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MARINE RESEARCH IN THE LATITUDINAL GRADIENT PROJECT ALONG VICTORIA LAND, ANTARCTICA

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Short title: Antarctic marine latitudinal gradient research

SUMMARY: This paper describes the conceptual framework of the Latitudinal Gradient Project that is being implemented by the New Zealand, Italian and United States Antarctic programs along Victoria Land, Antarctica, from 72^{o}S to 86^{o}S to assess the dynamics and coupling of marine and terrestrial ecosystem in relation to global climate variability. Preliminary information about the research cruises from the R/V "Italica" and R/V "Tangaroa" along the Victoria Land Coast in 2004 is presented. As a global climate barometer, this research along Victoria Land provides a unique framework to assess latitudinal shifts in 'sentinel' environmental transition zones, where climate changes have an amplified impact on the phases of water.

Key words: Latitudinal Gradient Project, Victoria Land, Antarctic, global climate change

RESUMEN: **Investigaciones marinas a lo largo de Victoria Land.**
Este trabajo describe el marco conceptual del proyecto "Gradiente latitudinal" que ha sido implementado por los programas antárticos de Nueva Zelanda, Italia y EE.UU. a lo largo de Victoria Land (Antártida), 72°S - 86°S). El objetivo de este proyecto es evaluar la dinámica y el acoplamiento de ecosistemas marinos y terrestres con relación a los cambios climáticos globales. Se presenta información preliminar acerca de los cruceros científicos de los buques

R/V "Italica" y "Tangaroa" a lo largo de la costa de Victoria Land en el año 2004. Como un barómetro climático global, esta investigación provee un marco de trabajo único para observar y evaluar cambios latitudinales en zonas de transición medioambiental, donde los cambios climáticos tienen un impacto amplificado en las fases del agua.

Palabras clave: Projecto Gradiente Latitudinal, Victoria Land, Antártida, cambio climático global

INTRODUCTION

Coastal zones of continents and oceans - where terrestrial and marine ecosystems interact - are regions of high biological and physical diversity, which generally are heavily utilized by human populations. Distinguishing natural and anthropogenic impacts in coastal zones and throughout the Earth system is a major challenge of science in our global society (Berkman 2002). The Antarctic coastal zone, while utilized by humans to a limited extent, is among the most pristine regions on the planet for unambiguously assessing such global changes. The purpose of this paper is to review the results of the Latitudinal Gradient Project (http://www.lgp.aq/) along the coast of Victoria Land, Antarctica, with emphasis on the marine research.

The Victoria Land coastal biome is defined by the complex of adjacent terrestrial and marine ecosystems that occupy permanently ice-free oases and outcrops on land, as well as periodically open-water and ice-covered habitats in the ocean, from approximately 72^{o}S to 86^{o}S (Fig. 1). Across this latitudinal gradient, ecosystems are operating at the liquid margin of life where climate changes have an amplified impact on the phases of water. This latitudinal gradient parallels the predominant trend of ice-sheet expansion and retreat associated with global climate changes (Conway et al. 1999). Consequently, in an experimental context, Victoria Land provides a spatial gradient for evaluating environmental and ecosystem variability that otherwise would be recognized only through time. These features frame the rationale and activities in the Victoria Land Latitudinal Gradient Project that began emerging in 1999 under the coordination of Antarctica New Zealand, Italian Programma Nazionale di Richerche in Antartide and United States Antarctic Program (Berkman and Everett 2001).

The Latitudinal Gradient Project along Victoria Land is complemented by the Regional Sensitivity to Climate Change program that is being sponsored by the Scientific Committee on Antarctic Research to assess terrestrial ecosystem responses to environmental and climate changes in the south polar region (http://www.riscc.aq). Together, the marine and terrestrial components of these latitudinal gradient research programs are contributing to our understanding of species, community and ecosystem responses to global changes (Walther et al. 2002).

