential effects of variations in marine resources on the population of these coastal villages, and to explore the potential effects of natural hazards, principally the impact of tsunamis triggered by giant earthquakes at the neighboring plate margin.

2. Occupational history of Čḯxʷicən

2.1. The radiocarbon record: Assumptions

As in other Native villages on the Pacific Northwest coast, samples for dating Čḯxʷicən were derived from the remains of wooden houses, domestic waste in buried house floors, and refuse in the village midden. Inferences about the relative activity levels at Čḯxʷicən through time rest on assumptions which relate to the nature of this dated material, site function, and archaeological excavation practice:

1. The dated material is not subject to age-correction effects which, because they may be spatially and temporally variable, may be of uncertain magnitude;
2. The availability of materials for dating is not limited by supply;
3. The rate at which organic residues are produced and dumped by households remains uniform over time;
4. The organic residues are not differentially preserved over the course of time; and,
5. The cultural detritus at the site is sampled in an unbiased fashion by the excavators; no temporal phases are over- or under-sampled.

Do the dated materials at Čḯxʷicən meet these requirements? For the most part, the answer is “yes”.

Assumption #1: All but one of the 102 ages in the catalog are derived from plant residues (a marine shell sample was excluded).

Assumption #2: Fifty of the samples are high precision AMS ages on short-lived plant taxa, which constrain the depositional event fairly precisely (Campbell et al., this issue). Although variable in abundance, charcoal was nearly ubiquitous in the site deposits, and there were consequently no constraints on sample selection.

Assumption #3: We have no a priori reason to believe that the exploitation of wood for construction or fuel changed through time.

Assumption #4: Wood and charcoal were well-preserved in site deposits, and preservation was apparently temporally uniform. Some of the earliest beach-front deposits, for example, were reworked by water, but still retained in situ cultural constructions and carbonized wood.

Assumption #5: This is the most problematic assumption, as there was explicit intention to estimate ages for initiation of cultural activities in different areas by dating deposits directly on the beach surface and those associated with house construction and use, as well as uppermost deposits (Campbell et al., this issue). This bias is common in palaeodemographic studies (Rick, 1987), and usually represents attempts to constrain the timing of specific events or to bracket cultural phases.

While we can conclude that the assumptions that underlie palaeodemographic reconstructions are not invalidated in the case of Čḯxʷicən, we acknowledge that the radiocarbon proxy is unlikely to precisely duplicate the tempo of population change or occupational intensity at the site.

2.2. The radiocarbon record: Initial observations

The earliest radiocarbon age we have from Čḯxʷicən (Beta-198745: 2480 ± 60 BP) dates the initial occupation of a newly stabilized shoreline to 2730–2360 cal BP (2-sigma limits [IntCal13, Reimer et al., 2013]; median age = 2520 cal BP). So the excavated part of the site was likely occupied by 2500 cal BP, and may have been occupied a century or two earlier (Butler et al. *a*, this issue). It is almost certain that people camped along this shoreline in earlier times, but the traces of those occupations either lie outside the excavated area or were destroyed by rising sea levels in the mid- to late Holocene.

The low density of radiocarbon samples in the early phase of site occupation, the lack of house remains, and the prominence of shells and other animal remains in the cultural deposits from this time period suggest that the site functioned for several centuries as a seasonal harvesting camp. The first evidence of permanent settlement (likely a winter village) is marked by the remains of house floors in the excavated deposits. The transition from the camp phase to the village phase occurred about 1300 years ago.

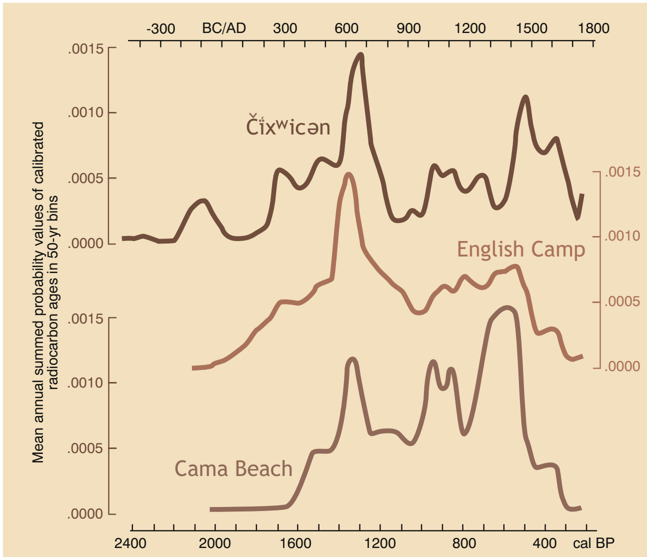

Fig. 2. Summed probability density function (50-yr bins) of calibrated radiocarbon ages at Čı́xʷicən, English Camp, and Cama Beach.

The summed probability density function (spdf) from the calibrated radiocarbon ages in the site catalog, binned into 50-year silos[3] to reduce noise, yields the distribution shown in Fig. 2. The spdf index suggests that the intensity of occupation at Čı́xʷicən varied somewhat during the centuries in which it functioned as a seasonal camp, and then increased rapidly. The spdf peaks at about 1300 cal BP, coincident with the first evidence of house construction within the excavated area, and then falls dramatically over the course of the next two centuries (Fig. 2). There was apparently a brief period of more intense occupation, a subsequent fall between about 700–600 cal BP, and second peak at about 500 cal BP. The archaeological record of occupation from that point on is ambiguous, largely as a result of industrial development of the site in the late 19th and 20th centuries, which disturbed the uppermost strata. The oral traditions of the Lower Elwha Klallam tribe and 19th-early 20th century historical records indicate that Čı́xʷicən was a substantial village during this period (Butler et al. *a*, this issue).

2.3. A null demographic model

Do these peaks and troughs in the spdf represent substantial fluctuations in the number of households setting up camp during the summer, or occupying the winter village? Or was the population in these phases quasi-stable, and the variation in the spdf is an artifact of the sampling process or the non-linearity of the radiocarbon calibration curve? We assess the latter possibility by comparing the spdf generated by a null model (representing a randomly-sampled, quasi-stable population) to the observed spdf.

Null models are widely employed as heuristic devices to test hypotheses and to delimit and investigate anomalous patterns, i.e., observed departures from expected values. The population trend at Čı́xʷicən, as it evolved from camp to village, for example, might be represented by linear, logistic, exponential, or step functions. Alternatively, a taphonomic function might be applied, if it is suspected that the older parts of the radiocarbon record have been lost to erosion, or buried to depths beyond the excavation limit.

We tested several of these options, by fitting linear, logistic, two-step, and Surovell et al.'s (2009) universal taphonomic correction to the Čı́xʷicən spdf (Fig. 3). The logistic equation yielded the lowest root-mean-square-error value (rmse; Fig. 3), and was therefore adopted as the null model, with population change modeled by a sigmoid function:

$$n(t) = n_{eq}/(n_0 + (n_{eq} - n_0))\, e^{-rt}$$

where: n_0 is the initial population, t is time, n_{eq} is the population at equilibrium, and r is the rate at which the population increases between these endpoints in this virtual settlement.

