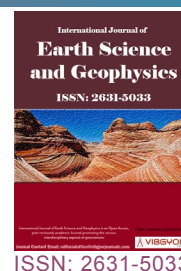


# Timing of Anomalous Rapid Ammonite Diversification and Extinction from the Upper Cretaceous (Santonian-Campanian) of James Ross Island, Antarctica using the First Antarctic Magnetostratigraphy for this Time Interval



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## Abstract

Searching for the causes and consequences of the Cretaceous-Paleogene mass extinction instigated decades of paleontological research on Seymour Island, Antarctica. However, biological changes, including rapid diversification followed by equally rapid extinctions of mollusks occurred more than 20 million years prior to the K/Pg boundary event in Antarctica, yet understanding these events has been hampered by the paucity of high-resolution correlation of what has been biostratigraphically identified as Santonian - through-Campanian Stage strata of the James Ross Basin (JRB) to the international stage stratotypes. This has been caused by endemism of ammonite species chosen as zonal indices, a lack of bentonite/ash age dating, and until recently, the absence of magnetostratigraphy. The publication by Tobin, et al. [1] produced a magnetostratigraphic record for the Maastrichtian Stage on Seymour Island, but earlier strata, and other islands in the (also referred to as the James Ross Maramba Basin or MB) were not included. Here we complete the magnetostratigraphic record from the base of the Maastrichtian down to the Coniacian Stage.

This stratal (and time) interval coincides with a still unexplained, rapid increase in ammonite diversity beginning during the Santonian Age, and an equally rapid extinction of all of the newly appearing species by the mid-to late Campanian Age, as recognized by chron boundaries presented here. The rapidity of both the Santonian Age diversification, and its mirror image reduction in diversity during the Campanian Age, is not explained through current understanding of Antarctic tectonics, paleoecology, and/or paleobiogeography. An alternative hypothesis can be found in invoking ecological effects caused by a previously reported episode of True Polar Wander, (or alternatively, Mantle Wander) a solid-body rotation of the planet over its spin axis, a process that is increasingly accepted as a major tectonic force in shaping crustal configurations [2], and as suggested here, in biological history as well. The ammonite fossil record from James Ross Island shows an increase in species from the Santonian and Campanian Stage strata there, an increase that is in part composed of the appearance of warmer water species of the Indopacific Biotic Realm, coupled with an apparent increase in paleotemperature of the basin over the same time interval. These separate lines of evidence are consistent with

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our hypothesis of a rapid northward movement of Antarctica during the Santonian Age, taking the James Ross Basin habitat into warmer waters, and into marine ecosystems that also were inhabited by Indopacific Province ammonites. Their equally rapid extinction several million years later is also consistent with the mirror image return of Antarctica (TWP movements are composed of a couplet of movements in opposite directions) back into higher latitudes during the Campanian Age, and in so doing into colder water, with cooling presumably the cause of the rapid extinction of the Indopacific fauna. The later re-population of ammonites from the well known beds on Seymour Island we also attribute to a slow, plate tectonic-driven movement into lower latitude during the Maastrichtian Age, as evidenced by the combined, Coniacian through Maastrichtian paleomagnetic record that we document here for the first time.

### Subject Terms

Geophysics, Paleobiology, Paleoclimatology

## Introduction

The thick and well-exposed, Upper Cretaceous beds cropping out in the James Ross Island region, Antarctica (including James Ross, Seymour, Vega, and Snow Hill Islands, [Figure 1](#)) may be the most expanded, fossiliferous beds with both micro- and macrofossils of Late Cretaceous-Early Paleogene age yet known anywhere in the globe. They also represent the southernmost known KPg boundary on land. As such, these Antarctic beds provide unparalleled opportunity to test hypotheses concerning the pattern, cause, and consequences of the KPg mass extinction in the Southern Hemisphere, including events and fossil ranges leading up to the terminal Cretaceous event, the event itself [[3-5](#)], and its aftermath, as well as documenting biotic events that occurred in zones and stages prior to, and after the K/Pg global mass extinction.

The fossil record for the ~20 million years prior to the KPg mass extinction event has yielded information about diversity and biogeography that remains both interesting and relatively unexplained [[6-9](#)]. These are the reason(s) for observed trends in ammonite diversity, disparity, and biogeographic affinities in fossils from the Santonian and Campanian Stages in the MG basin, as well as reasons for the rapid extinction of this fauna. However, to date there has been no means of high resolution chronostratigraphy allowing identification of the Coniacian, Santonian, and Campanian stage and substage boundaries, and this lack of temporal precision has limited the resolution of correlation to lower latitude, possibly global events that pre-dated the KPg mass extinction.

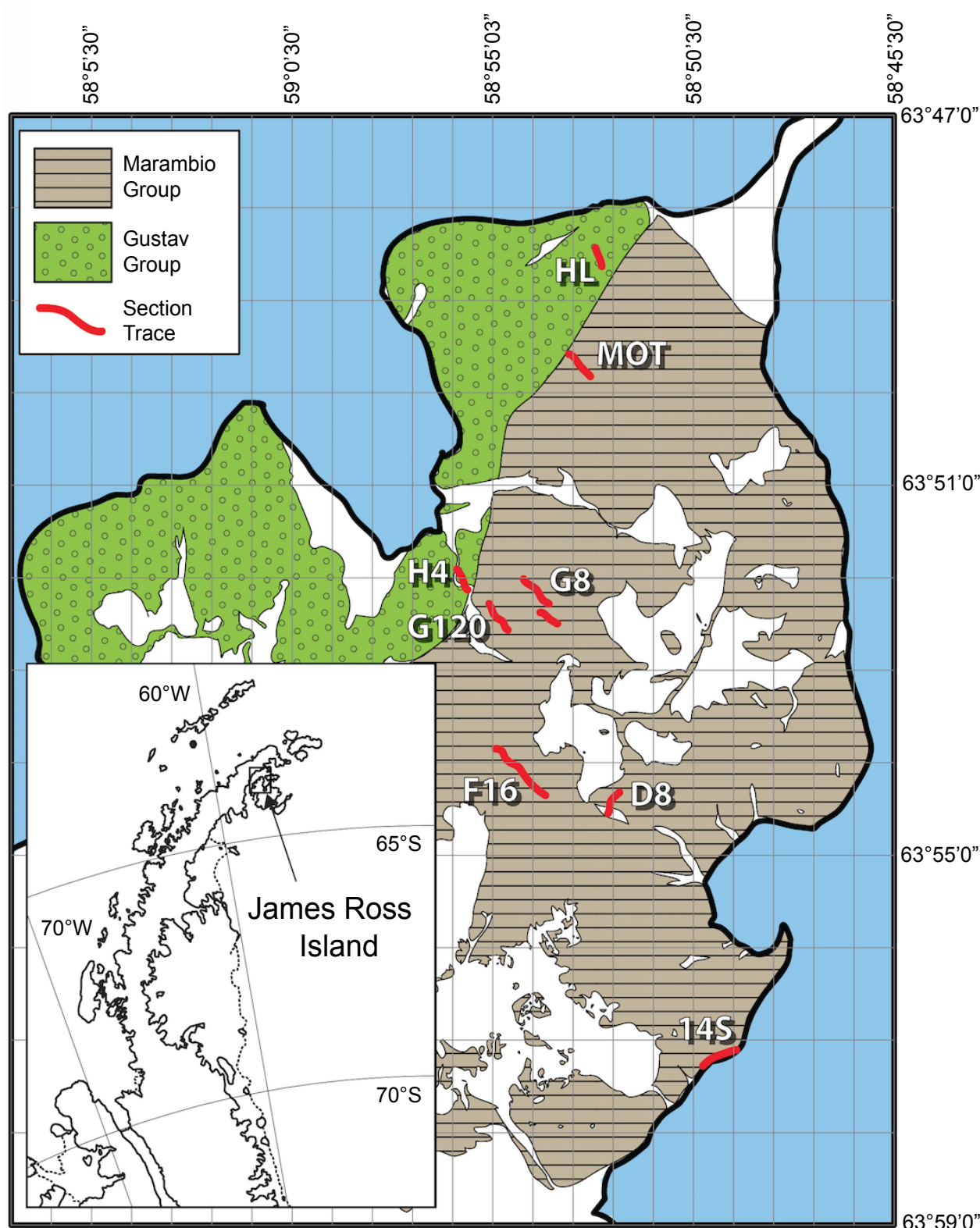
Here we use the first Coniacian through Campa-