Research Framework for the Latitudinal Gradient Project:

The climate-driven dynamics and coupling of marine and terrestrial environments and ecosystems along Victoria Land are influenced strongly by different forms of ice (Table 1). As the solid phase of water, ice represents aspects of the hydrological cycle that impact: moisture exchanges; marine, freshwater and terrestrial ecosystem dynamics; and the basic availability of liquid water for terrestrial life. In particular, sea ice has a pronounced influence on the dynamics of marine and terrestrial ecosystems as one of the most integrated natural phenomena in the Antarctic region. Because of diverse hydrological, glaciological, oceanographic and meteorological feedbacks, there also are numerous gradients and thresholds in the types and distributions of sea ice along Victoria Land today. For example, from west McMurdo Sound to the Drygalski Ice Tongue there is landfast sea ice that is associated with supercooled water moving northward from under the Ross Ice Shelf. In contrast, annual sea ice occurs in east McMurdo Sound and north of the Drygalski Ice Tongue, which also influences the open-water region of the Terra Nova Bay polynya. These features of ice formed the basis for the following collaboration topics in the Victoria Land Latitudinal Gradient Project:

Collaboration Topic 1: Environmental thresholds across the latitudinal gradient of Victoria Land (e.g. continental shelf break, Drygalski Ice Tongue and Ross Ice Shelf) have a significant influence on the complexity of associated marine and terrestrial ecosystems.

Collaboration Topic 2: Across the latitudinal gradient of the Victoria Land system, ecological responses to land-air-sea interactions associated with climatic variability are amplified by ice (Table 1) and the availability of liquid water.

Collaboration Topic 3: Marine-terrestrial coupling across the Victoria Land system varies over time and space in relation to transfers of mass (sediments, salts, gases, water, nutrients, organic matter and organisms), momentum (currents and winds) and energy (latent heat).

In effect, collaborative topics #1 and #2 provide alternative hypotheses that could be tested and modeled to interpret ecosystem and environmental variability along the latitudinal

gradient of Victoria Land (Fig. 2). In addition, the ice dynamics along Victoria Land, lead to the identification of three zones (Fig. 1) that are distinguished by the duration of ice cover in the ocean:

Open Water Zone	Annual sea-ice retreat and exposure of open water;
Fast Ice Zone	Episodic retreat of sea ice every few years; and,
Ice Shelf Zone	Continuous ice coverage on the ocean over millennia.

Marine Ecosystem Features along Victoria Land:

Marine ecosystems along Victoria Land are known to vary across the latitudinal gradient in terms of maximum sea-surface temperatures; sea-ice extent, productivity and species assemblages. Oceanographic surveys indicate that maximum sea-surface temperatures are greater than 2^{o}C north of the Drygalski Ice Tongue but are less than 0^{o}C in McMurdo Sound to the south (Jacobs and Guilivi 1998). Sea-ice along the coast of Victoria Land also varies with current patterns, harbours and embayments, katabatic wind regimes and ice-tongues. Generally, in west McMurdo Sound, there is multi-year sea ice, which can increase in thickness to nearly 6 metres depth over periods longer than six years. On the other end of the extreme are open-water areas, like the Terra Nova Bay and Ross Sea polynyas. Responding to their environments, marine species along Victoria Land may vary in terms of their distributions and abundances; life history patterns, morphologies and energetics; and biochemical and physiological adaptations.

Most of our understanding about benthic marine communities along Victoria Land is limited in geographic scope to McMurdo Sound (which has been extensively surveyed by the United States and New Zealand Antarctic programs) and Terra Nova Bay (which has been extensively surveyed by the Programma Nazionale di Richeche in Antartide). It is known that benthic algae are luxuriant in the Terra Nova Bay region with vibrant stands at depths less than 20 meters, whereas they are virtually absent in most areas in west McMurdo Sound. These benthic macroalgae also include extensive coverage of coralline red algae on virtually all rocks in shallow water in the Terra Nova Bay region while they are rare in McMurdo Sound. This distribution of calcareous benthic algae is, in part, related to the warmer sea-surface temperatures and decreased solubility of calcium carbonate in the Terra Nova Bay region. Current New Zealand research is utilising these natural gradients in environmental conditions and productivity along the latitudinal gradient encompassed by the Victoria Land Coast, to

investigate how variation in sea ice cover and primary production sources effects the structural and functional biodiversity of coastal benthic ecosystems. Climate related environmental processes will influence community dynamics and spatial structure of benthic populations, and hence there is potential for regional climate variability to impact on ecosystem structure and function.

Among the benthic macroinvertebrates, species like the circum-Antarctic scallop (A*damussium colbecki*) provide experimental templates for comparing and contrasting environmental conditions between habitats. For example, like the distribution of coralline algae, *Adamussium* shells are significantly thicker in Terra Nova Bay than in McMurdo Sound with stable isotope signatures that further reflect the relative seawater temperatures and production levels between these regions (Berkman et al. 2004). There also are indications that *Adamussium* are releasing their gametes later in the austral summer and producing larger planktonic larvae in Terra Nova Bay than in McMurdo Sound (Chiantore et al. 2000). In addition, there are marked differences in the abundance and depth distributions of both *Adamussium* and *Sterechinus neumayeri* (urchin) between McMurdo Sound and Terra Nova Bay (Chiantore et al. 1998, 2001).