The model is trained from the observed probabilities in the Čı́xʷicən spdf. A single radiocarbon sample, representing an assumed initial settlement of the site about 2500 years ago, is followed by about 1200 years of exponential growth, equilibrating in the last 1300 years during the village phase.

We simulated the dating of this virtual village by: 1) randomly selecting calibrated ages from the IntCal13 database (Reimer et al., 2013), 2) culling ages < 200 cal BP to mimic the reluctance of archaeologists to date samples associated with historic and proto-historic materials; 3) filtering the resultant age catalog by means of a random-number generator with acceptance/rejection regions constrained by cumulative probabilities from the logistic equation; 4) randomly selecting 101 ages from this filtered list to match the total number of samples from Čı́xʷicən; and 5) replacing these calibrated ages with their equivalents in radiocarbon years as listed in IntCal13 (Reimer et al., 2013).

These virtual radiocarbon samples were calibrated using the same sequence of laboratory errors as in the site data, and the spdf of each set of 101 ages was calculated. Fig. 4 shows the resultant annual probabilities from fifty bootstrapped samples from the logistic model in 50-yr bins[3], the 5th and 95th percentile limits of these distributions, and the equivalent spdf from the site catalog.

It is apparent from Fig. 4, and from the respective coefficients of variation[4] that the observed spdf is far more variable during both the camp and village phases than its simulated counterparts, and we therefore conclude that the observed fluctuations are real, and not products of the non-linearity of the radiocarbon calibration curve. The significant departures from null model expectations consist of three troughs (at, or about 1950 to 1750 cal BP, 1150 to 950 cal BP, and 650 to 550 cal BP); and two peaks (1350–1250 cal BP and 550–500 cal BP).

2.4. The occupational history of nearby villages

If other sites in the region exhibit similar temporal patterns, that would suggest that the troughs and peaks noted above were not specific to Čı́xʷicən, but were triggered by events operating over a broader area. Only two other late Holocene sites in the vicinity of Čı́xʷicən have a catalog of radiocarbon ages that we deem sufficiently large (≥40 samples) for comparative purposes: English Camp (a.k.a British Camp, designated as 45SJ24/25), which lies in a sheltered bay on the west coast of San Juan Island (Fig. 1), and Cama Beach (45IS2), located on the west coast of Camano Island (Fig. 1).

English Camp was a Salishan winter village until British forces constructed a garrison there in the 19th century (Stein, 2000). The village site has been excavated over the course of several decades, yielding 50 radiocarbon ages on fragments of charcoal (Stein et al., 2003). The ages are listed in Supplementary File 1A, and the resultant spdf (Fig. 2) indicates that English Camp was likely first occupied a few centuries after Čı́xʷicən. House construction at English Camp apparently began about 1400 years ago, about a century or so earlier than at Čı́xʷicən.

The Cama Beach site, like Čı́xʷicən, lies on a narrow beach-spit

[3] Optimal bin size was derived by plotting deviations of bin-mean probabilities against the annual probability value of equivalent age. No obvious inflection was detected in a plot of mean deviations for bin widths ranging from 10 to 100 years; we therefore chose a middle value, thereby retaining the characteristic signature of demographic change at Čı́xʷicən while suppressing spurious noise.

[4] The mean coefficient of variation for the binned probabilities in the camp phase (2500–1300 cal BP) is 0.672 in the 50 simulations, and 1.149 in the observed data; in the village phase (1300 cal BP – 200 cal BP) the equivalent values are 0.340 and 0.558.

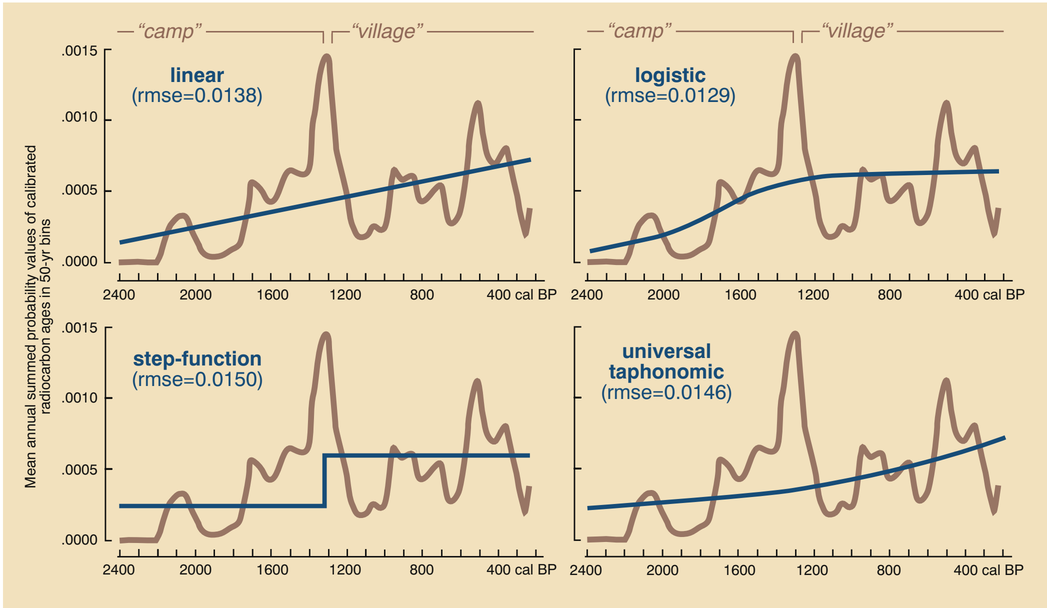

Fig. 3. Alternative null models (blue lines) and associated root-mean-square-errors of activity trends plotted against the observed summed probability distribution function (red line) of calibrated radiocarbon ages at Čḯxʷicən. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

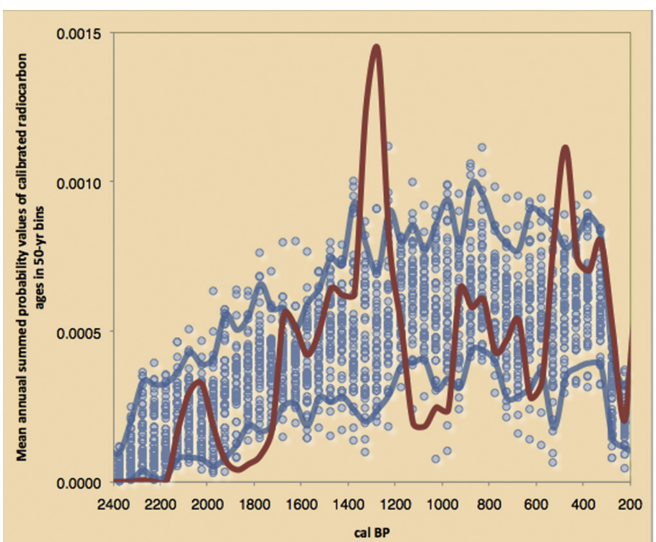

Fig. 4. Output generated by 50 bootstrapped samples of radiocarbon ages derived from a logistic equation of activity at Čḯxʷicən, compared to the observed spdf (red line). The dots represent the summed probability values in each 50-yr bin for each simulation run, and the blue lines show the 95th and 5th percentiles of the ranges of the simulated values in each 50-yr bin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

complex backed by a steep bluff. Excavation of the site by Schalk and Nelson (2010) yielded 40 radiocarbon ages on charcoal and woody detritus (Supplementary File 1B). The site was first settled about 1600 years ago, and until about 1100 years ago it served as a summer fishing and shellfish-harvesting camp. After that time houses were constructed and the site developed into a major village. The upper, proto-historic levels of the site were severely disturbed by the construction of resort buildings along the beach in the 1930's (Schalk and Nelson, 2010). The spdf from the Cama Beach site is shown in Fig. 2.

