Cyclic formation of debris avalanches at Mount St Augustine volcano

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VOLCANIC debris avalanches have been seen at many volcanoes since the 1980 eruption of Mount St Helens, but typically only one or two avalanche deposits are identified at each eruptive centre, suggesting that catastrophic slope failures are rare or even unique events in the lifetime of a volcano[1–4]. Here we present a series of radiocarbon dates from volcanic deposits showing that the summit edifice of Mount St Augustine, a 1,220-m-high active volcano on Augustine Island in the Cook Inlet area of south-central Alaska, has repeatedly collapsed and regenerated, averaging 150–200 years per cycle, during the past 2,000 years. The unprecedented frequency of summit edifice failure was made possible by sustained lava effusion rates over 10 times greater than is typical of plate-margin volcanoes.

Mount St Augustine has historically been the most active volcano in the eastern Aleutian arc of Alaska. Pyroclastic and dome-building eruptions occurred in 1812, 1883, 1935, 1963–64, 1976 and 1986[5–7]. The historic eruption of 1883 produced the Burr Point debris avalanche[8], which covered at least 20 km^2 on the north flank of Augustine Island, extending the coastline by 2 km and travelling more than 4 km into Cook Inlet (Figs 1 and 2). Displacement of sea water by the debris avalanche produced a 20-m-high tsunami at the island. Wave run-up as high as 10 m occurred over 100 km from the volcano[9]. Dome growth since the 1883 debris avalanche has buried the amphitheatre crater left by it and created a new, oversteepened summit dome complex, raising concerns that a future eruption might culminate in another debris avalanche and tsunami[8–10].

Studies of long-term eruption history are a useful technique for identifying patterns of volcanic behaviour and estimating typical repose times between eruptions[8,11–14]. There are no written records of the behaviour of Mount St Augustine before 1812, but sea cliffs around the perimeter of the roughly 100-km^2 island expose a series of discrete and overlapping debris avalanches which are locally separated by alluvium, lahars, pyroclastic flows, tephra layers and thin buried peat layers.

The well-exposed debris avalanches have characteristic features seen at similar deposits at other volcanoes, including irregular, hummocky topography, lithic heterogeneity, poor sorting, and discrete zones of shattered fresh rock and highly altered rock debris separated by sheared avalanche matrix[1,3,15]. The borders of the avalanches are delimited by semi-continuous lateral levees, 5–15 m high, which together with cross-sectional exposures in sea cliffs allow the number and dimensions of the deposits to be accurately mapped (Fig. 2). We determined the frequency of past debris avalanches at Mount St Augustine and evaluated the likelihood of a future avalanche by making a detailed stratigraphical and geochronological study of these prehistoric volcanic deposits.

Previous studies of Mount St Augustine indicated that the volcano was very young, and that its earliest eruptions occurred in latest Pleistocene time about 10,000–15,000 years ago[7,16]. But accelerator mass spectrometry (AMS) radiocarbon dating of small charcoal fragments found in the oldest fragmental volcanic rocks on the island shows that they are more than 40,000 years old (Table 1). These deposits of basaltic hyaloclastites and silicic pyroclastic flows and tephra occur with glacial deposits as high as 330 m above sea level[15], indicating that the volcano had grown at least to this height before the last glaciation[16,17]. One debris avalanche exposed on the east side of Augustine Island may also be Late Pleistocene or Early Holocene in age.

The central dome complex at Mount St Augustine is surrounded by very recent, overlapping debris avalanches which cover 90% of the area of Augustine Island, and are named for local geographic features (Fig. 2). We have obtained more than 30 radiocarbon and AMS dates on soils, peat and buried wood found above and below these avalanche deposits, and on intercalated tephra layers and pyroclastic flow deposits which contain charred wood. These radiometric dates closely bracket the age of the avalanche deposits (Table 1).