At the upper trophic levels, fish species have been an important research focus along Victoria Land because of their accessibility and utility for assessing adaptive responses to environmental variability. Fish trawls have provided important baselines for characterizing marine community structures, diversities and distributions in relation to oceanographic conditions along Victoria Land with additional sites proposed from south to north (Eastman and Hubold 1999):

- Erebus Basin as a baseline for high-latitude deep-water locality;
- Sponge beds as sites of topographic and trophic complexity leading to high fish diversity;
- Crary or Mawson banks as sites of high diversity surrounded by deep water areas;
- Drygalski Trough as site of deepest and largest inner shelf depression in the Ross Sea;
- Cape Adare as a continental shelf transition zone; and
- Iselin Seamount as a site of faunal transition and dispersal into the Ross Sea.

Antarctic fish are unique among vertebrates as the only fauna to have species (family Channichthyidae) without hemoglobin in their blood. Glycoprotein antifreezes, as well as other biochemical and physiological adaptations, reflect additional adaptive responses at the extreme of cold seawater temperatures. Relatively subtle increases in seawater temperatures could alter the physiological and biochemical processes among Antarctic fish faunas. Moreover, seawater

temperature increases could lead to the incursion of species not generally found in the high latitudes that would further alter fish community compositions, interactions and dynamics.

Environmental conditions and suitable habitats similarly influence the distribution of avian faunas in the Ross Sea region. For example, the distribution of penguin rookeries is closely coupled with sea-ice coverage because of their required access to open-water areas where they forage. Today, the largest Adélie penguin (*Pygoscelis adelie*) rookery in Antarctica occurs in Cape Adare with most southern rookeries along Victoria Land in the vicinity east McMurdo Sound, where there is direct coastal access to open water each year. Guano deposits from these penguin rookeries, which include remains of their prey as well as organic materials for radiocarbon dating (Emslie et al. 2003), provide information for assessing their past distributions and palaeo-environmental conditions.

Among the marine mammals, the southernmost seal species on Earth is the Weddell seal (*Leptonychotes weddellii*). This seal species, which is adapted to fast-ice environments, occurs throughout the coastal region of Victoria Land but with larger abundances in areas where there are cracks through the sea-ice and there is underwater access. In connection with the Antarctic Pack Ice Seal (APIS) program in the 2000 austral summer, monitoring of seal populations revealed an apparent latitudinal gradient in crabeater seal (*Lobodon carcinophagus*) density along four north-south transect lines in the Ross Sea. Long-term population measurements of seal populations in McMurdo Sound further reveal potential connections with inter-annual and inter-decadal oscillations in the global atmosphere.

The corresponding history of ecosystem development along Victoria Land, which only became possible after habitats were no longer covered by ice sheets, is reflected by Holocene deposits in marine sediments, emerged beaches, terrestrial lakes, terrestrial ecosystems, penguin rookeries and ice cores. In particular, beginning around 6000 years ago, the Ross Sea region entered a new phase in ecosystem dynamics in conjunction with global climate conditions and local environmental changes in sea-ice coverage (Emslie et al. 2003). These ecosystem changes are reflected by the geochemistry of the ice sheet in the terrestrial zone, occurrence of marine species in the coastal transition zone and deposition of phytoplankton species in the marine zone along Victoria Land (Berkman et al. 2004). This period during the Holocene, which represents the current interglacial climate phase that began 10,000 years ago, is most relevant to understanding ecosystem dynamics today.

Latitudinal gradient research cruises in the Ross Sea in 2004

The first ship-based marine campaigns in the framework of the Victoria Land Latitudinal Gradient Project were conducted in early 2004 on board the R/V "Italica" (3 - 22 February) and

R/V "Tangaroa" (3 February - 7 March). The principal sites investigated by the R/V "Italica" were Cape Adare, Cape Hallett, Coulman Island, and Cape Russell. Contemporaneously to this Italian expedition, a 'sister' cruise by the R/V "Tangaroa" from New Zealand explored the marine benthic biodiversity and mapped the seabed of the northwestern Ross Sea and Balleny Islands.