There are statistically significant correlations between the spdfs (in 50-year bins) of the three sites during the initial millennium of joint occupation (from 1600 cal BP to 650 cal BP). After that the temporal patterns vary substantially, possibly as a result of differences in the degree or spatial extent of disturbance or truncation of the uppermost strata at each site.

While we recognize that some of the peaks in these spdfs may be the result of over-sampling of temporal phases in midden strata by the excavators (particularly the initial house-building phases), the similarities that we observe among the sites, which were excavated by different crews at different times, suggests that such biases are probably minor. We propose, rather, that the variation represents real trends in occupational intensity, possibly in response to a fluctuating food supply or as a result of the impact of geologic hazards.

3. Potential controls on population: Marine resources

3.1. The Native fishery and the marine food web

On-going practices, oral traditions, and archaeological records demonstrate the diversity of marine resources procured by the Indigenous peoples of the northeast Pacific littoral (Chisholm et al., 1982, 1983; Suttles, 1990; Ames and Maschner, 1999; Butler and Campbell, 2004). Food detritus in their village middens predominantly consists of the shells of marine bivalves, but fish, marine mammal, and bird bones are also abundant (Butler and Campbell, 2004; McKechnie and Moss, 2016). The recent deployment of fine-mesh screens at archaeological excavations has revealed the importance of small fishes, especially Pacific herring (*Clupea pallasii*) in the diet of these coastal peoples (Moss et al., 2011, 2016). A synthesis of records from 171 archaeological sites by McKechnie et al. (2014) stresses herring's ubiquity and abundance; their bones comprise the majority of the fish remains at sites on the open coast of southern British Columbia. Čḯxʷicən is a further example of this pattern; some 55% of the fish bones identified to a taxonomic level below “fish” in the samples from the site as a whole are of herring (Butler et al. *b*, in this issue).

As a super-abundant forage fish, herring are major consumers of plankton and small fish, and in turn are preyed on by piscivorous fish, marine mammals and birds (Therriault et al., 2009; Levin et al., 2016). Their importance in the coastal marine food web is dramatically illustrated each spring, when masses of fish move inshore to spawn. The fish and their roe attract predators, including Pacific hake (*Merluccius productus*), Pacific cod (*Gadus macrocephalus*), salmon, dogfish (*Squalus suckleyi*), marine mammals, and sea birds. Indigenous people living in coastal villages took advantage of these "resource blooms", catching herring, harvesting their roe, and using the fish as both food and bait (Monks, 1987).

Given their fundamental role in the coastal marine food web, herring are a prime indicator species, useful as a gauge of the overall health of this ecosystem (Thornton et al., 2010). Any large-scale, long-term reduction in the availability of herring in the prehistoric era would almost certainly have led to a concomitant reduction in the number of people living along the shoreline. Over-fishing in the vicinity of a village ("exploitation depression" sensu Charnov et al., 1976) would reduce the food supply for a short time (Butler and Campbell, 2004), but those phases would not likely be coeval across a broad region. Concordant, region-wide resource depression ("microhabitat depression" sensu Charnov et al., 1976) would more likely to be attributable to sustained environmental change.

Populations of herring (and other forage fish) tend to respond dramatically to changes in the marine environment, particularly near their range limits (Soutar and Isaacs, 1974; Hunter and Alheit, 1995; Alheit and Hagen, 1997). Such short-term fluctuations in population may be discerned by detailed analysis of fish remains in cores from the deposits underlying coastal basins and lakes. Concurrent analysis of palaeoenvironmental proxies in these sedimentary archives affords an opportunity for investigators to assess environmental influences on fish populations, either directly (e.g. O'Connell and Tunnicliffe, 2001; Chavez et al., 2003; Wright et al., 2005), or indirectly, from biochemical markers of marine influence (e.g., Finney et al., 2002; Finney et al., 2010).

3.2. Fish remains from Saanich Inlet

We will likely never be certain that the apparent fluctuations in human populations at Čḯxʷicən and neighboring villages in the last two millennia result from booms and busts in the numbers of migrating herring, their predators, or other local marine resources, but there is strong circumstantial support for that contention. The evidence comes from a core (ODP-1034B) that was extracted from the seabed in a 200 m-deep basin in Saanich Inlet[5] (Fig. 1), about 55 km north of Čḯxʷicən. The 118-m long core recovered the entire post-glacial depositional sequence in the inlet (Bornhold et al., 1998; Bornhold and Kemp, 2001). Tunnicliffe et al. (2001) counted skeletal remains[6] of fish in 100-ml samples from this core, and noted that herring bones were the dominant constituent (~53% abundance), and that the number of fish remains in their samples was highly variable.

Short cores from a site about 5 km further north in Saanich Inlet suggest that the variations in herring bone frequency in the ODP core are not random, but track local fluctuations in herring abundance. O'Connell and Tunnicliffe (2001) counted herring scales in the annually-banded sediments in these short cores; the density of scales over a 30-year period at this site is highly correlated (Spearman's rho = 0.58; $p < 0.01$: Supplementary File 2) with annual fluctuations in the biomass of herring in the inlet, which predominantly congregate to spawn in a bay about 3 km northeast of the coring site (Hay and McCarter, 2015).