The frequency of edifice collapse can be assessed by converting the radiocarbon dates on debris avalanches to calendar years, using recent dendrochronological calibrations of the

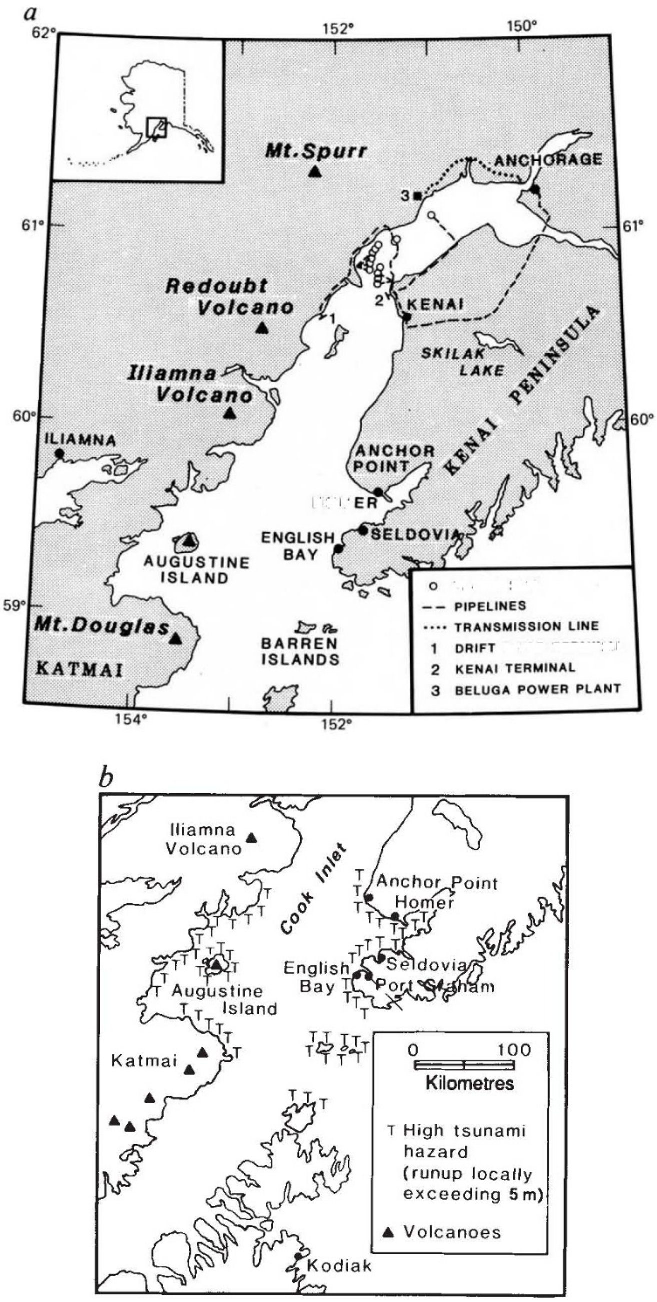


FIG. 1 *a*, Location of Mount St Augustine and Augustine Island in lower Cook Inlet, Alaska and other major volcanoes in the Cook Inlet area. Also shown are the locations of cities and towns, offshore oil platforms, coastal oil terminals, powerplants and power transmission lines in coastal areas. *b*, Areas of especially high tsunami hazard.

TABLE 1 Stratigraphy of radiocarbon dates, tephra layers and volcaniclastic deposits at Mount St Augustine

