Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami records of January 1700

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intermediate waters in the northeast Pacific and the associated concentration of dissolved oxygen. The absence of significant lags between changes in the GISP2 climate record and shifts in the palaeo-oxygenation at Hole 893A suggest that ocean circulation is tightly linked with global climate changes through the atmosphere. We cannot distinguish whether the character of northeast Pacific intermediate water was principally controlled by variation in production of young, proximally derived intermediate waters in the north Pacific or in flux of older, distally derived waters entering the Pacific basin. Shifts in atmospheric circulation associated with Northern Hemisphere cooling can rapidly change the location and flux of intermediate waters produced in the north Pacific[40], consequently influencing the ventilation of the Pacific. Likewise, deep-water production in the north Atlantic and flux of intermediate and deep water into the Pacific Ocean are also tightly linked with climate[41]. Changes in deep- and intermediate-water fluxes can be rapidly communicated to distant parts of ocean basins by shifting the production or contribution to other water masses[42]. For example, modelled shifts in deep-water production in the north Atlantic create changes in the upper part of the water column of the north Pacific within only a few decades (J. McWilliams, personal communication). Cessation or reduction of the flux of older 'conveyor-belt' water into the Pacific would increase the relative contribution of well oxygenated, proximally derived waters to intermediate depths in the northeast Pacific, producing the inverse relationship between water-mass age and palaeo-oxygenation found at Site 893. □

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Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami records of January 1700

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GEOLOGICAL evidence shows that great earthquakes have occurred in the recent prehistoric past in the Cascadia subduction zone, off the Pacific coast of North America. The most recent event (or series of events) is dated at about 300 years ago[1–4], but the precise date and magnitude have not been determined. Geological investigations have not been able to distinguish a single giant earthquake from a series of great earthquakes occurring over a timespan of a decade or two[4], although this information is important for the assessment of future hazard[5]. We have found several tsunami records in Japan from AD 1700 with no indication of a local cause. Historical earthquake records and palaeoseismic evidence indicate the absence of a large earthquake in 1700 in South America, Alaska or Kamchatka, leaving Cascadia as the most likely source of this tsunami. The estimated time of the earthquake is the evening (about 21:00 local time) of 26 January 1700. The magnitude is estimated as 9 from the tsunami heights, in which case the earthquake ruptured the entire length of the Cascadia subduction zone[2]. These estimates are consistent with Native American legends that an earthquake occurred on a winter night[6].

No great (moment magnitude $M_w \approx 8$) or giant ($M_w \approx 9$) earthquake has been historically or instrumentally recorded in the Cascadia subduction zone, where the Juan de Fuca plate descends beneath the North American plate (Fig. 1)[5,7]. By comparison, in many other subduction zones with a similar geological setting, such as southwestern Japan or southern Chile, occurrence of great subduction-zone earthquakes has been documented. For example, Japanese historical documents describe damage from great earthquakes and tsunamis along the undersea Nankai trough, southwest Japan, approximately every 100 years[8,9]. However, the relatively short documentary history (starting in the late eighteenth century at the earliest) prevents the use of American written records to estimate the size and recurrence interval of earthquakes at the Cascadia subduction zone. Several oral traditions of natives on the coast from northern California to British Columbia describe an earthquake and tsunami of unknown date[6,10–13].

Geological evidence for subduction earthquakes in Cascadia has been accumulated in the past decade (Fig. 1)[1–3] and radiocarbon and tree-ring dating of the most recent event indicates that it occurred within a decade or two of AD 1700[3,4]. Evidence distributed from California to British Columbia indicates that the entire Cascadia subduction zone was ruptured either by one $M_w \approx 9$ earthquake or by a series of $M_w \approx 8$ events[4]. A comparison of various geological features of subduction zones[5] suggests that the maximum size of Cascadia earthquakes is $M_w \approx 9.5$. A more recent study of geological features of the overlying plate[14] suggests that the maximum size is $M_w \approx 8$.