nian-aged magnetostratigraphy from Antarctica to identify stage and substage boundaries, and then use these to better constrain the age of the curious ammonite record obtained from James Ross Island. That record demonstrates that there was a rapid ammonite diversification beginning in the Santonian age, anomalous in its biogeographic affinity, and that this Indopacific fauna was entirely extinct by the end of the early Campanian age, or by about 80-78 mya [[3-5](#)].

As shown in [Figure 2](#), representatives of scaphitid, baculitid, and nosteratid ammonites as well as inoceramid bivalves whose families all disappeared at the KPg boundary in the northern hemisphere disappeared in non-synchronous fashion in the JRI basin as much as ten million years before the KPg boundary event [[6,8,10,11](#)]. As yet there remains no viable hypothesis explaining these early extinctions. Equally problematical is the rapid diversification of ammonites of Indopacific Province affinity during the Santonian Age.

## Materials and Methods

We sampled for magnetostratigraphy and biostratigraphy on James Ross Island in the (from oldest to youngest) Hidden Lake, Santa Marta, and Snow Hill Island Formations; [Figure 1](#). We located and used previously published, measured stratigraphic sections [[6-9](#)] for our sampling that were kindly pointed out to us in the field by Dr. E. Olivero, so as to be able to integrate his previous fossil collection and biostratigraphy with our magnetostratigraphic and ammonite specimen sampling. The longest continuous outcrop extends from the shores of Whiskey Bay up to the summit of Santa Marta Pass, in the Santa Marta Formation. We also sampled older strata of Hidden Lake Formation as shown in [Figure](#)



**Figure 1:** Geographic position of the Marambio Group (Upper Cretaceous) sedimentary basin on the Antarctica Peninsula, and the positions of the measured sections used in this paper.

1. From the top of Santa Marta pass, we further sampled Santa Marta beds in two, non contiguous sections, one starting from near the pass, one on the shore of Brandy Bay itself.

From oldest to youngest, these sections included H4, M0, G120, G8, F16, D8, and 14S. At each site we located the base of the section as described in previous work [6-9] and then re-measured each

**Table 1:** Magnetostratigraphy the inclinations and declinations of our samples.

Sample	Height	Composite	Declination	Inclination	Declination	Inclination	PLF		Inclination
			geographic	geographic	tilt-corrected	tilt-corrected			tilt-corrected
HL1A.1	0	-40	51.3	-77.7	353.1	-73.1	315.9	3.1	-73.1
HL2A.1	2.5	-37.5	32.6	-74.4	352.2	-67.6	28.2	-60.3	-67.6
HL2B.1	2.5	-37.5	6.9	-73.2	340.1	-62.4	7.3	-65.7	-62.4
HL3.1	4.8	-35.2	38.9	-55.8	20.2	-52.1	359	-34.6	-52.1
HL4.1	10.7	-29.3	36.9	-65.6	10.5	-62.6	13.5	-82.5	-62.6
HL5.1	13	-27	39.3	-70.9	5.5	-67.5	353.9	-63.9	-67.5
HL6.1	17.2	-22.8	349.6	-63.6	337	-53.1	56.8	-80.5	-53.1
HL7A.1	20	-20	356.2	-65.4	340.8	-55.5	353.6	-22.8	-55.5
HL8.1	25	-15	28	-64.5	4.6	-59.9	104.6	-75.5	-59.9
HL9A.1	29	-11	358.2	51.8	14.3	58.5	26.7	-83.7	58.5
HL9B.1	29	-11	199.6	56.9	182.4	51	19.7	-51	51
HL10.1	31.4	-8.6	182	37.9	174.6	29.9	349.5	-78.9	29.9
HL11.1	33.8	-6.2	159.7	39	155.2	27.8	2.5	-2.1	27.8
COL2.1	28.4	88.4	42.7	-66.5	18.4	-58.1	need to fit		-58.1
COL3.1	35.5	95.5	56	-71.2	21.7	-64.6			-64.6
COL4.1	41.5	101.5	353.9	-71.1	345.4	-56.6			-56.6
COL5.1	47.7	107.7	79.1	-78.4	17.4	-73.8			-73.8
COL6A.1	59.3	119.3	60.7	-58.9	18.6	-67.1			-67.1
COL7.1	91.6	151.6	21.5	-60.8	341.1	-67.1			-67.1
COL8.1	100	160	26.9	-60.5	334.4	-67.9			-67.9
H4-3.A1	0	120	342.7	-13.2	342.7	-13.2	226.8	49.2	-13.2
H4-3.B1	0	120	278.1	14.7	278.1	14.7	64.5	7.4	14.7
H4-4.A1	0	120	84.1	-68.1	55.2	-70.9	24.4	-27.2	-70.9
H4-4.A2	0	120	354.8	-84.4	335.3	-73.9	24.5	-32.4	-73.9
H4-4.A3	0	120	60.9	-69.7	32.4	-68	10.3	-40.2	-68
H4-4.A4	0	120	61.6	-82.5	1.8	-77.4	8	-39.3	-77.4
H4-4.A5	0	120	308.2	-78.7	316.5	-68	348.6	-35.8	-68
H4-5.A1	30	150	16.3	-65.1	2.4	-57.1	340	-39.8	-57.1
H4-5.A2	30	150	14.6	-71.2	357.6	-62.7	1.2	-39.2	-62.7
H4-5.A3	30	150	18.3	-74.7	357.1	-66.4	10.6	-21.7	-66.4
H4-5.A4	30	150	26.7	-73.1	4	-65.9	17.9	-58.6	-65.9
H4-5.B1	30	150	79.8	-71.4	45.3	-72.9	7.4	-32.3	-72.9
H4-5.B2	30	150	42.6	-75.4	11.1	-70	50.4	-50.5	-70
H4-5.B3	30	150	20	-78.6	353.6	-70.1	50.3	-52	-70.1
H4-5.B4	30	150	56.6	-69.6	29.1	-67.2	48.6	-49.5	-67.2
H4-5.C2	30	150	27	-74.5	2.6	-67.2	76.1	-40.2	-67.2
H4-5.C3	30	150	49.9	-70.6	22.8	-66.9	41.5	-31.7	-66.9
H4-5.C4	30	150	44.7	-68.1	21.6	-63.8	65.5	-30.1	-63.8
H4-7.A1	35	155	62.3	-63.9	40.2	-63.1	27.7	-50	-63.1
H4-7.B1	35	155	352.8	-73.5	342.2	-63.3	353.3	-38.7	-63.3
H4-7b.A1	35	155	45.9	-75.1	13.6	-70.2	37.6	-58.2	-70.2