Radiometric age	Calendar year (AD)	Laboratory number	Stratigraphic context	Reference
Burr Point debris avalanche (AD 1883)				
<185	—	I-14,922	U, P	This study
≤285	—	I-14,923	U, S	This study
140 ± 60	—	B-24773	U, S	This study
170 ± 70	—	B-24779	U, S	This study
195 ± 115	—	—	U, S	5
205 ± 90	1664 (1638–1700)	I-14,924	U, S	This study
Rocky Point debris avalanche				
280 ± 100	1642 (1480–1670)	B-24781	U, P	This study
330 ± 145	1521, 1590, 1623 (1430–1670)	—	U, L, S	5
West Island debris avalanche				
Tephra layer 'B'				
367 ± 55	1488 (1442–1529)	—	I, B	8
410 ± 50	1446 (1434–1491)	B-24777	U, L, S	This study
450 ± 80	1437 (1412–1487)	B-28536	U, L, S	This study
470 ± 140	1432 (1390–1520)	—	U, L, S	5
490 ± 70	1426 (1398–1444)	B-24776	L, S	This study
Grouse Point debris avalanche				
730 ± 60	1278 (1257–1284)	B-28537	U, S	This study
Tephra layer 'M'				
770 ± 50	1261 (1218–1279)			
Southeast Beach debris avalanche				
Lagoon debris avalanche				
800 ± 120	1230, 1243, 1256 (1150–1280)	—	U, L, S	5
860 ± 80	1191 (1148–1260)	B-24780	U, L, S	This study
1,000 ± 100	1004, 1008, 1019 (980–1130)	B-24780	U, L, S	This study
Tephra layer 'C'				
Southwest pyroclastic fan				
Long Beach debris avalanche				
1,130 ± 50	895, 922, 939 (865–982)	B-28535	C, I, U	This study
1,195 ± 120	780, 804, 823, 827, 841, 857 (670–980)	—	U, L, S	5
1,200 ± 140	780, 790, 802, 843, 853 (660–990)	—	U, L, S	5
1,290 ± 80	686, 754, 757 (652–779)	B-28539	C, I, U	This study
1,400 ± 50	643 (602–663)	B-28534	C, I, U	This study
1,420 ± 60	640 (576–658)	B-28538	U, L, S	This study
South Point debris avalanche				
Tephra layer 'H'				
1,470 ± 160	584, 587, 597 (410–680)	—	U, L, S	This study
1,500 ± 155	558 (410–660)	—	U, L, S	This study
1,610 ± 70*	426 (382–538)	ETH 3826	U, L, P	This study
Northeast Point debris avalanche				
Tephra layer 'I'				
1,830 ± 80	134, 152, 169, 200, 211 (72–257)	B-24775	U, L, S	This study
Southeast Point debris avalanche				
East Point debris avalanche				
Tephra layer 'G'				
Yellow cliffs debris avalanche				
Late Pleistocene volcanic deposits				
≥39,890*	—	ETH 7166	I, C	This study
≥40,440*	—	ETH 7167	I, C	This study

Calendar ages and range (at 1 s.d.) based on dendrological calibration from ref. 18.
U, upper age limit; L, lower age limit; I, incorporated in deposit; C, burned alder branch; P, peat; S, soil.
* AMS date.

radiocarbon method[18]. Altogether, at least 11 discrete large debris avalanche deposits formed during the past 1,800–2,000 years can be identified in sea cliffs on the flanks of Mount St Augustine. Seven of these, at Burr Point, Rocky Point, West Island, Grouse Point, Southeast Fan, Long Beach and the Lagoon, are less than 1,000 years old, four occurred in the last 800 years, and three occurred in the past 500 years, with the most recent in 1883. The avalanche deposits are typically 5–30 m thick in seacliff exposures, and cover areas similar to the historic 1883 avalanche. Thus, a geological record lasting two millennia records repeated debris avalanche activity with an average recurrence interval of about 150–200 years.

All 11 avalanches mapped by this study entered the sea, and their submarine extents can be determined from the irregular hummocky topography found extending 3–6 km offshore on almost all flanks of the island as seen on a new, detailed bathymetric survey (Fig. 2). Because the travel distance and overall mobility of debris avalanches is in part a function of the source area elevation[19–21], the similar extent of these deposits suggests they originated from about the same elevation and that the Mount St Augustine central dome complex regenerated after each cycle of collapse.