The earthquake magnitude affects ground shaking[15] and tsunami height[16], and hence damage to humans and property. If a giant ($M_w \approx 9$) earthquake occurs in the future, the seismic and tsunami hazards in the Pacific Northwest would be considerable[5] and the tsunami would probably cause damage across the Pacific

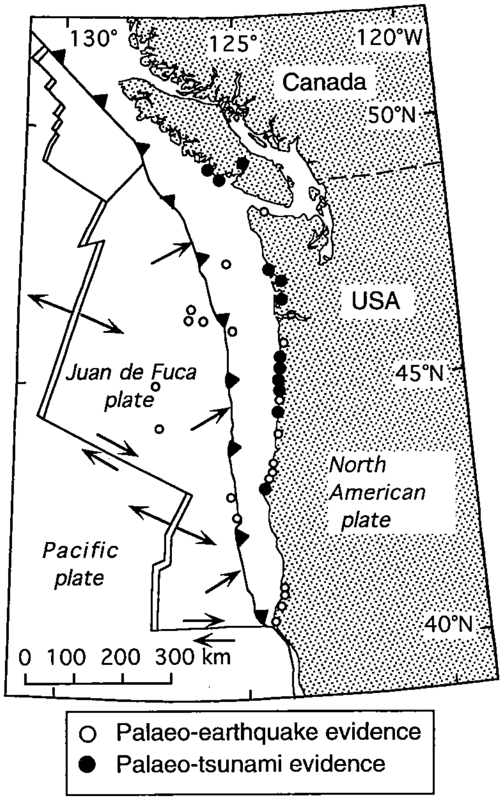

FIG. 1 Map of the Cascadia subduction zone and sites of palaeo-earthquake (open circles) and palaeo-tsunami (solid circles) evidence for the 300-year-old event(s)[2]. The palaeo-earthquake evidence includes offshore turbidites, buried soils and dead forests that indicate sudden coastal subsidence, and liquefaction on land due to ground shaking. The palaeo-tsunami evidence is sand layers deposited by tsunamis. The arrows indicate relative movements of the plates at their boundaries.

Ocean including Hawaii and Japan. It is therefore important to estimate directly the size of the past earthquake(s).

In Japan, where historical documents of earthquakes have been collected and analysed, tsunami damage from an unknown source was documented at several places on 27–28 January 1700, by the gregorian calendar[17]. At Miyako on the Pacific coast (see Fig. 2), 20 houses were damaged. The tsunami height there is estimated as 2–3 m from our field measurements based on the description of historical documents, with an error no larger than 0.5 m. At Otsuchi, about 30 km south on the coast, another documents describes a tsunami arriving around midnight on 27 January, inundating rice paddies and damaging two houses. We estimate the tsunami height as 3 m. At Tanabe, approximately 1,000 km southwest along the coast, flooding of a storehouse floor the next morning (28 January) was reported, indicating a 2-m tsunami. In addition to these three localities, independently reported in four different documents, a tsunami of unknown height on that date was documented at two other locations, Nakaminato and Miho (Fig. 2).

These waves have features characteristic of a far-field tsunami. The wide and apparently uniform distribution of water heights (Fig. 2) excludes the possibility of a meterological origin such as a storm surge. Most storm surges in Japan are caused by typhoons, which are observed only from August to October. In fact, the weather on 27–28 January 1700 was reported to be sunny or cloudy in central Japan. There is no record of an earthquake in Japan on that day, which excludes the possibility of a tsunami from a local earthquake. The Pacific coast of Japan has experienced tsunamis from far-field earthquakes around the Pacific Ocean several times in this century. For example, the tsunami from the 1960 Chilean earthquake (M_w 9.5) travelled across the Pacific Ocean in about 24 hours and caused extensive damage including about 140 fatalities in Japan[18]. The tsunamis from the 1964 Alaska (M_w 9.2) and 1952 Kamchatka (M_w 9.0) earthquakes were much smaller (Fig. 2) yet caused some damage. The smaller tsunamis were partly due to the directivity effect; tsunami heights are usually smaller in the direction parallel to the orientation of the fault[19]. Abe[20,21] defined a tsunami magnitude scale, M_t, which represents an earthquake size estimated from observed tsunami heights and has been calibrated in such a way that it is approximately equal to the moment magnitude M_w.