Fluctuations in the number of herring bones in the ODP cores are matched by contemporaneous fluctuations in diatom abundance (Tunnicliffe et al., 2001). That indicates that the local marine

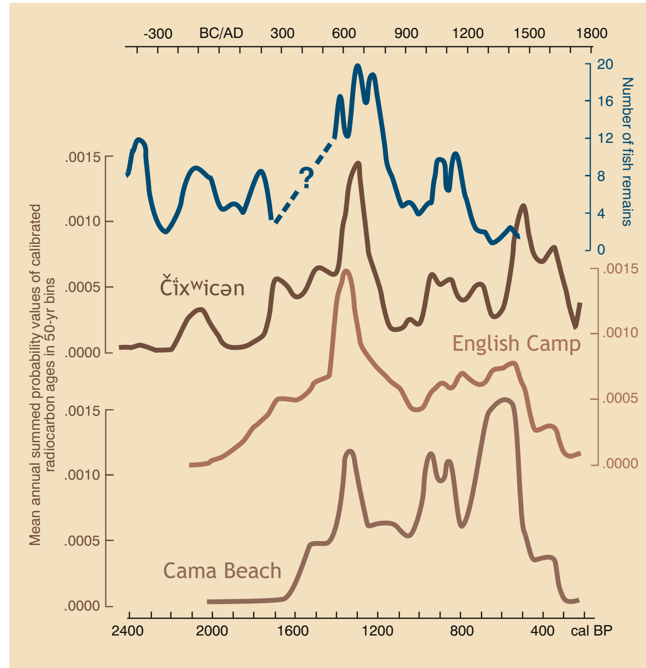

Fig. 5. Top) Number of fish remains (3-sample means) in 100 ml-samples of sediment from ODP core 1034-B from Saanich Inlet (Tunnicliffe et al., 2001). A gap between core segments is marked by the dashed line; and below) the mean annual summed probability density functions (50-yr bins) of calibrated radiocarbon ages at Čḯxʷicən, English Camp, and Cama Beach.

ecosystem, like its modern counterparts from California to Alaska, was predominantly under "bottom-up" control (Ware and Thomson, 2005) over the course of the Holocene, with changes in oceanic regime prompting phases of greater or lesser primary productivity, which then concatenated through a series of trophic linkages to the resident fish populations and their consumers. The people living in the coastal villages on the shorelines of the Strait of Juan de Fuca intercepted this food chain in several places, consuming filter-feeding shellfish and planktivorous fish such as herring and their predators.

It is perhaps not surprising therefore that a plot of the number of fish remains (as a 3-sample mean count) in the ODP core against the inferred age of the samples (see Supplementary File 3 for age determinations for this core based on IntCal13) shows a significant correlation (Fig. 5) with the population proxy from Čḯxwicən (rho = 0.59; $p < 0.01$) in the period from 1500 to 550 cal BP.

A detailed examination of the potential couplings between the climatic, ecological, and demographic elements in this relationship is beyond the scope of this paper, but it is apparent that the critical links are the role of oceanic-atmospheric regimes in the late Holocene on primary production, fish recruitment, survival, and migration, and the concomitant effects of the resultant fluctuations in fish stocks on the populations of the coastal villages.

The potential complexity of the relations between ocean climate (particularly sea-surface temperature [SST]) and forage fish stocks is illustrated by interactions between Pacific herring and their competitors and predators in the waters off the southwest coast of Vancouver Island in recent years. Herring stocks in the Gulf of Alaska tend to increase in warm [SST] years (e.g., Zebdi and Collie, 1995; Williams and Quinn, 2000a, 2000b). But, according to Schweigert (1995) and Williams and Quinn (2000b), the converse holds true for herring stocks in British Columbia coastal waters, although herring stocks on the north-central coast of the province appear to mimic those in the Gulf of Alaska (Ainsworth et al., 2008). The stocks that migrate each spring to the shallow banks off the southwest coast of Vancouver Island from Barkley Sound or through the Strait of Juan de Fuca do, however, show

[5] Tidal intrusions from the southern Strait of Georgia bring nutrients and phytoplankton into Saanich inlet. The ODP-1034 core is therefore indicative of palaeoenvironmental conditions in neighboring coastal waters, not just those in the inlet itself (Hobson and McQuoid, 2001).

[6] Only fish bones, teeth and scutes were enumerated; scales, because they were differentially preserved down-core, were not.

an inverse relationship with SST. Their numbers have declined in recent decades as the coastal waters on the continental shelf have warmed.

Given that there is a considerable degree of genetic mixing between these stocks (Flostrand et al., 2009), these varied responses to SST are unlikely to be a result of differences in ecophysiology, but appear to result from SST-triggered changes in the abundance of prey (Ware, 1991), competitors, and predators in the local pelagic community. The southern stocks, unlike their northern counterparts, are subject to competition from Pacific sardines (*Sardinops sagax*), and intense predation (and competition) from larger races of Pacific hake (Ware and McFarlane, 1995). Until the mid-1970s these large hake were summer migrants to the banks off southwestern Vancouver Island from their spawning grounds off southern California. Since the late-1970s, however, their numbers have increased dramatically as a result of warming of these coastal waters, and many are now resident year-round (Benson et al., 2002). They are now, along with northern fur seals and groundfish, major predators on these herring stocks (Schweigert et al., 2010). Pacific sardines, which feed on many of the same prey as herring, recolonized these banks on the continental shelf in the late 1980s, and now millions of sardines compete for food each summer (Schweigert et al., 2010). The relationship between these herring stocks and SST can therefore be envisaged as a dome-shaped function – at lower temperatures herring recruitment increases as surface waters warm and primary productivity increases (i.e., "bottom-up" control), until at some threshold temperature an influx of competitors and predators drives numbers down (i.e., "top-down" control).

We acknowledge that the chronological resolution of the zooarchaeological record, even at an intensively-dated site such as Čǐxʷicən, is far too broad to allow us to describe the effects of changes in SST in the late Holocene on the intertwined fates of herring, sardines, hake, and their human predators on an annual – multi-decadal scale, but it should be possible to elucidate the effects of changing environmental conditions on the availability of marine resources at century – millennial scales from palaeoclimatic records.

3.3. Marine resources and late Holocene palaeoclimate

It would appear to be self-evident that the most appropriate reconstructions of SST in the late Holocene should be derived from proxies in local marine sedimentary archives. Variations in diatom and dinoflagellate assemblages and the abundance of biogenic opal in the sediments in Effingham Inlet, on the southwest coast of Vancouver Island, for example, have all been proposed as proxies that track thermal regimes offshore (Hay et al., 2007; Ivanochko et al., 2008; Bringué et al., 2016). But, as these authors acknowledge, the abundance and composition of these protist communities and their diagenetic products may be as strongly influenced by the salinity and turbidity of surface waters, or the frequency of bottom-water renewal events in the fjord, or by the intensity of grazing by zooplankton, as by offshore SST.

Reconstructions of changes in oceanic climate from the record of marine microfossils in fjord basins may therefore not be as reliable as indicators of oceanic climate as some proxies derived from terrestrial sedimentary archives. Of these, the record of glacial advances and retreats in the Pacific Northwest, representing responses to multi-decadal to millennial-scale shifts in atmospheric temperature (and, to a lesser extent, moisture supply), is likely the most relevant in the context of this paper.

Late Holocene (< 2500 ^{14}C BP) glacial dynamics in the Coast and Cascade mountains of southwestern British Columbia and northern Washington State are constrained by 91 radiocarbon ages (Osborn et al., 2012; Mood and Smith, 2015; Supplementary File 4), derived from samples of wood from the outer rings of ice-sheared tree stumps or logs, or from branches, twigs, or peat in palaeosols below or within morainal deposits in glacier forefields.