The R/V "Italica" cruise involved extensive sampling of a range of deeper environments along the Victoria Land Coast, that will enable both latitudinal and depth-related comparisons of the benthic communities and habitats. At each location, sampling was conducted along transects arranged along depth gradients, with stations at nominal depths of 500, 400, 300, 200 and 100 m. Preliminary benthic community characteristics are shown in Table 2.

In addition, scientists from the Seafloor Mapping Lab from California State University Monterey Bay performed high-resolution acoustic remote sensing (multibeam and sidescan sonar) along with remotely operated vehicle video mapping. All sites were investigated with these remote survey tools, with the exception of Coulman Island where a heavy sea-ice cover extended from shore out to the 400 m depth contour (Table 3). The multibeam imagery revealed extensive ice scouring that varied with location, depth and exposure. A wide variety of ice disturbance features were clearly visible from shallow scrapes less than 1-m deep to broad gouges 100 m wide with greater than 8 meters of vertical relief from trough to berm (Fig. 3).

In general, the preliminary multibeam results reveal a subtidal landscape dominated by a mosaic of disturbance patches stratified by depth and in various stages of recovery. Habitats at depths of 200-300m and unprotected by topographic highs are exposed to the massive impact of tabular icebergs hundreds to thousands of metres in horizontal dimensions that come from the 300m thick Ross Ice Shelf. The scours made by these giants are unmistakable due to the depth range in which they occur, and by the characteristically broad and extremely flat "road-like" appearance of the features. In the 40-150 m depth range, the scours tend to be narrower, carved by more pointed ice keels ending in a terminal pit.

Antarctic benthic communities are strongly influenced by iceberg disturbance (Gutt 2001), but to date there have been few investigations on the extent (or frequency) to which this occurs in the coastal Ross Sea region (Lenihan and Oliver 1995). Preliminary investigations of shallow water benthos (<30 m) on the R/V "Italica" cruise indicated striking differences in abundance and diversity of macroalgae, and biogenic habitats in the northwestern Ross Sea compared with McMurdo Sound. This cruise has provided valuable insights into the relative importance of different environmental variables that structure communities in the coastal Ross Sea region and how they might change with latitude (e.g., iceberg disturbance, sea ice cover, light regime primary production sources), which will be assessed with future sampling.

A major objective of the *R/V Tangaroa* voyage was to collect information on the diversity of benthic macroinvertebrate and fish communities, and habitat types, along the northern Victoria Land coast and around the Balleny Islands. Phytoplankton productivity of the overlying water, physical disturbance of the bottom by icebergs, and the complexity of habitat forming species in affecting faunal distribution and biodiversity were also investigated. Together, this provides baseline information against which any impacts of the growing human presence in Antarctica and its increasing affects on the environment can be assessed.

Five across-shelf (generally aligned SW-NE) transects from 50 m bottom depth to the shelf edge (approx. 750m) were multibeamed to establish bathymetry, and benthic sampling was conducted within three depth strata (750-500, 500-250, 250-50m). The transects ran roughly perpendicular to the shoreline and were evenly spread from Cape Adare down to Cape Hallett. A wide variety of gear types was deployed: bottom trawl, beam trawl, epibenthic sled, and grabs each sampled different assemblages, and gave a much greater appreciation of macrofaunal diversity than would be gained from using just one or two types of gear (e.g., Arntz 1999). Camera deployment further added to information on the nature of benthic habitats, and information on sediment characteristics (e.g., particle size, organic carbon, chlorophyll content) was also collected. Preliminary results indicate marked differences in species composition between the Ross Sea and Balleny Island locations. In addition, the sessile fauna was dominated by sea squirts and corals in offshore (deeper) areas, and by sponges inshore.

CONCLUSIONS

Research along the Victoria Land Coast goes back to the end of the 18th century, with the first winter-over expedition in Antarctica (Borchgrevink 1901), and the 2004 research cruises of the R/V "Italica" and R/V "Tangaroa" are part of this rich history. The Latitudinal Gradient Project along Victoria Land provides an interdisciplinary umbrella to compile and integrate data, maps, figures, tables, geographic information systems and publications that have been collected for more than a century regarding the components, dynamics and chronologies of terrestrial and marine ecosystems and environments over diverse time and space scales in Antarctica. These interdisciplinary data involve the geology, limnology, meteorology, glaciology, oceanography and ecology associated with the southernmost ecosystems on Earth. For the future, this research on the coupling and dynamics of marine and terrestrial ecosystems along Victoria Land provides a unique framework to assess latitudinal shifts in ‘sentinel’ environmental transition zones (Fig. 1), as a global barometer that reflects climate dynamics.