We estimate earthquake magnitudes for possible source regions of the 1700 tsunami and examine historical and geological evidence for such an event in each region. The possible sources

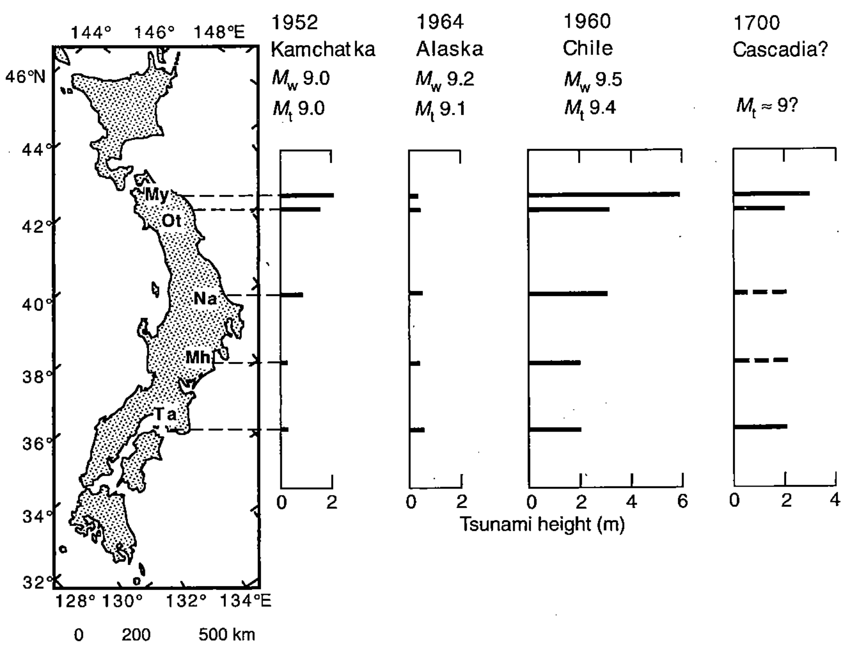

FIG. 2 Tsunami heights along the Japanese coast (at the locations where the AD 1700 tsunami was observed) from the 1952 Kamchatka, 1964 Alaska and 1960 Chile earthquakes, in addition to the 1700 tsunami from an unknown source[18] (My, Miyako; Ot, Otsuchi; Na, Nakaminato; Mh, Miho; Ta, Tanabe). Earthquake moment magnitude M_w and tsunami magnitude M_t are also shown for each event. The dashed lines for the 1700 tsunami indicate that the tsunamis were observed, but the estimation of heights is difficult.