H4-7b.B1	35	155	35.8	-85.8	343.2	-77	46.5	-48.6	-77
H4-7b.B2	35	155	64.4	-65.9	39.9	-65.3	11.9	-71.2	-65.3
MOT1.1	10	150	57.9	-48.2	61.4	-38.8	13.6	-73.7	-38.8
MOT3.1	44	184	11.4	-66.8	29.6	-61.9	15.5	-65.5	-61.9
MOT4A.1	49	189	205.5	-63.5	185.3	-67.7	298.8	-56.5	-67.7
MOT4B.1	49	189	192.2	-62.6	172.2	-64.6	24.9	-55.5	-64.6
G120-1.1	0	227	185.4	62.3	170.9	55.7	341.8	-68.8	55.7
G120-2.1	0.75	227.75	168	44.5	161.6	36.7	23.1	-63.5	36.7
G120-4.1	1.6	228.6	90.8	69.1	101.5	60.4	37.5	-73.3	60.4
G120-5.1	5.4	232.4	232.8	57.8	216.3	58.8	12	-56.2	58.8
G120-6.1	7.2	234.2	56.7	81.9	95.2	75.1	343.9	-62	75.1
G120-7.1	7.4	234.4	193	61.5	178.6	56.4	31.6	-58.9	56.4
G120-15b.1	42.6	269.6	158.6	58.3	151.9	49.5	347.8	9.8	49.5
G120-16.1	47	274	114.6	58.1	117	48.3	359.4	-10.4	48.3
G120-18.1	52.8	279.8	206.9	72.9	180	68.9	44.8	-13.3	68.9
G120-19a.1	57.6	284.6	106.7	78.9	113.8	68.4	5.3	-25.3	68.4
G120-19b.1	57.6	284.6	12.8	68.6	47.2	69.3	85.9	-39.8	69.3
G120-24.1	81.4	308.4	144.4	69.3	136.6	56.7	345.7	-70.4	56.7
G120-26.1	90.6	317.6	292.7	30.8	291.7	41.7	321.7	50.7	41.7
G120-27.1	90.8	317.8	124.6	46.9	123.8	35.9	139.8	32.8	35.9
G120-29.1	107.5	334.5	227.7	51.2	213.2	53.2	192.7	-52.7	53.2
G8_32.1	0	345	156	38.4	149.3	45	16.5	-67.5	45
G8_34.1	14.5	359.5	251.4	62.7	270.2	67.9	60	-67.2	67.9
G8_35.1	19	364	155.4	66.1	133.6	71.7	344	-59.6	71.7
G8_36.1	22.2	367.2	244.7	74.4	283.6	79.2	15.2	-53.4	79.2
G8_37.1	25	370	201	58.1	199.5	68	356.7	-70.3	68
G8_38.1	26.4	371.4	256.2	74	294.1	77	32.3	-57	77
G8_39.1	30.4	375.4	210.3	50.5	212.2	60.4	36.7	-60.5	60.4
G8_42.1	40	385	185.4	40.2	180.9	49.8	45.2	-38.4	49.8
G8_58.1	166.6	511.6	101.7	78.2	64.2	71.2	83.5	71.9	71.2
G8_59.1	170.6	515.6	194.6	41.2	191.7	52.8	285	-60.7	52.8
G8_60.1	176.6	521.6	90.5	82.1	51.2	73	290.2	48.2	73
G8_61.1	188.6	533.6	169.1	-81	10.4	70	305.7	-82.7	70
G8_63.1	203	548	139.3	67.9	110.7	69.4	297.5	-14	69.4
G8_64.1	209	554	236.5	63.8	252.8	72.8	302	-46.6	72.8
G8_65.1	215.1	560.1	196.5	78.6	140.8	86.9	225.8	72.7	86.9
F16_1C.1	0	690	100.8	83	105.5	69.6	96	6.7	69.6
F16_3A.1	4.5	694.5	189	72.5	156	66.1	3.9	-8.4	66.1
F16_4A.1	12	702	284.2	79.5	122.8	87.9	357.2	-45.7	87.9
F16_4B.1	12	702	319	84.3	86.9	82.7	133.3	-15.4	82.7
F16_5A.1	13.6	703.6	152	79	130	66.4	32.4	-21.2	66.4
F16_5B.1	13.6	703.6	217.7	65.1	186.9	64.6	17.6	0.9	64.6
F16_6B.1	15.8	705.8	210.3	77.4	159.7	74.4	343	-13.8	74.4



F16_7A.1	16.8	706.8	130.9	42.8	130.7	30.8	338.2	-50.7	30.8
F16_8A.1	17	707	195.9	48.2	183.3	45.5	348.5	-13.8	45.5
F16_10A.1	82.6	772.6	244.2	74.6	194.6	78.4	344.3	24.2	78.4
F16_13A.1	94.6	784.6	232.7	61	209.2	63.4	33.3	-43	63.4
F16_13B.1	94.6	784.6	211.1	67.7	182.8	64.6	52.9	-78.2	64.6
F16_14A.1	112	802	62.3	83.2	102.5	72.6	35	-29.3	72.6
F16_14B.1	112	802	181.7	57.9	167.6	49.8	180.6	47.1	49.8
F16_15B.1	112.9	802.9	77.2	60.9	89.4	50.8	294.9	-27.6	50.8
F16_16A.1	125.6	815.6	338.9	76.3	48.6	81	1.3	-66.5	81
F16_16B.1	129.9	819.9	192.6	52.3	178.6	46.3	354.5	-23	46.3
F16_16E.1	130	820	170.8	58.2	157.8	48.4	138.8	48.4	48.4
F16_17A.1	130.6	820.6	222.4	59.7	200.1	59.4	297.4	-42.5	59.4
F16_18A.4	131.5	821.5	180.7	54	167.7	45.3	359.5	-18.9	45.3
F16_22.1	141.8	831.8	172.7	77.4	145.8	67.3	60.6	-30.7	67.3
F16_23A.1	144.4	834.4	65.7	43.6	74.9	35	149.8	-79.1	35
F16_23B.1	144.4	834.4	133.7	65.9	130	52	178.9	-20.9	52
F16_25.1	147	837	168.1	77.4	144.6	65.5	194.7	18.4	65.5
F16_28A.1	160.6	850.6	197.2	72.4	166.6	66.1	136.1	54.1	66.1
F16_28C.1	160.8	850.8	180	77.5	147.8	67.2	33.5	-70.6	67.2
F16_28E.1	161	851	215	77.3	164.6	72.6	349.6	-71.6	72.6
F16_29B.1	169.8	859.8	286.7	84.7	131.7	81	16.7	-50	81
D8_7.1	8.6	1008.6	49.3	-51.8	37.9	-55.1	need to fit		-55.1
D8_10b.1	16.4	1016.4	66.8	-46.7	58.7	-52.6			-52.6
D8_11a.1	18.5	1018.5	82.7	-43	77.6	-50.6			-50.6
D8_15.1	64	1064	50.6	-66.7	29.2	-69.4			-69.4
14S_1.1	2.4	1352.4	323	-69.4	313.1	-76.9	need to fit		-76.9
14S_2.1	2.45	1352.45	141	49.2	137.1	56.7			56.7
14S_3.1	8.4	1358.4	310.9	-61.1	301.5	-67.7			-67.7
14S_7.1	10.6	1360.6	56.8	65.9	41.1	63			63
14S_14.1	15.6	1365.6	102	22	99	26			26
14S_17.1	18.8	1368.8	145.2	30.2	143.8	37.9			37.9
14S_20.1	19	1369	172.7	84.4	314.9	87.2			87.2
14S_23.1	20.1	1370.1	159.7	24.3	159.7	32.3			32.3
14S_24.1	20.4	1370.4	162.8	62.1	163.7	70.1			70.1
14S_27.1	21.6	1371.6	332.6	-78.7	319.5	-84.4			-84.4
14S_32.1	40.4	1390.4	163	66.3	160.8	73.8			73.8

section using Jacobs staff fitted with Abney Level. All sample levels come from our re-measures. Strike and dip was taken at each locality. The majority of samples were drilled into concretions, in a small number, where drilling was not possible, we used plastic box samples covering oriented samples carved from a single bed. Each site that was sampled (magnetic cores or box samples taken) had GPS information recorded for it, and

this information available upon request.