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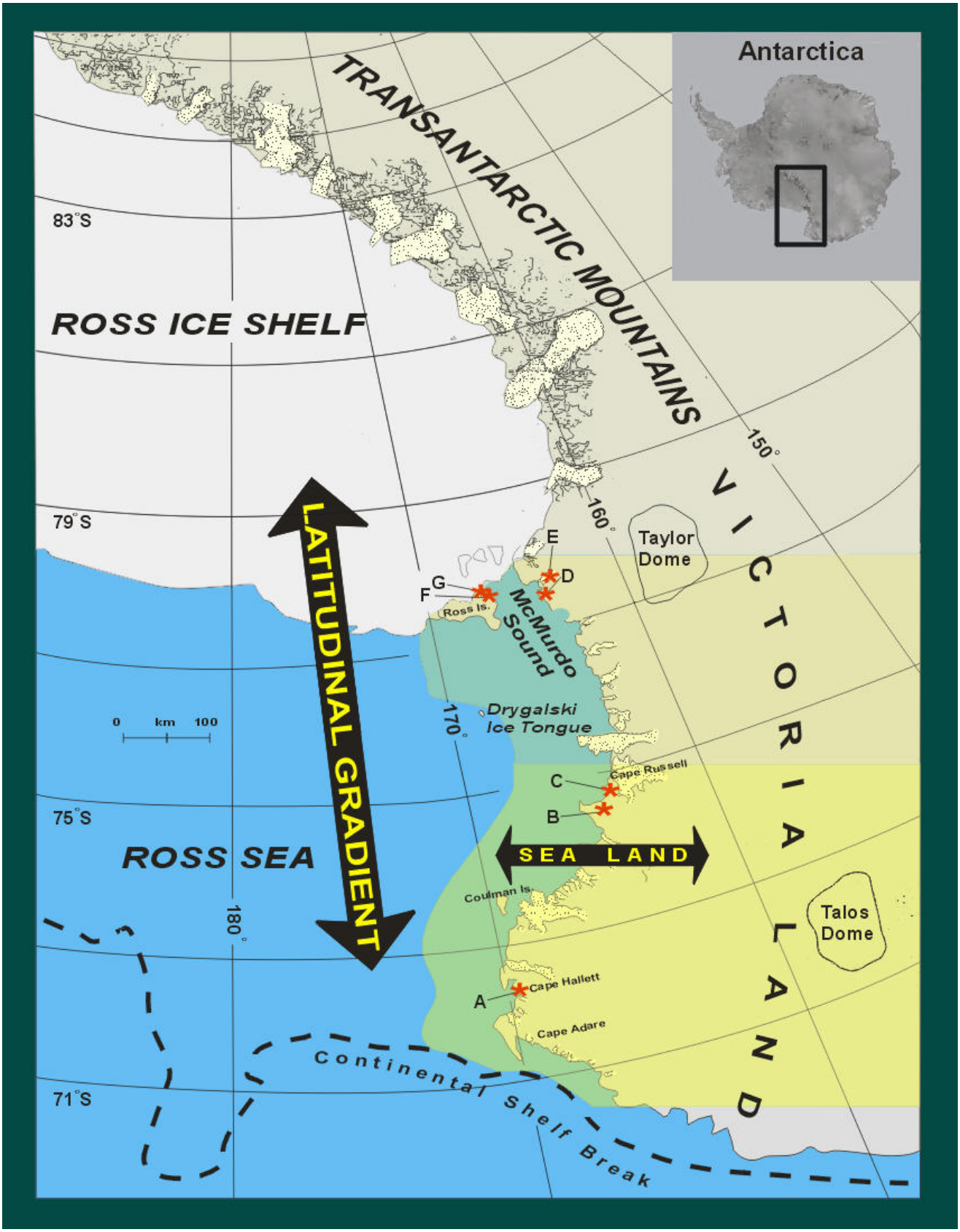
FIGURES