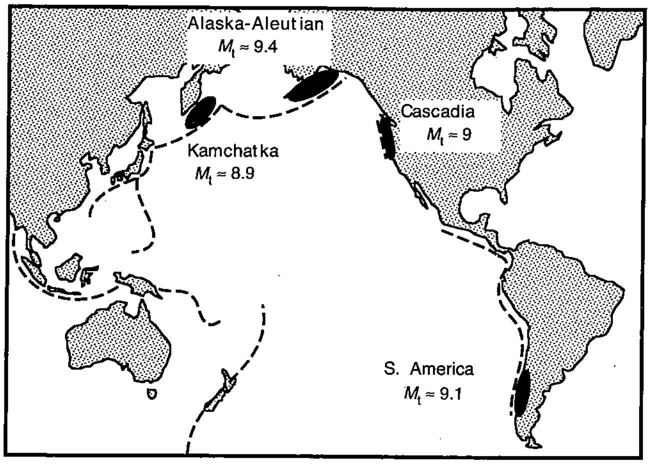

FIG. 3 Possible source regions for the 1700 tsunami observed in Japan and the estimated earthquake size M_t derived from the tsunami heights. We used $M_t = \log H_t + B$ where H_t is the local mean tsunami run-up (or inundation) height in metres, which has been shown to be equal to twice the peak-to-trough amplitude measured by tide gauges[21]. We used $H_t = 2$ m from our observations. The constant B is 8.8 for South America, 9.1 for Alaska–Aleutian and 8.6 for Kamchatka sources. Maximum tsunami run-up height on land has been shown to be equal to $\sim 2H_t$ (refs 21, 29). If we use the maximum observed height (3 m at Otsuchi and Miyako) as the maximum run-up height, then the M_t estimates are 0.1 smaller than those shown here, which indicates a possible error range. For the Cascadia source, however, both the M_t and error estimates are difficult because of lack of knowledge of the appropriate value for B.

of the 1700 earthquake besides Cascadia are South America, Alaska–Aleutian and Kamchatka[20]. If the tsunami came from South America, the earthquake would be $M_t = 9.0$–9.1; for the Alaska or Aleutian source $M_r = 9.3$–9.4; and for the Kamchatka source $M_t = 8.8$–8.9. Written documents of past earthquakes exist for South America around AD 1700 and such a great earthquake should have been documented. For example, the 1687 Peru (Callao) earthquake (M 7.6), the 1730 Valparaiso earthquake (M 8.7) and 1751 Concepción earthquake (M 8.5) generated tsunamis and were recorded in Japan[18,22,23]. However, there is no corresponding earthquake record in South America for 26 January 1700. For the Kamchatka region, Russian settlers started to immigrate in the 1680s, and the oldest record of an earthquake is 1737[24]. There is no written record or corresponding geological evidence for a large earthquake in 1700 (V. K. Gusiakov, personal communication). In addition, tsunami height from a Kamchatka source would decay with distance along the Japanese coast as demonstrated by the 1952 earthquake (see Fig. 2). Tsunami heights from earthquakes in Alaska or the Aleutian Islands are not very large in Japan because of the directivity effect. For example, they were mostly less than 0.3 m for 1964 Alaskan earthquake (M_w 9.2). Therefore, to produce the observed tsunami heights in Japan, the earthquake source must be larger. There has been no geological or historical evidence found in the region for such an event[25,26]. On the other hand, palaeoseismological evidence for a great or giant earthquake exists in the Cascadia subduction zone, hence we conclude that Cascadia is the most likely source of the 1700 tsunami.

If the 1700 tsunami came from Cascadia, we can estimate the origin time and magnitude of the earthquake. The earliest documented tsunami arrival time was around midnight on 27 January Japan time, or around 15:00 on 27 January GMT. Because tsunami travel time from Cascadia to Japan is about 10 hours, the earthquake origin time is estimated at around 5:00 on 27 January GMT or 21:00 on 26 January local time in Cascadia. This time is consistent with Native American legends that an earthquake occurred on a winter night[6].

We estimate the moment magnitude of this earthquake to be 9. Although the tsunami magnitude formula[20] has not been established for a Cascadia earthquake owing to lack of instrumental data, the estimated magnitude values for all other possible regions are about 9 as we have already seen (Fig. 3). We can also simulate tsunami propagation across the Pacific Ocean by applying a finite-difference method to real bathymetry data[27]. Preliminary computations indicate that a Cascadia earthquake with $M_w \approx 8$ produces only a 0.3-m tsunami in Japan, too small to cause damage and easily missed if it happened at night. If the earthquake size is $M_w \approx 9$ (Fig. 4), the tsunami height becomes 2 m, large enough to cause damage. A recent earthquake provides observational support in a reciprocal way; an earthquake ($M_w = 8.2$) occurred in the Kuril Islands, near Japan, on 4 October 1994[28], and the tsunami heights were only 0.3 m or less on the Pacific coast of California, Oregon and Washington. A Cascadia earthquake with $M_w \approx 8$ would therefore produce similar tsunami heights in Japan. (The rupture length of an $M_w \approx 8$ earthquake is only $\sim$ 100–200 km, so that directivity effects are negligible.) An earthquake with $M_w \approx 9$ extending along the entire Cascadia zone, on the other hand, would cause a damaging tsunami in Japan, which lies in the direction perpendicular to the fault, because of the directivity effect as well as the larger deformation of the ocean bottom. □