The sampled sections produce a nearly continuous outcrop that atextends from the shores of Whiskey Bay up to the summit of Santa Marta Pass, thus extending from the Hidden Lake Formation through much of the Santa Marta Formation. However, strata on these transects were often covered by overburden. In general there was more expo-

sure on the Whiskey Bay side of Santa Marta Pass (Sections H4 to near the top of F16), but less coverage from F16 through D8; A pronounced missing interval separates these two. Also, the sections of HL and MO were isolated, and their relative stratigraphic positions one to another (relative to their base and tops) was not clear in the field.

For magnetostratigraphic sampling, we took either block samples (a minority) or more frequently used a specially built gasoline powered drill (modified from a chain saw) that took 2.5 cm wide cores up 5-8 cm deep into the rock. Most cores were taken from concretions, which were common throughout both formations sampled. These cores were oriented using both a sun compass (when sun was available) and a magnetic compass, then extracted from the rock. Samples were taken to the paleomagnetism lab at the California Institute of Technology (Caltech), part of the RAPID consortium of paleomagnetism labs.

In the laboratory, cores were cut into slices, and slices furthest from the weathering surface were analyzed preferentially. Natural remanent magnetization (NRM) was measured in both the up and down positions using automated techniques of the Rock and Paleomagnetic Instrument Development consortium (RAPID) system. Samples were then subjected to several sequences of alternating immersion in liquid nitrogen and remanence measurement to remove viscous components held by multi-domain magnetite. Subsequently, they were subjected to increasingly strong low alternating field demagnetization up to roughly 7.0 mT to remove spurious signals that may be introduced by airport X-ray machines and the like. Finally, samples were then treated with thermal demagnetization in an oxygen-free (pure N<sub>2</sub>) atmosphere, alternating oven heating and remanence measurements from 60 °C until they started displaying unstable behavior between ~250 to 500 °C. From our earlier paleomagnetic work on Seymour Island, [1] we found that most secondary components were removed below these levels. Examples of sample behavior of paleomagnetic cores from the basin have previously been illustrated [1].

These results were then quantified by standard principle component analysis [12]. Previous work using a fold test on Seymour Island [1] indicated that results obtained were primary, Cretaceous-

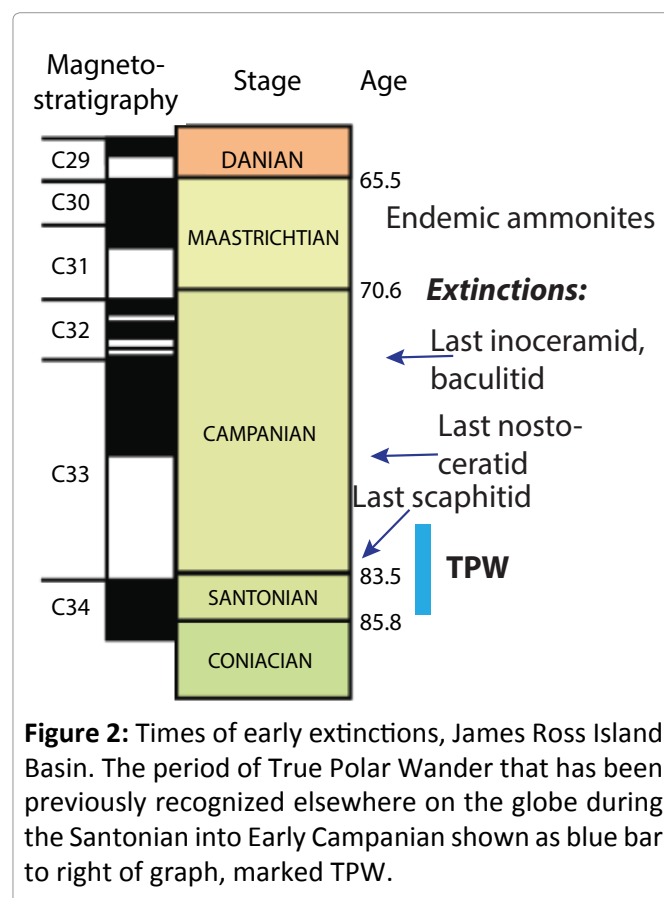
aged directions, rather than modern field overprint. This previous work used secondary samples of all lithologies to determine magnetic mineralogy, including anisotropy, IRM, ARM, RRM, and backfield measurements, using standard laboratory methods [13].

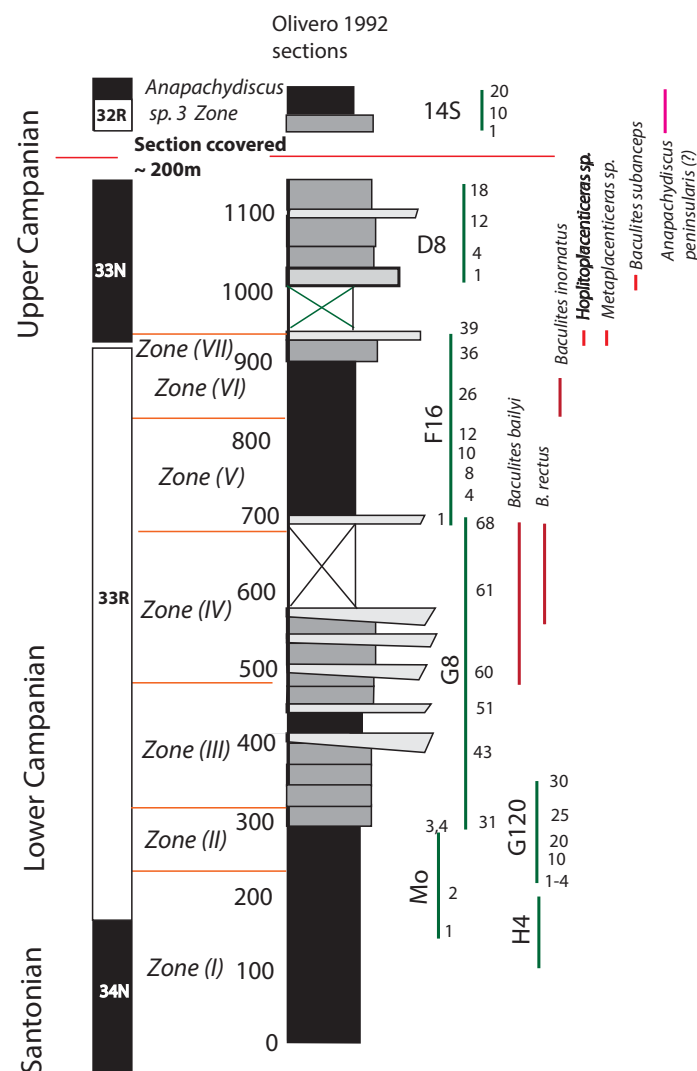
The Inclination results from our interpretable samples can be placed in their stratigraphic order to provide a magnetostratigraphic record for our sampled sections. When combined with biostratigraphic information, the magnetostratigraphy provides the highest resolution chronostratigraphic framework possible in the JRB to date, and allows completion of the Santonian through Maastrichtian Age magnetostratigraphic record in the James Ross Basin.