The repeated emplacement of debris avalanches requires that unusually high lava effusion rates have been maintained at Mount St Augustine for the past two millennia. Following the 1883 debris avalanche, a horseshoe-shaped crater similar to that created in 1980 at Mount St Helens occupied the summit of Mount St Augustine[22] and had a volume of 2.5×10^8 m^3, whereas the avalanche deposit has a greater volume of about 3.0–3.5×10^8 m^3 which is due to fragmentation and expansion of the dome

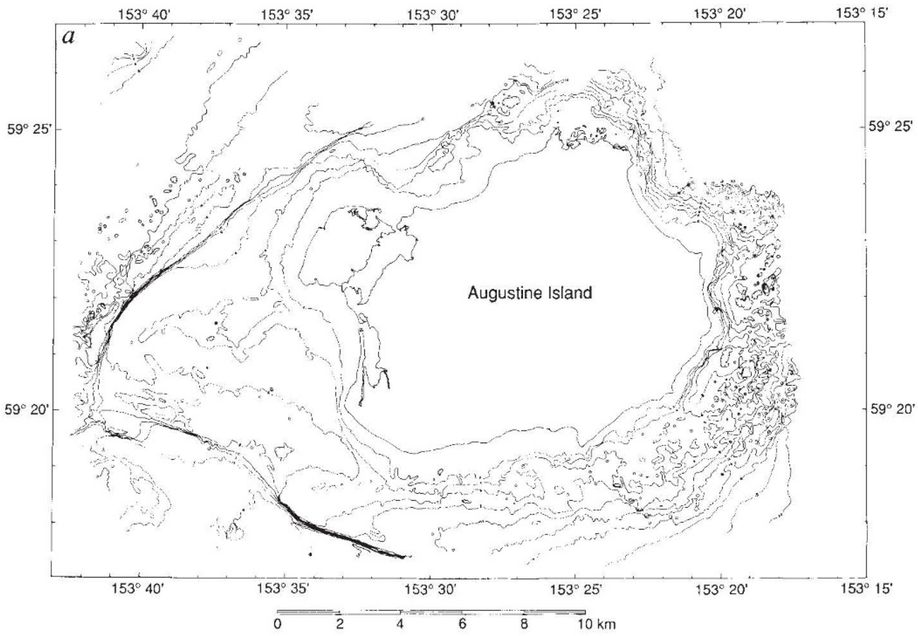
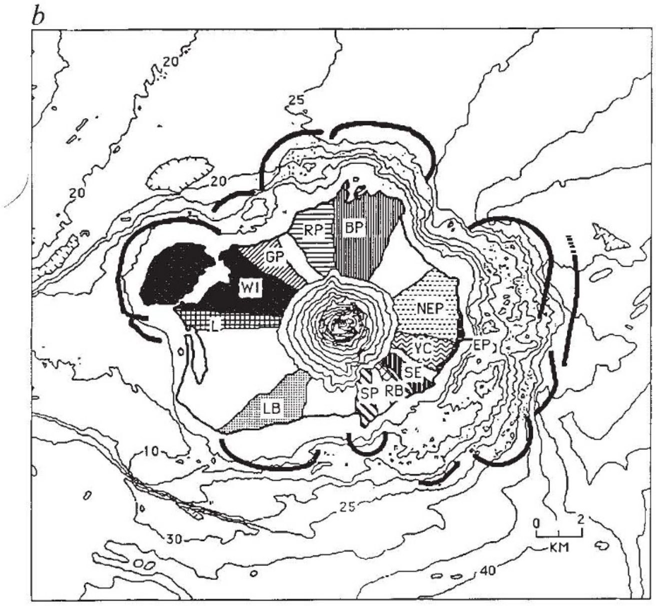