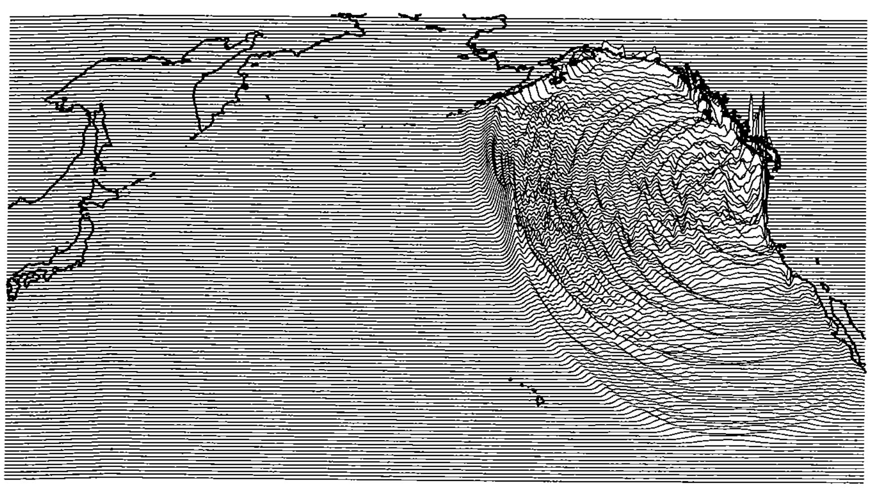

FIG. 4 Snapshot of computed tsunami propagation across the Pacific Ocean from a Cascadia earthquake. The tsunami propagation is simulated using a finite-difference method[27] and digital bathymetry data of the area shown. The ocean-bottom deformation calculated from an M_w 9 earthquake extending along the entire Cascadia subduction zone is used as an initial condition. Water height distribution 4 hours after the earthquake is shown here. The peak water height in the central Pacific north of Hawaii is about 1 m. The large tsunami height towards Japan is due to the directivity effect; the tsunami amplitude is larger in a direction perpendicular to the fault orientation.

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Manufacture and use of hook-tools by New Caledonian crows

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Tool behaviour in wild birds has been described as mostly stereotyped[1,2], and tool manufacture involves little modification of material[3–5]. Here I report in New Caledonian crows *Corvus moneduloides* the manufacture and use of two different types of hook tool to aid prey capture: hooked-twig and stepped-cut barbed pandanus leaf. Crow tool manufacture had three features new to tool use in free-living nonhumans: a high degree of standardization, distinctly discrete tool types with definite imposition of form in tool shaping, and the use of hooks. These features only first appeared in the stone[6] and bone[7] tool-using cultures of early humans after the Lower Palaeolithic[6,7], which indicates that crows have achieved a considerable technical capability in their tool manufacture and use.

Crows are forest birds endemic to New Caledonia, where they are omnivores and live in family groups[8]. Like Corvids generally[9–14] they are resourceful, for example manipulating twigs with their bills to search for prey in dead wood[15] and dropping *Aleurites moluccana* nuts onto rocks to get their seeds. In rainforest on Pic Ningua (950–1,300 m above sea level), I observed non-banded, non-aged and non-sexed crows between November 1992 and March 1995 in all months except January. On 52 different occasions between 07:00 and 15:30 I observed tool behaviour by one or more (up to four) birds. Observations were made of four crows manufacturing tools and 68 crows using or carrying tools. On average, three birds (range, 1–9) were present on each occasion. Crows used tools in holes in living and dead wood (Fig. 1*a*,*b*) and among the bases of palm and *Freycinetia longispica* (Fig. 1*c*) leaves, where they captured unidentified prey. I found larvae, spiders, millipedes, weevils, cockroaches, flatworms, amphipods, isopods, centipedes and earwigs at similar search sites.