## Results

### Magnetostratigraphy

The inclinations and declinations of our samples are listed in Table 1. The positions of the chron reversals allowed us to correlate to the Global Polarity Time Scale, and thus to stage boundaries and substage boundaries. The positions of our measured sections are shown in Figure 1, and





**Figure 3:** James Ross Island sections sampled for this paper, with lithostratigraphy, magnetostratigraphy and ranges of important ammonites. Each of the sections sampled is shown relative to its stratigraphic height as measured from low in the Hidden Lake Formation. The numbers to the right of each section refer to a single paleomagnetic sampling site (one or more cores taken and analyzed. The results from the core analyses are listed in Table 1. Biostratigraphic zones from prior work are listed to left of column (Zones I-VIII) of [6-8].

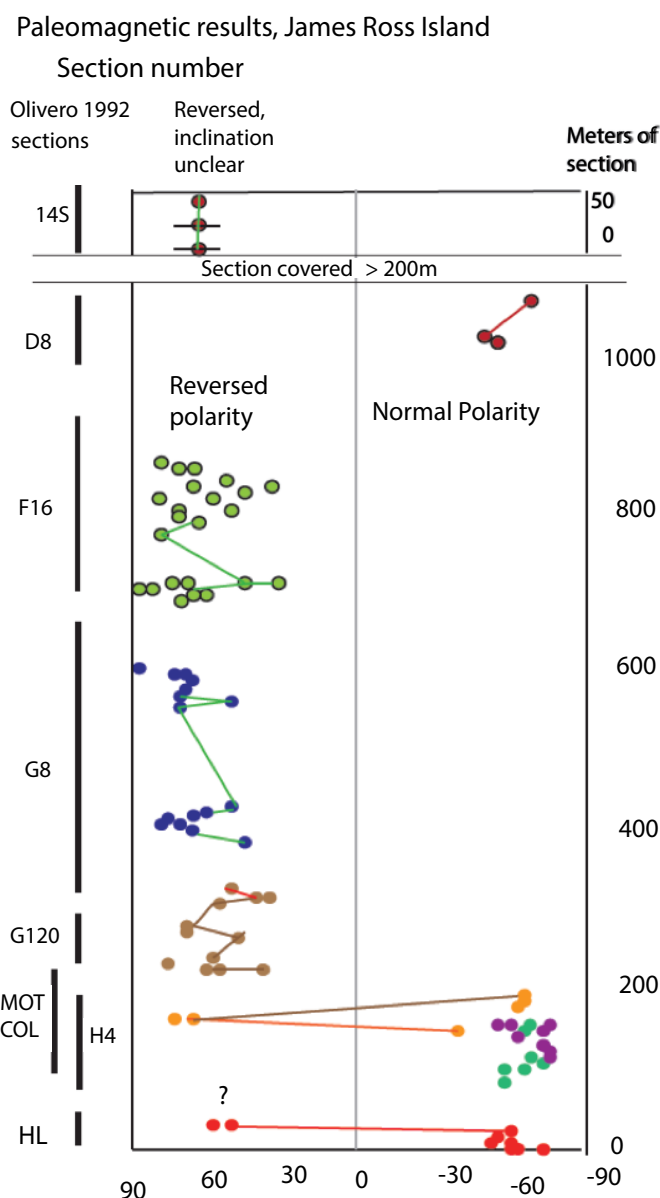
their correlation to the GPTS based on our magnetostratigraphic results is shown in Figure 3, Figure 4, Figure 5 and Figure 6.

The lowest reversal was observed in section HL, although there are also normal directions from this section, suggesting that these early reversal results from HL might be spurious. The ammonite record of lower Santonian baculitids suggests that this section, as well as section MO, and reversed polarity was continuous through sections G120, the superjacent G8, and through most of superjacent F16. The geographic separation of HL from H4 and MO has Normal polarity was observed high in section F16, and then was continuous through

section D8 (although magnetic behavior of many of the cores from the latter precluded accurate polarity determination. Both well behaved normal and reversed polarities were observed in section 14S.

The sequence of Chrons extends from an indeterminate level within the Cretaceous “Long Normal” (Chron 34N) up to the vicinity of the Campanian-Maastrichtian stage boundary as understood in the European type regions, which corresponds to the top of the *Nostoceras hyatti* ammonite zone. The lowest reversal boundary (interpreted here as the 34N/33R boundary) recognized here was in the vicinity of the Hidden



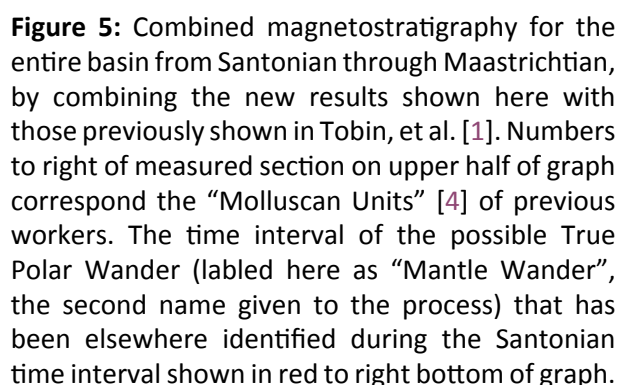


**Figure 4:** Primary paleomagnetic results from the measured sections shown in Figure 3. The sections sampled shown on left. A long missing (covered) interval (not previously quantified) separates the top of section D8 and the base of 14S, as is also shown in our Figure 1. This interval is at least 200m thick stratigraphically, and we interpret it to include much of the time of Chron 33N, as well as being correlative in age to Rabot Point, James Ross Island [15].

Lake - Santa Marta Formation boundary, while the superjacent, 33R/33N boundary was found near the Santa Marta Pass, but within the Santa Marta Formation. The highest reversal boundaries, 33N/32R, and 32R/33N, were found in the Snow Hill Island Formation, in section 14S; these positions related to lithostratigraphy and biostratigraphy are shown in Figure 4 and Figure 5.