Although the probability density function derived from these ages has a strong taphonomic bias (older deposits are more deeply buried, and therefore less accessible), there appear to have been two major ice advances in the last 2500 years. The first advance phase starts at or shortly before 1500 cal BP, and ends at, or shortly before, 1300 cal BP. The second advance phase begins at or about 1000 cal BP, is followed by a small-scale retreat at about 850 cal BP, and culminates in a major advance beginning at or about 600 cal BP (Fig. 6A).

Such changes in glacier frontal position are triggered by climatic conditions that influence winter snowfall and summer melt volumes. The general agreement between the advance-retreat phases in the Pacific Northwest and reconstructions of summer temperatures from tree-ring width indices from western North America (Trouet et al., 2013) and Eurasia (Büntgen et al., 2016) indicates that the glacial phases are local expressions of hemispheric-global changes in climate (Fig. 6).

The initiation of the first advance precedes the onset of "Late Antique Little Ice Age" (LALIA; also known as the "Dark Ages Cold Period" (Helama et al., 2017)), that Büntgen et al. (2016) date to ~1450 cal BP by about a century, but their reconstruction (generalized in our Fig. 6C) indicates that temperatures were beginning to decline considerably earlier, at or about 1750 cal BP, at the end of the "Roman Warm Period" (RWP). The termination of this advance in the Coast-Cascade mountains closely matches their cited LALIA end-date of 1290 cal BP (Fig. 6).

The subsequent warming phase (the "Medieval Warm Period" [MWP]) is interrupted by a brief, slightly cooler episode at ~950 cal BP (Fig. 6B, C), which may be represented by the minor glacial advance at ~1000 cal BP. Peak warmth in the MWP occurs one to two centuries later, with a transition to the lower temperatures of the "Little Ice Age" (LIA), at ~750 cal BP. The coldest episodes in the LIA are centered on ~650 cal BP, ~470 cal BP, and ~250 cal BP (Fig. 6B, C). All of these appear to be represented in the record of glacial advances in the Pacific Northwest by peaks in the spdf of overridden trees (Fig. 6).

The global climatic pattern is not only echoed by glacial advances and retreats in the local mountains, but is also mirrored in the record of fish remains in Saanich Inlet (Fig. 6). Unfortunately, there is a ~2 m wide gap between segments of the long core (ODP 1034-B) from Saanich Inlet, which results in a gap in the fish-remains record of ~250 years duration at the time of the LALIA. Both the RWP and MWP are marked by an abundance of fish bones in the sea-floor deposits, particularly during the initial transition to warmer conditions. The results suggest that forage fish stocks may have increased initially as a result of enhanced growth and greater survivorship in warmer waters, and then, as at present, declined as a result of greater competition and predation as waters continued to warm.

4. Potential controls on population: Seismic hazards

4.1. Seismic hazards: The geological record

If, given the evidence presented so far, we conclude that the occupational history of Čǐxʷicən primarily reflects fluctuations in the local availability of marine resources, does the fact that the village lies in the zone that emergency managers consider to be at risk from locally-generated tsunamis play any part in its history?

The local plate-boundary, forming the northern end of the Cascadia subduction zone (Fig. 7A), lies about 220 km to the west of Čǐxʷicən. It has ruptured on several occasions since people first occupied the village site (Hutchinson and Clague, 2017). Those earthquakes have been dated from turbidites (debris flow deposits in submarine canyons that record severe shaking; Goldfinger et al., 2012), buried soils in coastal lowlands that record episodes of coseismic subsidence (Atwater et al., 2004), and sand beds in coastal marshes and lakes that record high-energy transport of marine sediment by tsunamis. The most accurate ages are from the stumps of trees that were entombed in intertidal mud during episodes of coseismic subsidence (Atwater et al., 2004). These studies indicate that the northern plate boundary ruptured, and

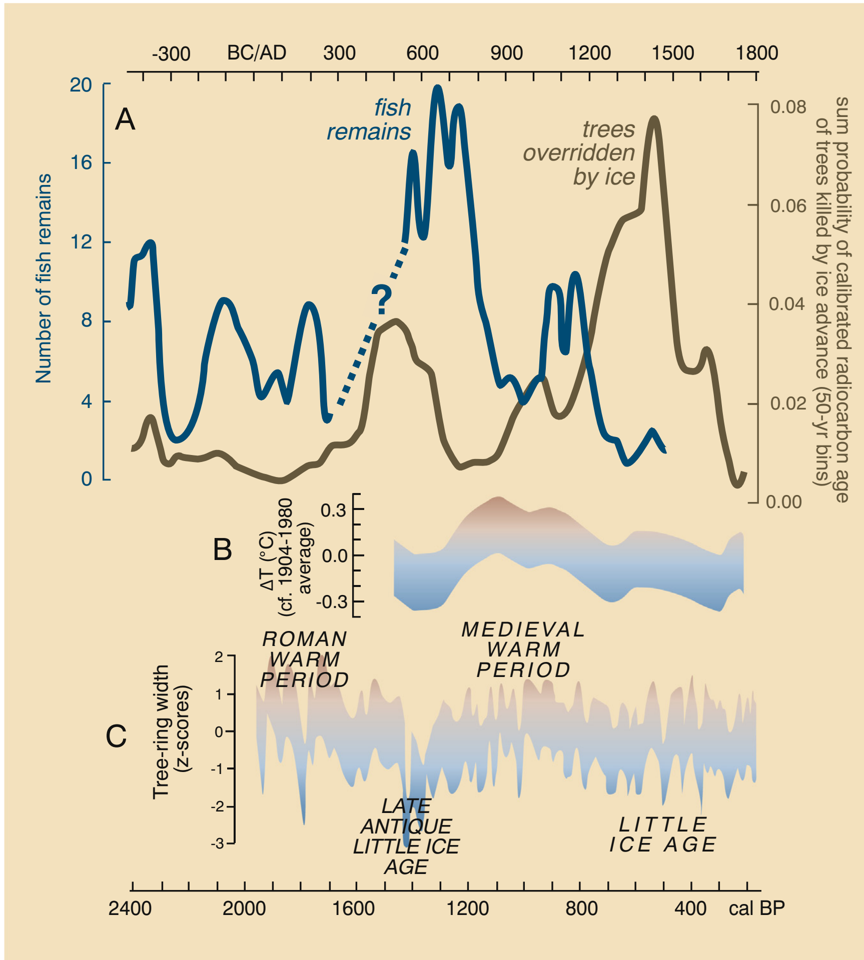

Fig. 6. A) Number of fish remains (3-sample means) in ODP core 1034-B from Saanich Inlet (Tunnicliffe et al., 2001), and calibrated age probability distribution of trees killed by glacial advances in southwest British Columbia and adjacent areas of Washington State (this study);
B) Palaeotemperature indices from western North America (redrawn from Trouet et al., 2013), and
C) Eurasia (redrawn from Büntgen et al., 2016).

generated potentially devastating tsunamis, in 1700 CE (250 cal BP – demarcated by buried soil “Y” in Willapa Bay [Figs. 7A, 8]), and about 600 cal BP (no buried soil in Willapa Bay), 850 cal BP (soil “W”), 1250 cal BP (soil “U”), 1550 cal BP (soil “S”), and 2520 cal BP (soil “N”). These events, plus at least three others, likely associated with local crustal earthquakes, are recorded in Discovery Bay, located about 50 km to the east of Čı́xʷicən in the Strait of Juan de Fuca (Fig. 1B), by thick sand beds marking tsunami inundation of the marshes at the head of the bay (Williams et al., 2005; Garrison-Laney, 2017).