Crows searched many sites in different trees with the same tool. The longest period I could stay in visual contact with a tool-using bird was 30 min. I could not establish tool life because birds changed foraging localities frequently, taking their tools with them. Tools I collected from crows I frightened away or those they dropped in my presence were of fresh plant material.

Between foraging episodes, crows often transferred their tools to their feet or placed them in a secure position on their perch, retrieving them with their bills before departing (Orenstein[15] observed a bird put down a tool-like object, then pick it up soon after and fly off with it). Two birds changed trees after putting down their tools, returning within minutes to retrieve them. When feeding on prey, birds left tools in search sites or transferred them to their feet. In the breeding season I observed an adult with both

TABLE 1 Data on stepped-cut tool cutouts from *Pandanus* spp. trees at two areas on Pic Ningua, and one at Mt. Cindoa.

Tree no.	No. cutouts collected per tree	No. cutouts estimated as present	Mean cutout length (cm) for each area/ s.e.m./(range)	Mean no. of steps per cutout for each area/ s.e.m./(range)
Pic Ningua (area 'A')				
1	13	17		
2	23	30		
3	18	21	14.95/0.172/	3.10/0.037/
4	37	53	(10.6–22.2 cm)	(2–5 steps)
5	14	15		
Pic Ningua (area 'B')				
6	17	18		
7	52	72		
8	23	28	16.65/0.170/	3.11/0.037/
9	51	65	(12.1–24.9 cm)	(2–6 steps)
10	14	14		
Mt Cindoa				
11	9	9		
12	10	10		
13	5	5	20.65/0.644/	3.49/0.102/
14	7	7	(11.8–40.0 cm)	(2–5 steps)
15	12	13		

Pandanus spp. trees can be single or multitrunked, with long, narrow leaves at the top of a trunk that spiral outwards and upwards around it. Trees 12 and 15 were double-trunked. I chose trees from two separate areas on Pic Ningua (minimum distance separating the trees between the two areas was 900 m) to try and detect differences in the structure of tools manufactured by crows. I chose a tree from a distance without knowledge of the number or shape of cutouts on it, and finally selected it if sufficient cutouts were present (> 9 at Pic Ningua; > 4 at Mt Cindoa). The five selected trees within each area were widely distributed. I removed as many undamaged cutouts as possible from living leaves (cutouts were mostly near leaf bases). I measured cutout length (length of missing leaf edge) off the (undried) cutout shape I outlined on paper. Mean cutout length was different between all three areas when the significant variation between trees within each area was removed (Nested ANOVA, $F = 21.88$, d.f. = 2, $P \ll 0.05$; and $F = 4.37$, d.f. = 12, $P \ll 0.05$, respectively). Available space (estimated number of cutouts present) on leaf edges of individual trees at Mt Cindoa and Pic Ningua was not associated with the mean cutout lengths for the trees (Pearson correlation coefficient, $r = -0.0682$, $n = 5$, $P \gg 0.05$, and $r = 0.165$, $n = 10$, $P \gg 0.05$, respectively). The number of stepped-cuts (the square root normalized data) on cutouts was different between Pic Ningua (data for areas A and B combined) and Mt Cindoa when cutout length was accounted for (ANCOVA, F (area) = 9.72, d.f. = 1, $P \ll 0.05$; and F (length) = 3.29, d.f. = 1, $P > 0.05$).