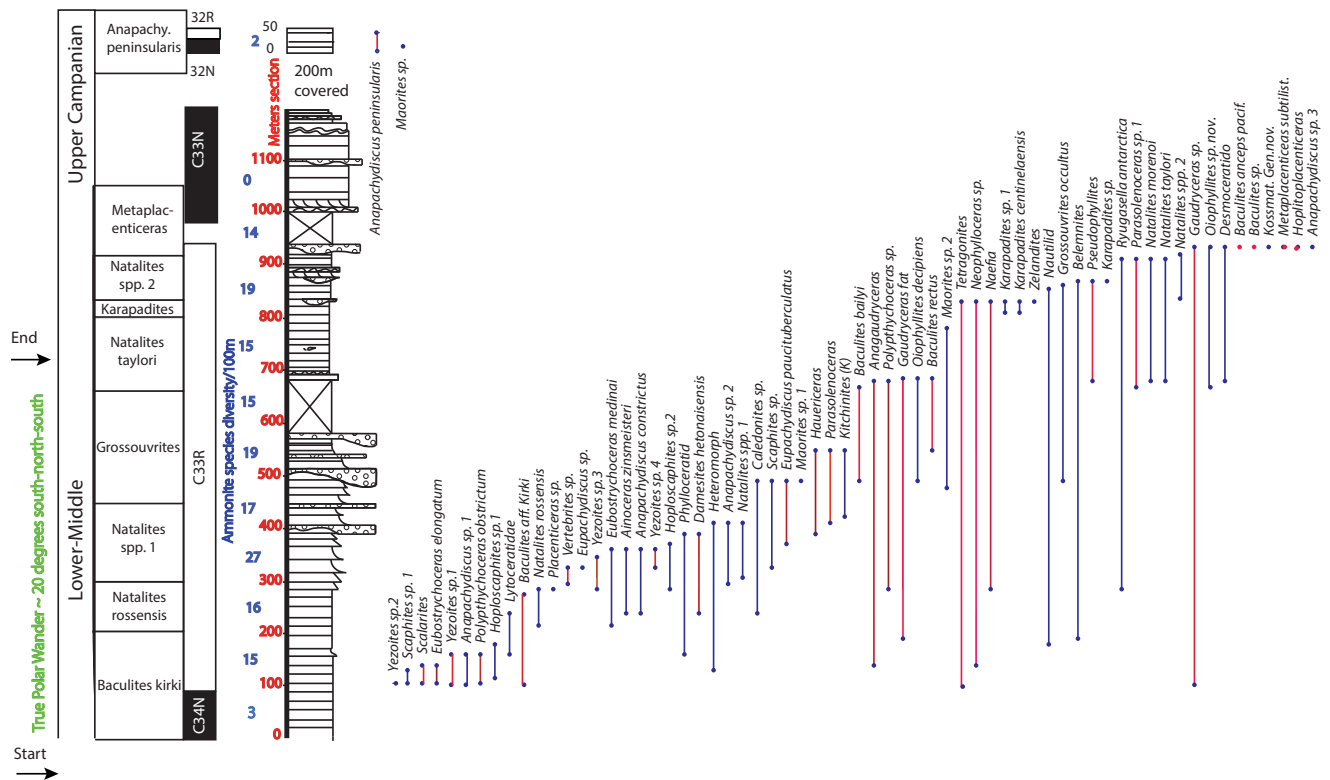
**Reversal boundaries and biostratigraphy:** Our oldest samples (Hidden Lake Formation, from section HL) are of normal polarity, and, as noted

above, are overlain by a thick succession of reversed polarity, making up most or all of the Santa Marta Formation on James Ross Island. These lowest samples (in section HL) we interpret as correlative with magnetochron 34N, the highest part of the "Cretaceous Long Normal", because of the presence of Santonian-aged fossils (among ammonites [6] and inoceramid bivalves [14], among other taxa, in the high part of the Hidden Lake Formation and the basal Santa Marta Formation. Samples from H4 and MOT showed both normal and reversed polarity,

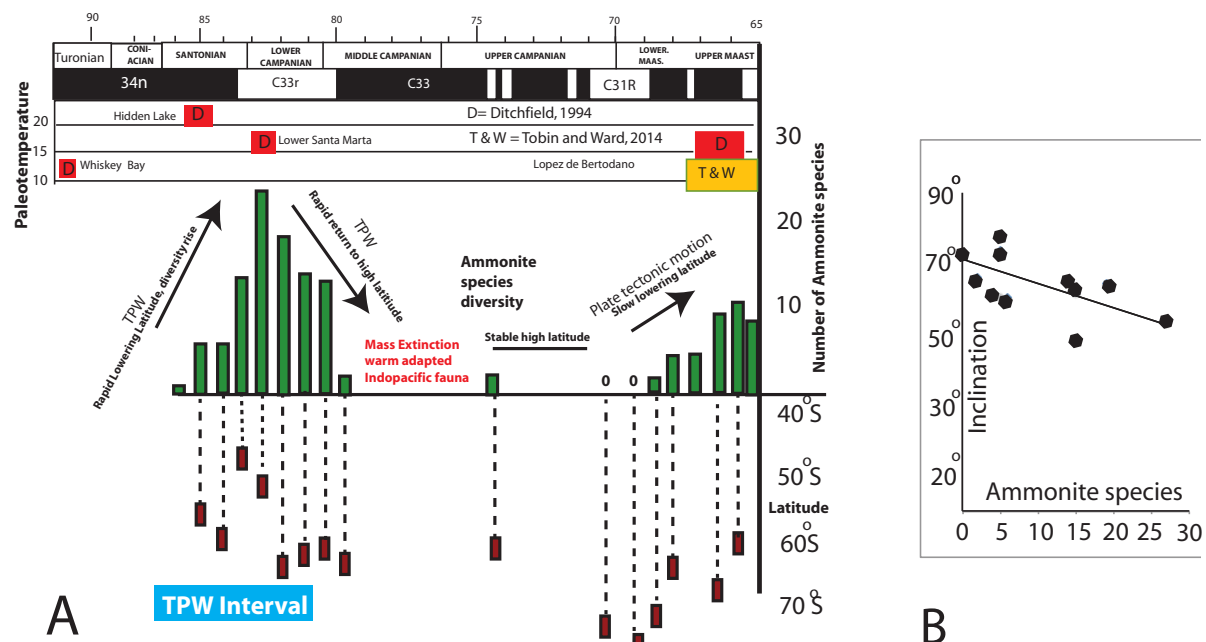


The strata of normal polarity are overlain by a thick interval of reversed polarity of the Santa Marta Formation; the greatest part of this formation, in fact, is reversed being composed of strata deposited during Chron 33R. Near the top of that formation, near the top of section F16, we recovered normal polarity once again. We interpret this as the 33R-33N-chron transition, which would make it correlative to the recently described transition from Reverse to Normal Polarity from another, but isolated section on James Ross Island [15], which has yielded an ammonite fauna that is equivalent to the *Baculites inornatus* assemblage recognized from our study area, as well as to the ammonite

From the base of section D8 upward, there is in-



**Figure 6:** Ranges of ammonites from James Ross Island plotted against sections. Ammonite species shown in red are shared with Indopacific Province ammonite species, [6-8]. Ranges of Indopacific ammonites come from [16]. The interval of True Polar Wander identified on far left of graph.



**Figure 7:** Summary figure integrating time, ammonite diversity, paleotemperature, and interpolated paleolatitude (from inclination data presented here and in Tobin, et al. [1] for the entire basin for the Late Cretaceous. There is a significant correlation between ammonite diversity and inclination, in line with ecological results from modern day organisms of higher diversity correlated to lower latitudes. Temperatures come from sources listed in the figure.

creasing cover, and little fossil record in the stratal layers that are exposed. Between (or perhaps partially overlapping) section D8, and the base of section 14S there is a further fossiliferous section, section QF, that unfortunately appears to be a slump block and not in place. It was not sampled for magnetostratigraphy. However, section 14S, exposed along the shoreline of Whiskey Bay, was sampled, and is extremely important for both chronostratigraphic as well as paleoecological results. This approximately 60 m thick section was exceptionally fossiliferous, and is also the sole place in our study on James Ross Island where unaltered aragonitic fossils could be recovered. We found a final, normal-to-reversed polarity change in the section 14S. However, at least 200 m of covered section separates the highest samples of section D8 from the lowest of 14S.

This section (14S) represent the highest Campanian beds on James Ross Island. This section is represented graphically as continuous with the long section of Santa Marta Formation, and lowest Snow Hill Island Formation beneath it [7]. Based on the magnetostratigraphic results, it is older (lower) than the Campanian-Maastrichtian boundary, and probably one zone older than even the last ammonite zone of the Upper Campanian in the Northern Hemisphere, the *Nostoceras hyatti* Zone. This locality is entirely within the Snow Hill Island Formation, and is of both reversed and normal polarity, placing it within the C32R-32N chron boundary transition. While ammonites in section are numerous, (and large; virtually all are planispiral ammonites up to 1.3 m in diameter), their diversity is low: only two species, and all other invertebrate fossils are rare. The most common species, earlier identified as *Anapachydiscus* sp. 3) [6] is, based on our interpretation, a homeomorph (or is) the well-known Indopacific species *Anapachydiscus peninsularis*.