Trees entombed in intertidal mud at Willapa Bay by coseismic subsidence during earthquake “N” yield a calibrated age (2650–2430 cal BP; 2-sigma limits [Atwater et al., 2004; Hutchinson and Clague, 2017]) that is statistically indistinguishable from the oldest age from Čı́xʷicən. It is tempting to consider the possibility that survivors displaced from nearby sites by the tsunami triggered by earthquake “N” camped at Čı́xʷicən in its aftermath, and founded the settlement there. Was Čı́xʷicən a safe haven, or did more recent plate-boundary earthquakes (Fig. 8) prompt temporary abandonment of the site?

Inter-plate earthquakes at the Cascadia convergent margin during the late Holocene are estimated to have varied from $M_w \sim 9$, in the case of the 1700 CE (250 cal BP) event, to a minimum of $M_w \sim 8.7$, in the case of the penultimate event at about 600 cal BP (Rong et al., 2014). The relative energy release from the latter, and the resultant tsunami, was therefore likely to be about 30% smaller than in the 1700 CE earthquake (Kanamori, 1977; Abe, 1989). The five events that Atwater et al. (2004) document during the 2500-year occupation of Čı́xʷicən are therefore unlikely to have all been equally damaging, and the effects on the settlement may consequently have varied considerably.

4.2. Seismic hazards: Tsunami models

The principal hazards for people living in coastal settlements during these seismic events are severe shaking, and inundation by tsunamis. If recent events at other subduction zones are a reliable guide, shear waves released by a $M_w \sim 9$ earthquake induce severe ground-shaking for 3 to 5 min. Traveling at velocities of ~200–400 m s^{-1} through the wet sandy substrates of shoreline villages such as Čı́xʷicən, the shear waves would likely cause some of the plank-houses to collapse. The risk of injury or death for survivors of the earthquake would be greatest in the next 24 h as tsunamis made landfall.

The threat to human life from Cascadia plate-boundary earthquakes has prompted the development of computer models to simulate tsunami propagation and run-up. The models developed by Cherniawsky et al. (2007), and Cheung et al. (2011), see also (AECOM Canada Ltd., 2013), predict that the first tsunami waves reach the shoreline in the vicinity of Čı́xʷicən about 70 min after the earthquake. The largest wave (ca. 2.9 m above mean tide level [Fig. 7], and flowing at ca. 1 m/s across the base of Ediz Hook [Fig. 7]) occurs about two hours later. If that wave coincided with low tide, the village site might not be inundated. But if the

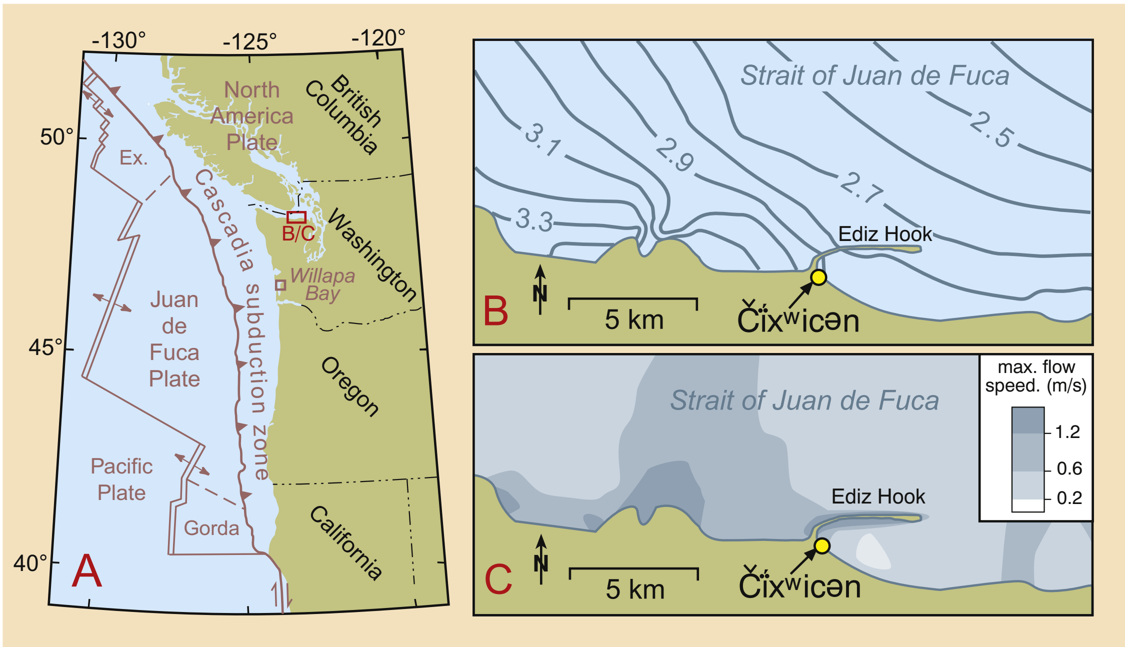

Fig. 7. A. Northwestern North America showing tectonic plate boundaries and the Cascadia subduction zone (triangles).
B. Inferred maximum water level (in metres above mean water level, augmented to include coseismic subsidence) in the vicinity of Čɪ́x̣ʷicən during a tsunami triggered by a "typical" giant earthquake on the Cascadia megathrust; and
C. Maximum flow speed (m/s) of the tsunami wave in the vicinity of Čɪ́x̣ʷicən.
Source: B and C are redrawn from maps in the report by AECOM Canada Ltd. (2013), based on the NEOWAVE model of Cheung et al. (2011).

tsunami coincided with high tide, then houses, canoes, fishing gear and food supplies would almost certainly be washed away. Few people in the run-up zone would survive.

4.3. Seismic hazards: The Čɪ́x̣wicən record

Can any episodes of tsunami inundation be identified in the deposits at Čɪ́x̣wicən? The original excavators of the site identified a variety of culturally depauperate deposits, which they classed as beach sands, midden-stained sands, beach berms, or swash deposits (Campbell et al., this issue). Are the beach berms a result of coseismically induced land-level changes? And could the swash deposits be the product of high-energy, landward-directed flows of sea water during a tsunami?

The radiocarbon ages from these sand-rich horizons are all derived from reworked cultural material, so they are all maxima for the emplacing event. Plots of the probability density functions of each set of radiocarbon ages (Fig. 9) indicate that they seem to be primarily associated with plate-boundary earthquake U, at about, or shortly after, 1250 cal BP. Tsunami deposits from earthquakes S and Y may also be present in the midden, but they appear to be of limited extent, and there's no stratigraphic evidence of overwash by the penultimate event.