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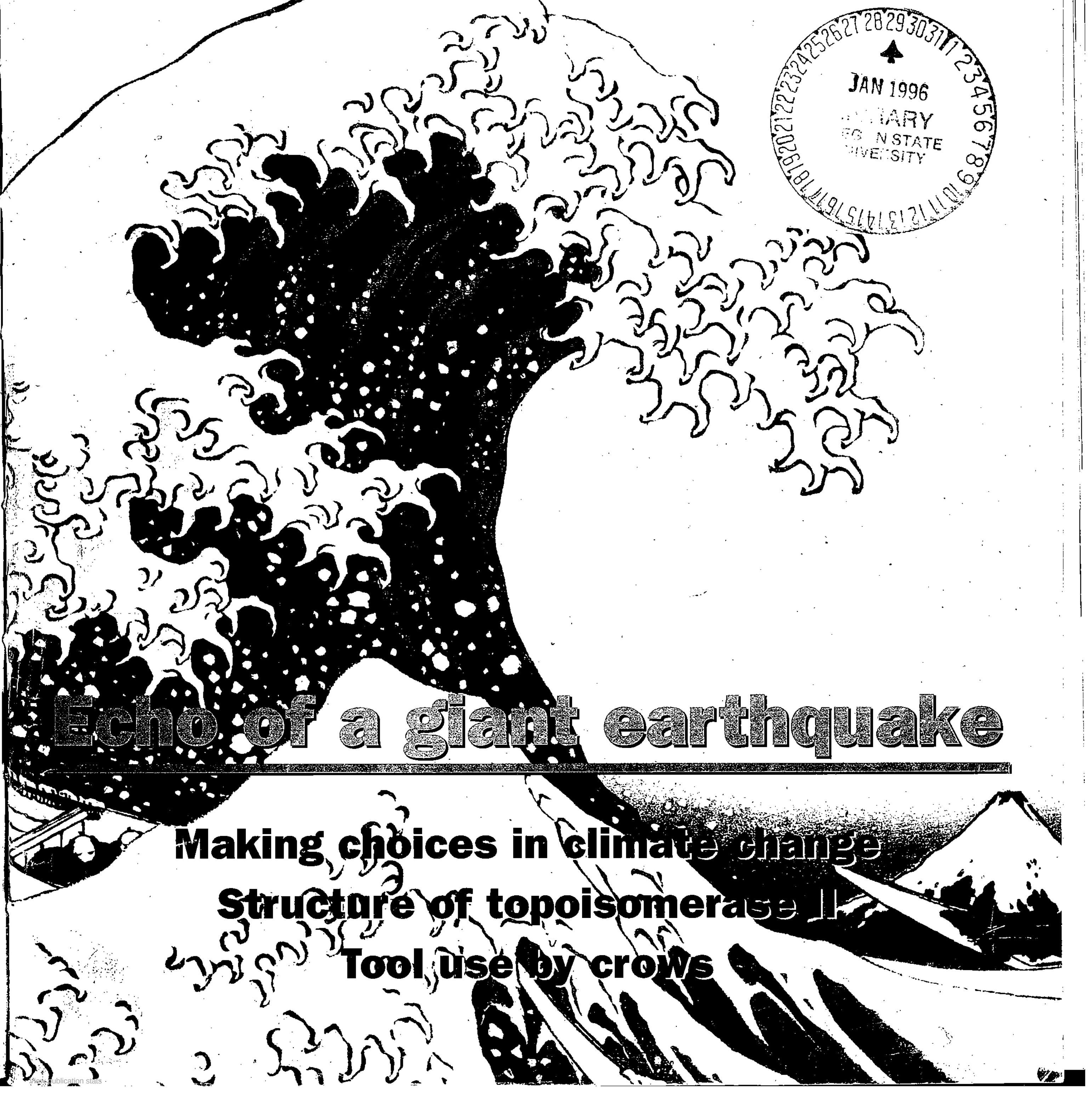

Echo of a giant earthquake

Making choices in climate change

Structure of topoisomerase II

Tool use by crows