In Baja California, at the locality known as San Antonio del Mar, this species ranges through part of Chron 32R [16]. Thus for structural (position within the succession) and biostratigraphic reasons. this reversed interval on James Ross Island is most parsimoniously identified as 32R, making it the same age as the well-studied beds of Hornby Island, Vancouver Island region, that contain *Baculites occidentalis* and *Nostoceras hornbyense* as well as in the Rosario Formation of Baja California.

## Ammonite diversity and identifications

The identities of the ammonites observed in this study are the result of the superb, lifetime work of Eduardo Olivero, who not only collected the vast majority of specimens from James Ross island, but was the first to recognize the appearance of Indopacific species, and the species shown and their ranges are mainly the product of Olivero and his co-workers. The only significant change we propose is that *Baculites rectus* is a junior synonym of *B. chicoense*. This change, however, is important, and allows a further erection of a zonation based on cosmopolitan, Indopacific ammonite species that can augment the current biostratigraphy, that is based mainly on endemic species. The only morphological difference between *Baculites rectus* and *B. chicoense* is that most of the James Ross Island specimens lack the ventral keel that many (but not all) of *B. chicoense* from California and the Nanaimo Group possess. However, recent work [16] showed that presence or absence of a keel is not sufficient to serve as a single character that identifies a specific species. Keels were observed to appear in changing percentages of both *B. inornatus* from the Nanaimo Group, California, and the Rosario Formation of Baja California, as well as among specimens of *B. gregoryensis* of the Western Interior. The recognition of *B. chicoense* from James Ross Island is not particularly surprising because of the presence of many other species of western, North America affinity amid the strata of Chron 33R on JRI, as shown in Figure 6, based on prior identifications [6-8] and our own identifications of ammonites. The complete diversity of ammonites we recognize from JRI, tied to the GPTS is shown in Figure 6.

## Inclination, diversity and paleotemperatures

We show the relationship between ammonite diversity, inclination, and previously published paleotemperatures in Figure 7. These data show that the rapid diversification of ammonites coincided with a reduction in paleolatitude (toward warmer water), while the reverse of this trend, starting in the Lower Campanian, coincided with the observed Campanian extinctions. The new chronostratigraphic data also confirms that the time interval of these ammonite diversity changes was consistent with the time interval previously identified for a Late Santonian into early

Campanian TWP event. The rate of movement of a 20° Santonian TPW event that was identified from other regions [18] indicates no less than a half meter per year movement, compared to the plate tectonic speed limit of less than 20 mm/year.

Our data indicate that maximum ammonite diversity corresponded to both the most outward (lowest latitude) position as well as the highest measured temperatures in the MG basin [19], while subsequent diversity lows from the Upper Campanian to the Upper Maastrichtian all took place while the MG was at or above 70° South. The significant relationship between MG paleolatitude and ammonite diversity that our data has revealed is shown in Figure 7.

Finally, there was a new movement toward lower (warmer) latitudes in the Late Maastrichtian, one that also corresponded to both an ammonite diversification, as well as temperature increase in the basin (Figure 7). However, this Late Maastrichtian ammonite fauna never reaches the number of species from the basal Campanian, maximum outboard position, and in comparison to other regions with latest Maastrichtian ammonites is of lower diversity. These species, including the important, zonal index pachydiscid as well as kosmaticeratid ammonites are all endemics.

The same trend may have occurred in inoceramid bivalves. In the Upper Santonian beds on James Ross Island, we collected numerous specimens of mytiloid and platycerimid bivalves belonging to the Inoceramidae. Both are morphologically similar to the Indopacific species *Inoceramus (Mytiloides) naumanni* and *I.(M). orientalis*, as well as *Inoceramus (Platyceramus) ezoensis*, indicating that like the ammonites, an Indopacific inoceramid fauna was present. However by the early Campanian ammonite diversity crash, the Indopacific inoceramid fauna also went extinct, and probably for the same reason. Only in the Upper Campanian is there a new record of an inoceramid in the basin, but it was short lived, endemic, and highly unusual in morphology compared to the Santonian, Indopacific inoceramids. For all practical purposes, the extinction of the (typical) inoceramids occurred early in Chron 33R.

Among the early extinctions, from strata now magnetostratigraphically dated, were scaphitid, baculitid, and nostoceratid ammonites (including

species of the Indopacific (or global) genera *Baculites*, *Polypychoceras*, *Eubostrychoceras*, *Ryugasella*, *Ainoceras*, *Pseudoxybeloceras*, and at least two different species of coleoids. These “early” disappearances were unique for the Late Cretaceous marine world as has been previously pointed out by Antarctic paleontologists as referenced above. To date there have been no explanatory hypothesis, other than generalized suppositions that temperature change, or oxygenation of the deeper basinal waters, may have been involved. None of these seem viable [20].

Re-diversification of ammonites did not occur until the start of the Late Maastrichtian, and even then the diversity and more importantly the assemblage of ammonite morphotypes of this last Antarctic ammonite fauna was different from all other known Late Maastrichtian ammonite faunas, which elsewhere have significant numbers of scaphitid, diplomoceratid, nostoceratid, and baculitid heteromorphs. For example, in the Bay of Biscay, the best studied Late Maastrichtian to K-Pg boundary site known, over 25% of the fauna (33 species) were heteromorphic, compared to one out of the only nine species of Late Maastrichtian ammonites from Antarctica.

## Discussion

Because of the presence of Indopacific ammonites in Antarctica, an important question is whether the ranges in both places are similar, and if not, which occurred first: Did the species first appear in Antarctica and migrate north, or vice versa? Vertebrate paleontologists are asking similar questions: Was the JR Basin a cradle of origination?

The ranges of Nanaimo Group ammonites over the approximate Santonian through Campanian from the Vancouver Island (Figure 6) region has the best stratigraphic range information of anywhere in the Indopacific Province. The recent discovery that Chron 33N extends down into the Elongatum Zone of both the Vancouver Island as well as Sacramento Valley (Forbes Formation and Chico Formation; Mitchell, et al. in Review) [21] appears to be significantly different than its lower range on James Ross Island, where the index species is entirely contained in 33R, indicating that its range in the Indopacific Province might predate its first appearance in the Antarctic province. The majority of the Elongatum Zone in North America is within



Chron 34N, whereas it does not appear in normal polarity beds on JRI, indicating that it arrived only later in Antarctica.

The only other difference (if indeed there is one with *Eubostrychoceras elongatum*) in ranges based on presence or absence of chrons could be for *Baculites inornatus*, which is known to range across the Chron 33R -33N transition, appearing in the Rosario Formation in normal polarity, but in reversed polarity elsewhere in the province (Sucia Island, of the Nanaimo Group, and Sand Creek and elsewhere in the Forbes Formation of the Sacramento Valley [16,17]. On JRI, all specimens of *B. inornatus* come from reversed polarity (Chron 33R). However, the large covered interval between sections D8 and 14S could very well obscure a similar higher range of this taxon in the Antarctic Province.

To date there has been no single (or multiple hypotheses) that could explain the biogeographic, diversity, and extinction patterns of ammonites in the Marambio Basin during the Santonian through Maastrichtian Age time interval that seem viable. There are only guesses. One such that we propose here is that the circum-Antarctic current was present in the late Cretaceous (Santonian, shut off for the late Santonian into Campanian) and then started again, with its presence essentially fencing off the MG basin from any other kind of faunal exchange. However, there is abundant geological evidence that this circum-Antarctic current did not start up until age estimates of 32 to 35.5 Ma [20], and in any case this cannot explain the paleolatitudinal data reported here. That there was a TPW event seems more likely.