FIG. 2 *a*, Bathymetric map showing hummocky topography associated with offshore extent of debris avalanches. *b*, Distribution of debris avalanches on Augustine Island and hummocky terrain offshore showing their lateral extent. BP, Burr Point Avalanche; RP, Rocky Point avalanche; GP, Grouse Point avalanche; WI, West Island avalanche; L, Lagoon avalanche; LB, Long Beach avalanche; SP, South Point avalanche; RB, Rocky Beach avalanche; SE, Southeast avalanche; YC, Yellow Cliffs avalanche; NEP, Northeast Point avalanche; EP, East Point avalanche.



debris during transit downslope[8]. The present summit dome complex was produced by intermittent eruptions in 1883-84, 1935, 1964, 1976 and 1986. It has almost completely buried the 1883 crater and is about 800 m in diameter and 520 m high, with an estimated volume of 2.6×10^8 m^3 (Fig. 3).

We have evaluated long-term eruption rates by estimating the cumulative volume of the dated prehistoric avalanche deposits. Lava and dome-building eruptions during just the last century reflect an average effusion rate of about 2.5×10^6 m^3 yr^{-1} (exclusive of small tephra falls), whereas the series of 11 avalanches deposits indicates average effusion rates of about $1\text{-}3 \times 10^6$ m^3 yr^{-1}. This eruption rate, although much less than found at active hotspot volcanoes like Mauna Loa and Kilauea in Hawaii[23,24], is as much as 10-100 times greater than for typical calc-alkaline arcs and volcanoes[25-27], indicating that during the past 2,000 years Mount St Augustine has sustained one of the highest known rates of volcanic output attributable to subduction-zone-related magmatism[28].

The high eruption rates of silicic domes and lava flows at Mount St Augustine repeatedly produced an oversteepened, unstable volcanic cone which then collapsed. Volcanoes are usually thought to consist almost entirely of lava flows and pyroclastic rocks, but Mount St Augustine shows that in some cases volcanic edifices may consist largely of debris avalanche deposits. This mode of behaviour may be short-lived, but at Mount St Augustine it has produced a radial volcanic platform 15 km in diameter and tens to hundreds of metres thick (Fig. 2).

More than 70 tsunamis of volcanic origin worldwide have caused devastation and at least 50,000 fatalities during the past 200 years[4,29-31]. In North America, apart from Alaska, there are few volcanoes that lie near enough to the sea to generate tsunamis during eruptions. The past pattern of behaviour at Mount St Augustine indicates there is a high likelihood of another debris avalanche occurring in the near future. The current sea shore lies only 3-7 km from the summit dome complex, whereas previous avalanches have typically travelled 7-11 km from the summit (Fig. 2). The 1883 tsunami produced a small amount of damage to boats and houses in scattered coastal villages, but today about 250,000 people live near Cook Inlet, and offshore oil platforms, oil storage and tanker facilities, fishing and recreational marinas are in coastal areas which might be affected by the recurrence of such a tsunami (Fig. 1).

The tsunami hazard may be exacerbated by the regional tectonic setting of Mount St Augustine. The volcano lies in the part of Alaska affected by great subduction zone earthquakes of M8 or greater. A small M5 earthquake contributed to the collapse of Mount St Helens in 1980, and sharp earthquakes probably caused the 1792 Unzen volcanic debris avalanche in Japan which produced a tsunami and perhaps 15,000 fatalities[4]. Future large earthquakes could easily weaken the summit dome complex and induce edifice collapse at Mount St Augustine, quite independently of future eruptive behaviour.

Concentric north-facing 10-20-m-high scarps appeared around the southern part of the 1986 dome and the summit during the 1986 eruption of Mount St Augustine (Fig. 3), raising concerns that deep-seated fault planes were propagating through the volcano, but the volcano has been seismically quiet and the summit area stable since the end of the 1986 eruption. An island-wide geodetic deformation net involving 30 EDM (electronic distance measurement) lines and a short-distance EDM net at the volcano summit was established in 1988 to monitor future creep and deformation of the summit edifice.