FIGURE 1: Spatial context of the Latitudinal Gradient Project along Victoria Land, Antarctica, from approximately 72°S to 86°S in the Ross Sea region. The principal research zones, which are recognized to have decreasing water vapor exchange between the ocean and land, from north to south are the: **Open-Water Zone** (south of Cape Adare to the Drygalski Ice Tongue in the Terra Nova Bay region); **Fast-Ice Zone** (south of the Drygalski Ice Tongue to McMurdo Sound and the edge of the Ross Ice Shelf; and **Ice-Shelf Zone** (south of the Ross Ice Shelf edge). National research stations, which represent the logistic centers for research along Victoria Land, are from north to south: **A** Cape Hallett (New Zealand and United States, summer only); **B** Gondwana (Germany, unoccupied); **C** Terra Nova Station (Italy, summer only); **D** Marble Point (United States, summer only); **E** McMurdo Long-Term Ecological Research sites (United States, summer only); **F** McMurdo Station (United States, year-round); **G** Scott Base (New Zealand, year-round). The map shading along Victoria Land represents the approximate boundaries between the open-water, fast-ice and ice-shelf zones that reflect the decreasing availability of surface seawater in its liquid phase with increasing latitude.

FIGURE 2: Alternative explanations for the variability in comparable ecosystem processes in marine, freshwater and terrestrial habitats (Table 1) across the latitudinal gradient of Victoria Land, Antarctica: **A** and **D** (linear ecosystem changes associated with environmental phenomena such as solar radiation and photo-periods) and **B, C and E** (non-linear ecosystem changes associated with environmental phenomena such as the number of freeze-thaw cycles and ice-tongue thresholds). From Berkman and Everett (2001).

FIGURE 3: Representative shaded relief multibeam image of the marine bottom in the Cape Hallett area along the Victoria Land Coast of Antarctica in the vicinity of 72°18'S and 170°16'E at 40-50 m depth. Topographic Position Index (TPI) analysis was applied to a 2-m Digital Elevation Model (DEM) grid of the same area and "tuned" to detect troughs (blue) and berms (red). These results indicate that 28.95% (12.72% troughs and 16.23% berms) of the 1,376,328 m^2 area was scoured by icebergs. The multibeam surveys on the R/V "Italica" cruise were produced by the Seafloor Mapping Lab from California State University Monterey Bay.