Until now, two large scale biotic process (pre-KPg extinctions, and a short-lived interval of changing biogeographic affinity in the basin), and one physical change (a major paleotemperature change independently reported affecting the Marambio Group (Late Cretaceous-Eocene) of the Antarctic Peninsula have been treated as independent, and both have remained unexplained for decades, beyond unsatisfactory generalization about changing sea level and ocean temperatures caused by gradual climate change over this time interval. The data presented here provide evidence for a paleobiologically significant TPW event, and in so doing finally answer long running paleobiological questions about the Late Cretaceous macrofauna

of Antarctica. There is previous evidence that such an event occurred in the Late Cretaceous [18], and prior paleotemperature analyses indicate warmer temperatures during the late Santonian than from the Maastrichtian fossils studied to date [19].

The James Ross Island data also can now be appended to the prior, published magnetostratigraphic record of the Maastrichtian on Seymour Island to present a combined, Santonian through Maastrichtian paleomagnetism record for the James Ross Basin Upper Cretaceous. While there remain “holes” in this record, most noticeably the exact placement of the top of chron 33R, in fact the all post 34N, “long normal” chrons of the Upper Cretaceous can now be recognized, which allows a new, independent dating scheme for testing hypotheses of global biotic and environmental change in high southern latitudes for the end of the Cretaceous.

It is the latter series of bioevents that are perhaps the most interesting development to come from the biostratigraphic studies of Late Cretaceous fossils in the James Ross Island Basin. These include what appear to be both anomalously early appearances of groups (such as the early appearance of the otherwise, Late Maastrichtian planktonic foraminifera *Abathomphalus mayaroensis* from Campanian strata) as well as the early extinctions of fossil groups that elsewhere ranged higher in time. For instance, the disappearance of inoceramid bivalves occurred earlier in Antarctica than anywhere else in the world, as did the disappearance of both baculitid and nostoceratid ammonites. By the *Nostoceras hyatti* zone, the highest zone of the Campanian with almost worldwide extent and a zone that in time immediately succeeds our highest magnetostratigraphic samples on James Ross Island, the ammonite faunas of the Antarctica region appear to have been totally cut off from the rest of the world, fueling speciation of endemics. This change-over to a highly endemic assemblage of zonal index fossils, and because of the lack of aragonite from James Ross Island Late Cretaceous aged strata has precluded the use of Sr isotope dating, and is in large part a reason that independent age control for verifying age calls at even a substage level have been important.

While the Santonian-aged species noted from the lowest Santa Marta beds have been given names identified from southern, Indopacific-aged

inoceramid taxa, we find (although none of us are specialists on inoceramids) that the Santonian-aged inoceramids appear morphologically indistinguishable from *Sphenoceras orientalis*, and *Platyceras ezoensis*, (Figure 4) both of which are found in California and the Vancouver Island region with *Eubostriocheras elongatum*, *Eupachydiscus* sp. aff. *E. haradai*, and *Baculites baileyi* in both North Pacific, Indo-Pacific, and Antarctic strata. Our new magnetostratigraphic data thus provides and opportunity to test whether these co-occurring species have similar time ranges or are diachronous in FADs or LADs. It appears, in fact, that the appearance and disappearance of these taxa relative to the Chron 33R boundary are synchronous in both places.

The most striking aspect of the ammonite record from the Santonian-through Campanian strata of James Ross Island concerns the rapidity of diversity in the high Santonian, and and equally rapid (and equally puzzling diversity drop between the rich and diverse ammonite fauna below our section D8, and from D8 all the way up to the Upper Maastrichtian of Seymour Island [22].

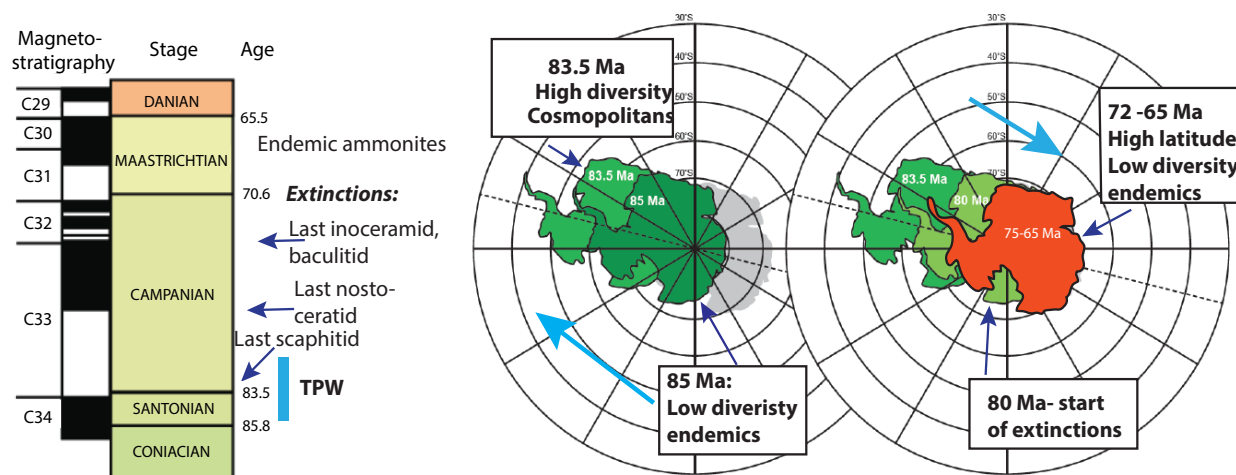
For the first time, the presence of a shared magnetostratigraphic record allows comparison of the JRI diversity drop to coeval time in the Indopacific Basin. Using Figure 6, it appears that there is also a diversity drop (albeit of less magnitude in the Nanaimo and Sacramento Basins. The rich and diverse fossils of the Vancouverense Zone in both places is followed by the extremely low diversity assemblages of Chron 33N in both Nanaimo and

Sacramento Valley, on both sides. For instance, the fossil rich assemblage of low 33N at Punta San Jose contains no planispiral ammonites at all [16,17]. Similar strata on Vancouver Island also shows a marked diversity drop late in Chron 33R and into 33N. These beds are overlain by a low diversity assemblage with mainly *Metaplacenticeras* spp. for some millions of years, prior to the advent of the return to high diversity present in California (the Pachydiscus Silt of the San Joaquin Valley) and Hornby Island, Nanaimo Group. Whether this is an effect of sea level, or other, perhaps global events remain to be seen.

What remains enigmatic are 1) The anomalously high diversification of ammonites, 2) Of a different biogeographic realm than was present in Coniacian time, that 3) Occurred in a short interval of geological time and, was 4) Accompanied by evidence of rapid warming, followed by 5) Equally rapid extinction, and 6) Cooling. The movement of Antarctica during the Santonian and early Campanian, as shown in Figure 8, is a viable hypotheiss explaining all of these lines of evidence.

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**Figure 8:** Graphic showing proposed TPW movement of Antarctica, illustrating the relative geographic movement of Antarctica during the hypothesized True Polar Wander event in the Santonian.

Antarctic program. Thanks to Tom Tobin for running the magnetic core samples while at Cal Tech, to Joe Kirschvink, Tobin, Shane Schoepfer, Kelly Hillbun, and David Smith for help in the field. Tom Tobin drafted Figure 1.

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