Did these palaeotsunamis result in abandonment of the village or a

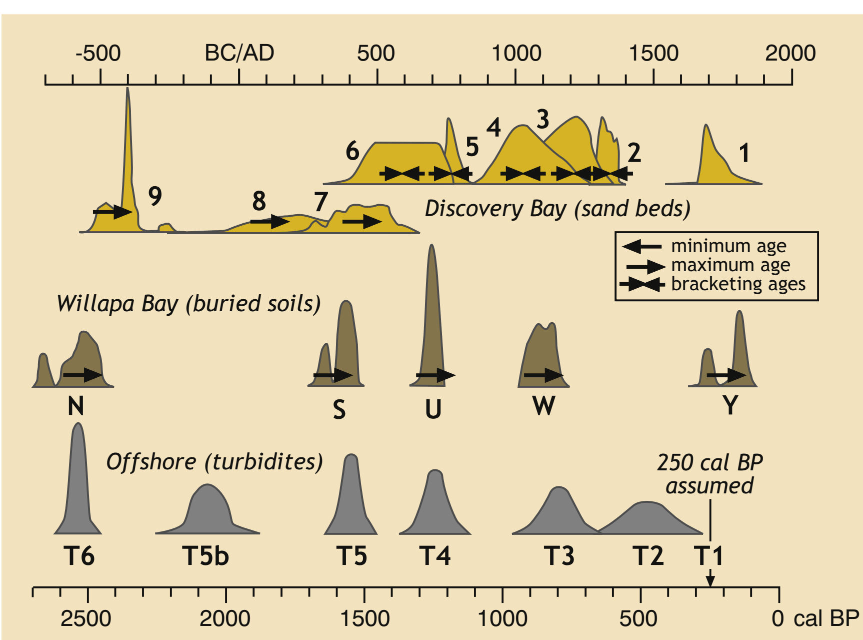

Fig. 8. Probability density functions of calibrated radiocarbon ages of inferred plate-boundary earthquakes at the northern Cascadia subduction zone from geological evidence (data: Discovery Bay [beds 1–6: Garrison-Laney, 2017; beds 7–9: Williams et al., 2005]; Willapa Bay [Hutchinson and Clague, 2017, from data in Atwater et al., 2004; Atwater and Griggs, 2012]; turbidites [Goldfinger et al., 2012]).

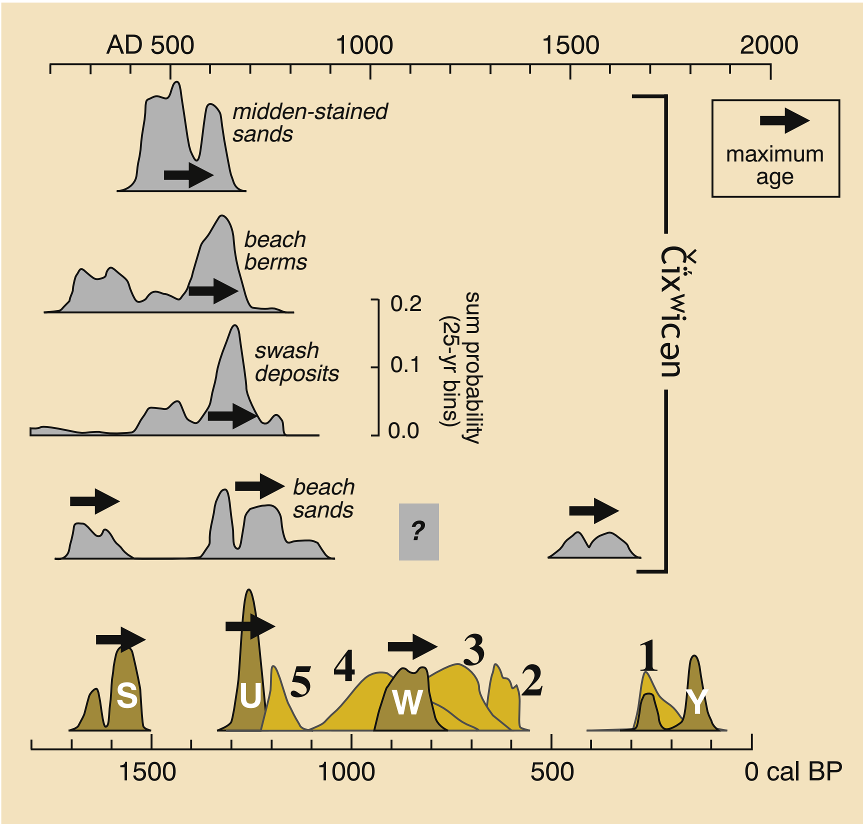

Fig. 9. Above) Age of sandy deposits at Čı́xʷicən and, Below) calibrated radiocarbon ages of inferred plate-boundary earthquakes at the northern Cascadia subduction zone from geological evidence (dark gray fill = buried soils [Atwater et al., 2004; Atwater and Griggs, 2012]; light gray fill = high-resolution ages from tsunami deposits, Discovery Bay [Garrison-Laney, 2017]).

substantial decline in village population for an extended period? Some of the apparent falls in the spdf appear to correlate with Cascadia earthquakes, shown in Fig. 8 by the high-resolution ages on buried soils in southwest Washington and the tsunami sand beds at Discovery Bay. To test this hypothesis we compare the record at Čı́xʷicən with that at English Camp and Cama Beach, where the risk of tsunami inundation is slight. According to the model developed to evaluate tsunami hazards for the San Juan Islands from a $M_w \sim 9$ earthquake at the plate boundary, the maximum wave height is likely to be < 1 m in Garrison Bay, adjacent to English Camp (Fig. 13 in Gica et al., 2013). The AECOM Canada Ltd. (2013) model shows a maximum wave height of < 1 m in Garrison Bay, and ≤ 1 m on the west coast of Camano Island, in the vicinity of Cama Beach (Fig. 1).