Antarctica
TRANSANTARCTIC MOUNTAINS
ROSS ICE SHELF
83°S
79°S
75°S
71°S
150°
160°
170°
180°
VICTORIA LAND
Taylor Dome
Talos Dome
McMurdo Sound
Ross Is.
Drygalski Ice Tongue
Cape Russell
Coulman Is.
Cape Hallett
Cape Adare
Continental Shelf Break
ROSS SEA
LATITUDINAL GRADIENT
SEA LAND
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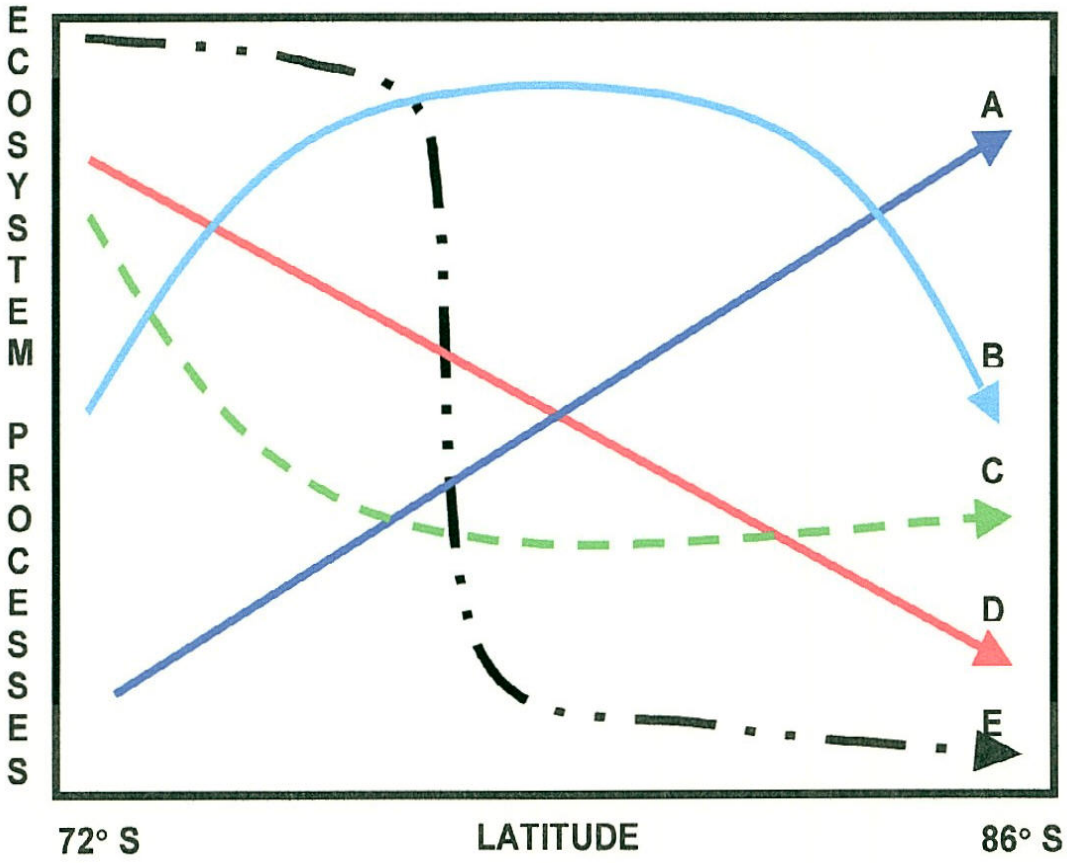
ECOSYSTEM PROCESSES
A
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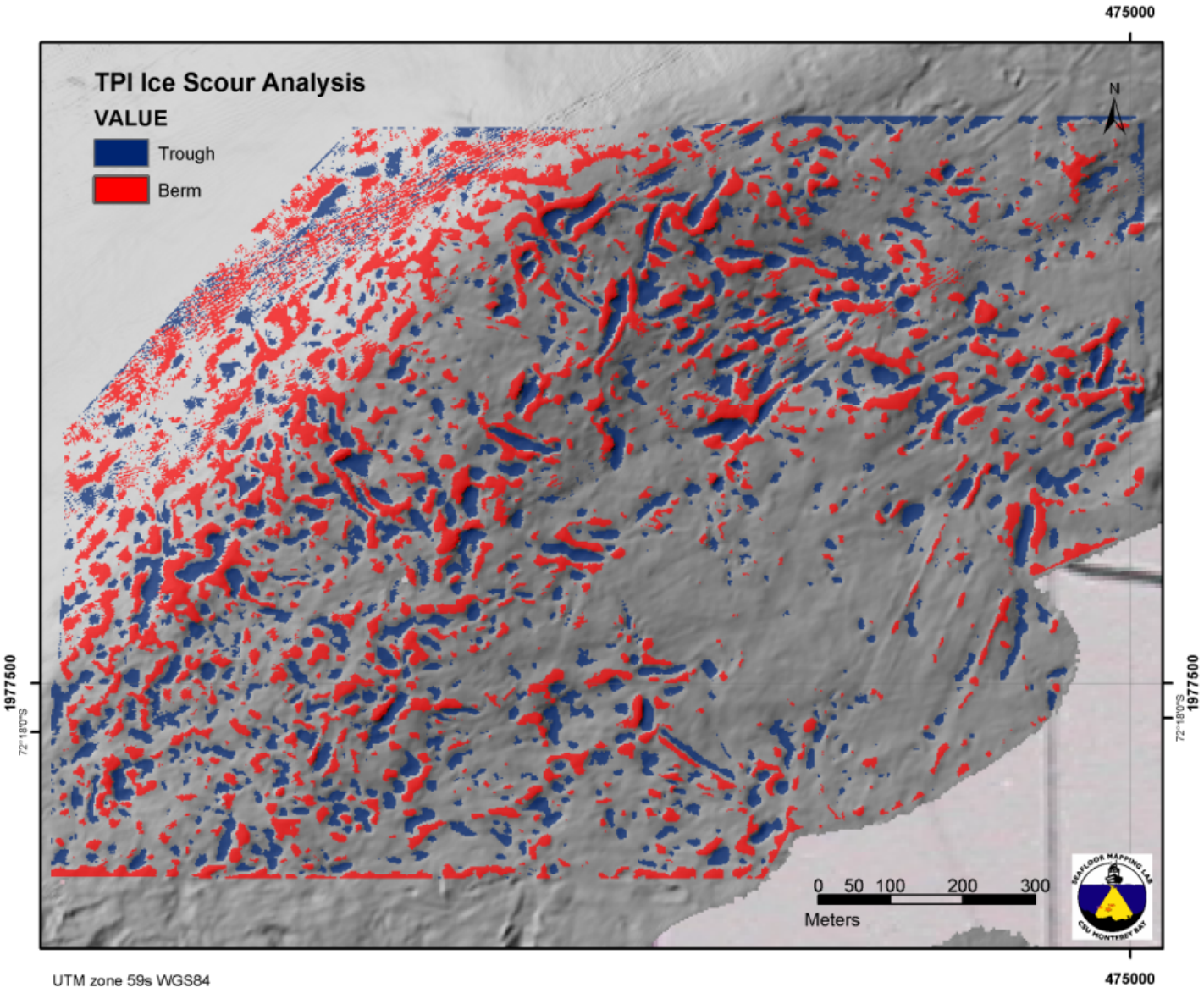
TPI Ice Scour Analysis
VALUE
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475000
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0 50 100 200 300
Meters
SEAFLOOR MAPPING LAB
CSU MONTEREY BAY
UTM zone 59s WGS84