Although it is at present quiescent, the high frequency of

FIG. 3 The summit of Mount St Augustine, Alaska as viewed from the north, showing the location of the 1935, 1964 and 1986 domes. The prominent, concentric, north-facing scarps, which are 10–20 m high, developed during the 1986 eruption. The coastline of Augustine Island and the waters of Cook Inlet lie only 4–6 km to the north of the summit.

historic eruptions and the evidence of an average 150–200 year recurrence interval between large debris avalanches during the past 2,000 years raises concerns about the future stability of Mount St Augustine. This concern is compounded by the complete reconstruction of an oversteepened summit edifice by four major dome-building eruptions since the 1883 debris avalanche. Any future dome eruptions will contribute to additional growth and oversteepening or deformation of the summit region. If Mount St Augustine continues to follow the pattern that it has maintained for the past 2,000 years, it is likely that another debris avalanche will occur sometime in the next century, which in turn will produce a tsunami by displacing the waters of Cook Inlet. □

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1. Ui, T. *J. Volcan. geotherm. Res.* **18,** 135–150 (1983).
2. Siebert, L. *J. Volcan. geotherm. Res.* **22,** 163–197 (1984).
3. Ui, T., Yamamoto, H. & Suzuki-Kamata, K. *J. Volcan. geotherm. Res.* **29,** 231–243 (1986).
4. Siebert, L., Glicken, H. & Ui, T. *Bull. volcanol.* **49,** 435–459 (1987).
5. Swanson, S. E. & Kienle, J. *J. geophys. Res.* **93,** 4500–4520 (1988).
6. Kienle, J. & Swanson, S. E. *Volcanic Hazards from Future Eruptions of Augustine Volcano, Alaska,* (Geophysical Institute, Univ. of Alaska, Fairbanks, 1985).
7. Kienle, J. in *Volcanoes of North America* (eds Wood, C. A. & Kienle, J.) 79–80 (Cambridge Univ. Press, 1990).
8. Siebert, L., Glicken, H. & Kienle, J. *J. Nat. geogr. Res.* **5,** 232–249 (1989).
9. Kienle, J., Kowalik, Z. & Murty, T. S. *Science* **236,** 1442-1447 (1987).
10. Kienle, J., Davies, J. N., Miller, T. P. & Yount, M. E. *EOS* **67,** 580–582 (1986).
11. Crandell, D. R., Mullineaux, D. R. & Rubin, M. *Science* **187,** 438–441 (1975).
12. Begét, J. E. *Science* **215,** 1389–1390 (1982).
13. Tilling, R. I. *et al. Science* **224,** 747–749 (1984).
14. Tilling, R. I. (ed.) *Volcanic Hazards* (American Geophysical Union, Washington DC, 1989).
15. Glicken, H. *US Geol. Surv. Prof. Paper* **1488** (1991).
16. Johnston, D. A. *US Geol. Surv. Circ.* **B804,** 78–80 (1979).
17. Detterman, R. L. *US Geol. Surv. Map* GQ-1068 (1973).
18. Stuiver, M. & Becker, B. *Radiocarbon* **28,** 863–910 (1986).
19. Hsü, K. *Geol. Soc. Am. Bull.* **86,** 129–140 (1975).
20. Eppler, D., Fink, J. & Fletcher, R. *J. geophys. Res.* **92,** 3623–3633 (1987).
21. Melosh, H. J. in *Debris Flows/Avalanches: Process, Recognition and Mitigation* (eds Costa, J. E. & Wieczorek, G. F.) 41–50 (Geological Society of America, Boulder, Colorado, 1987).
22. Becker, G. F. *US Geol. Surv. Ann. Rep.* **18,** 28–58 (1898).
23. Holcomb, R. T. *US Geol. Surv. Prof. Paper* **1350,** 243–260 (1987).
24. Lockwood, J. P. & Lipman, P. W. *US Geol. Surv. Prof. Paper* **1350,** 509–536 (1987).
25. McBirney, A. *A. Rev. Earth planet. Sci.* **6,** 437–456 (1978).
26. Sugimura, A., Matsuda, T., Chinzei, K. & Nakamura, K. *Bull. volcanol.* **26,** 125–140 (1963).
27. Civetta, L., Cornette, Y., Gillot, P. Y. & Orsi, G. *Bull. volcanol.* **50,** 47–57 (1988).
28. Crisp, J. *J. Volcan. geotherm. Res.* **20,** 177–211 (1984).
29. Latter, J. H. *Bull. volcanol.* **44,** 467–490 (1981).
30. Simkin, T. & Fiske, R. S. *Krakatau 1883* (Smithsonian Institution, Washington DC, 1983).
31. Blong, R. J. *Volcanic Hazards* (Academic, Orlando, 1984).