The mix of ages of reworked cultural material in the sandy layers in

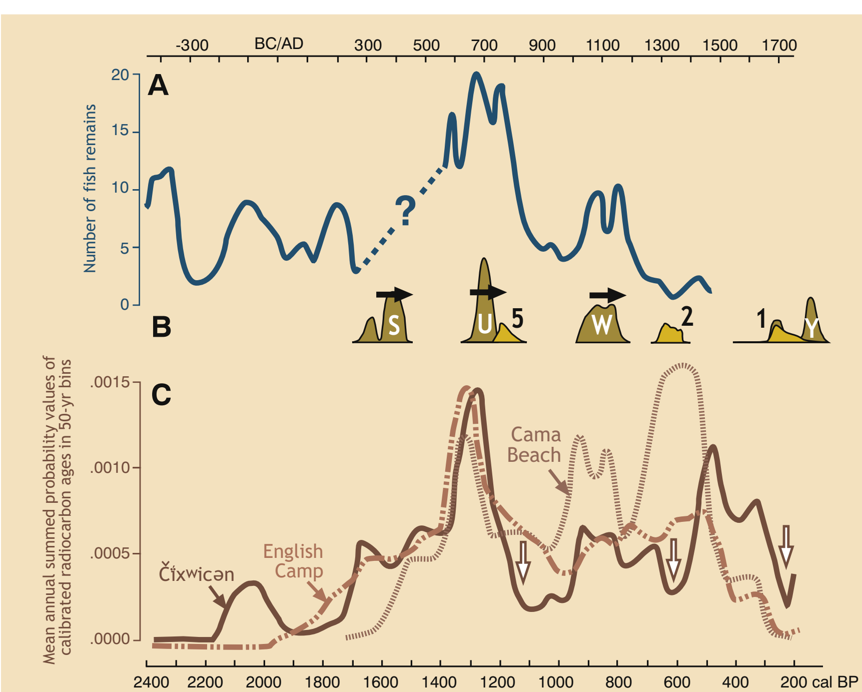

Fig. 10. A) Number of fish remains (3-sample means) in 100-ml samples of sediment from ODP core 1034-B from Saanich Inlet;
B) Ages of inferred plate-boundary earthquakes at the northern Cascadia subduction zone from geological evidence (dark gray fill = buried soils [Atwater et al., 2004; Atwater and Griggs, 2012]; light gray fill = high-resolution ages from tsunami deposits, Discovery Bay [Garrison-Laney, 2017]);
C) Summed probability density function (50-yr bins) of calibrated radiocarbon ages at Čı́xʷicən and English Camp and Cama Beach. Outlined arrows mark potentially significant impacts of tsunamis at Čı́xʷicən.

the midden at Č́íxʷicən (Fig. 9), and the discrepancies between the spdf record at Č́íxʷicən and English Camp and Cama Beach (shown by the downward arrows in Fig. 10), lead us to conclude that Č́íxʷicən may have been devastated on two occasions by tsunamis in the last 2500 years, and suffered minor damage at other times.

As noted above, wave-transported charcoal fragments in the sandy deposits in the midden predominantly date from the period immediately prior to earthquake U. The Č́íxʷicən spdf value is also much lower in the century following this event than in the preceding century. While this may be due in part to a concurrent climate shift and a resultant reduction in fish stocks, the fact that the nadir of the Č́íxʷicən spdf is much lower than that from English Camp and Cama Beach suggests that the tsunami associated with earthquake U may have led to a reduction in the village population, either because of a high death toll, or because the survivors sought refuge elsewhere. The aftereffects of earthquake U appear to have been particularly prolonged, but that may just reflect the effects of an extended period of relative resource scarcity, which appears to have continued for at least another 200 years (Fig. 10).

Unfortunately, the strata in the Č́íxwicən, English Camp and Cama Beach middens representing the immediate pre-contact period have been truncated and disturbed; the effects of events in the immediate pre-contact period on village populations are therefore unknowable. Was Č́íxʷicən damaged, for example, by the shaking and tsunami that accompanied the Cascadia plate-margin rupture of January 26, 1700? The stratigraphic and chronological evidence concerning the impact of this event is equivocal, and the spdf suggests that even if part or all of the village was abandoned after the tsunami, it was likely rebuilt shortly thereafter.

The preceding and intervening earthquakes (S, W and the event marked by sand bed 2 at Discovery Bay) were apparently not as calamitous as U or Y. While the spdf from Č́íxʷicən consistently falls below that at English Camp and Cama Beach at those times, the differences are relatively modest (Fig. 10), which suggests to us that the effects of those tsunamis were much more limited.

5. Conclusions

The spdf derived from the 101 radiocarbon ages from the Č́íxʷicən midden reflects an increase in activity at the site over the course of the last 2500 years as the occupation evolved from a seasonal camp to a winter village. The spdf suggests that the activity levels or population during these phases was variable, with considerable instability in the last 1300 years, during the village phase. Those temporal fluctuations exceed the expectations derived from a null model that assumes 1) that the intensity of occupation at the settlement grows logistically over time, and 2) that any variations result from the non-linear nature of the radiocarbon calibration curve, which was tested by sampling virtual radiocarbon ages supplied by the logistic equation.

The major departures from expectations at Č́íxʷicən are troughs in activity at, or about, 1950 to 1750 cal BP, 1150 to 950 cal BP, and 650 to 550 cal BP, and peaks in activity in the village phase at, or about 1350–1250 cal BP and 550–500 cal BP. These apparent fluctuations in the village population are echoed in the spdfs generated from the radiocarbon catalogs from the two next-best dated sites in the area: English Camp (45SJ24/25) and Cama Beach (45IS2).

The most marked peak, at 1350–1250 cal BP, is associated with development of a permanent settlement at Č́íxʷicən. That development may have been prompted by a substantial increase in marine productivity in the waters of the Strait of Juan de Fuca, as evidenced by the abundance of fish bones from this period in the sea bed beneath Saanich Inlet. A strong concordance between that record of fish remains and glacial advance-retreat phases in the Coast Mountains of southwestern British Columbia and Washington State suggests that the variable abundance of forage fish in local waters in the late Holocene is related to long-term variations in SST, which in turn reflect regional/hemispheric-scale changes in climate. Analyses of forage fish population dynamics in the last few decades in the northeast Pacific, however, suggest that this relationship is not a simple one; primary productivity and recruitment initially increase as waters warm, but an influx of competitors and predators eventually drives numbers down. The indication of shifting marine productivity based on fish remains from the seabed core, however, is at odds with the archaeo-fishbone record synthesized by McKechnie et al. (2014) that shows broad consistency in herring representation for the past 2500 years. We are unable to account for this discrepancy here, but we make these observations: McKechnie et al. (2014) summarized observations from southeast Alaska to Puget Sound; our results apply to a much smaller geographic area; and marine cores, such as that from Saanich Inlet, provide a means of tracking paleoenvironmental trends with much higher resolution than that afforded by archaeological data on site faunas.

The postulated decline in activity at Č́íxʷicən after 1250 cal BP may therefore be ascribed to the reduction in the availability of marine resources as SST increased during the Medieval Warm Period. But the fact that the contemporaneous reduction in activity at both English Camp and Cama Beach appears to have been less than at Č́íxʷicən introduces another possibility. Unlike English Camp and Cama Beach, Č́íxʷicən lies in the potential run-up zone of tsunamis generated by mega-earthquakes at the neighboring plate boundary. A giant earthquake, referred to by local geologists as earthquake "U", occurred at about 1250 cal BP, and sandy deposits in the midden at Č́íxʷicən that date from about this time may mark the inundation of the site by the resultant tsunami. The trough in the spdf after about 1250 cal BP may therefore signify a temporary abandonment or limited re-occupation of the village, rather than a reduction in the food supply. Other tsunamis from this source over the last 2500 years have apparently had more modest effects on the site, although the effects of the tsunami generated by the Cascadia earthquake of 1700 CE are difficult to determine, given the disturbance of the upper layers of the site by industrial development of the waterfront in the late 19th and early 20th centuries.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2018.04.001.

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