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First discovery of monotremes in South America

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UNTIL now, the egg-laying monotremes were only known from the Australian continent, where they have lived since the early Cretaceous period to the present[1]. Here we report the first monotreme from outside the Australian continent, an ornithorhynchid, from sediments of late early Palaeocene age in Patagonia, southern Argentina. This discovery demonstrates the Gondwanan nature of monotremes and supports the hypothesis that the Patagonian Terrane of southern South America had a biotic history distinct from that of the rest of the continent.

The South American monotreme is represented by an isolated upper right second molar (Fig. 1, M^2). The crown morphology is monotreme-like and resembles the upper second molars of Oligo-Miocene species of the ornithorhynchid genus *Obdurodon*[2,3] in having two parallel anteroposteriorly compressed, occlusally concave, V-shaped blade systems (triakididrepanons[2,4]) terminated buccally by four small cuspules. At the lingual end of the midvalley of the tooth, between the bases of the two transverse blade systems, there is a low ridge (or cuspule) that probably occluded with the apical margin of the principal buccal cusp of the 'talonid' of the lower molars. At the buccal end of the midvalley, there are two additional minor cuspules that contribute to the ornithorhynchid-like multicuspidate buccal margin of the crown. As in the M^2 of species of *Obdurodon*, the Argentinian tooth has posterior and anterior cingula, no buccal or lingual cingula and four anteroposteriorly compressed roots. In contrast to species of *Obdurodon*, the tooth is larger, has an elevated posterior cingulum, a more buccal position of the posterobuccal cuspule, a swollen basal portion of the anterolingual cusp and extensive occlusal wear. The Argentinian animal, although only known from an upper molar, appears to have been larger than *Steropodon galmani*, which is known from a portion of a lower jaw. A detailed comparison with all other monotremes will be presented elsewhere[34].

Enamel ultrastructure of the Argentinian tooth resembles that reported for *Obdurodon*[5]. The middle enamel shows a Pattern 2 enamel-packing pattern[6]; tubules are present and there is a distinct inter-row sheet and inter-prism component present. Prisms are generally ovoid and ~3 μm in diameter. This combination of features exists in *Obdurodon* and some marsupials but not in placentals or multituberculates (C. Gilkeson, personal communication). The inability to examine ultrastructural features on etched surfaces prohibited a definitive examination for marsupial versus monotreme features. Gross crown morphology is almost indistinguishable from the pattern of ornithorhynchid monotremes but is unlike that of any marsupial or placental mammals.

The mammal-bearing deposit ('Banco Negro Inferior', BNI) occurs at 45° 30′ S; 67° 11′ W, Golfo de San Jorge, Chubut province (central Patagonia), Argentina. The BNI deposit occurs above the marine Salamanca Formation[7], whose uppermost part has been determined to be Upper Danian on the basis of foraminiferal biostratigraphy[8,9]. On the basis of palaeomagnetic data, the BNI sediments have been determined to be between 63.2 and 61.8 Myr BP (before present; ref. 10). Mammals from this level are most similar to those from the Tiupampian Local Fauna of Bolivia[11], both assemblages having been referred to