TABLE 1: ICE ALONG VICTORIA LAND, ANTARCTICA

Habitats	Types of Ice
Marine	snow, sea ice, ice tongues, ice shelves, icebergs
Freshwater	snow, lake ice, glaciers, permafrost
Terrestrial	snow, glaciers, permafrost, land ice, ice sheets

TABLE 2: BENTHIC COMMUNITY CHARACTERISTICS ALONG VICTORIA LAND, ANTARCTICA, FROM THE 2004 R/V "ITALICA" CRUISE (FIG. 3)								
Site	**Latitude (S)**	**Longitude (E)**	**Station**	**Depth (m)**	**Substrate**	**Assemblage**	**Relative Biodiversity**	**Percent Dry Weight (mainly CaCO3)**
Cape Adare	71°15'.5	170°42'.2	A1	515-476	sand, cobbles	Ophiuroid community	LOW	69
Cape Adare	71°17'.3	170°39'.2	A2	430-421	Sand	Stylasterinids	LOW	
Cape Adare	71°18'.7	170°33'.5	A3	312-305	sand, rocks	Stylasterinids	MEDIUM	36
Cape Adare	71°18'.4	170°28'.9	A4	235-223	sand, cobbles	Tube-like ascidians	HIGH	47
Cape Adare	71°18'.8	170°26'.7	A5	139-124	sand, cobbles	Foliose ascidians	HIGH	41
Coulman I.	73°24'.5	170°23'.2	C1	480-474	mud, cobbles	Ophiuroid community	HIGH	94
Coulman I.	73°22'.7	170°06'.9	C2	410-372	mud, cobbles	Pterobranchia community	HIGH	85
Cape Hallett in	72°16'.7	170°09'.8	H-in 2	408-391	mud, cobbles	Gorgonians community	MEDIUM	79
Cape Hallett in	72°17'.2	170°12'.3	H-in 3	369-312	mud, sand, cobbles	Tube-like ascidians	HIGH	35
Cape Hallett in	72°17'.7	170°12'.2	H-in 4	266-228	mud, sand	Ophiuroids	LOW	43
Cape Hallett in	72°17'.1	170°14'.0	H-in 4bis	196		Botriform ascidians	HIGH	
Cape Hallett in	72°17'.6	170°12'.8	H-in 4tris	156-152	mud	Polychaetes	LOW	
Cape Hallett in	72°17'.2	170°17'.9	H-in 5	84		Botriform ascidians	HIGH	70
Cape Hallett out	72°15'.5	170°28'.3	Hout 1	537-475	mud, cobbles	Bryozoans + gorgonians	LOW	
Cape Hallett out	72°17'.1	170°29'.9	H-out 2	388-353	mud, sand	Flustridae	HIGH	77
Cape Hallett out	72°16'.3	170°24'.9	Hout 2bis	337-332	cobbles	Bryozoans	HIGH	
Cape Hallett out	72°17'.5	170°26'.1	Hout 3	289-246	sand, cobbles	Bryozoans	HIGH	
Cape Hallett out	72°17'.2	170°23'.9	Hout 4	235-195	cobbles	Bryozoans (Celleporinidae)	HIGH	84
Cape Hallett out	72°16'.9	170°17'.0	Hout 5	106-103	sand, cobbles	Mixed community	HIGH	61
Cape Russell	74°49'.0	164°18'.1	R 2	364		Bryozoans	MEDIUM	71
Cape Russell	74°49'.8	164°12'.9	R 3	330-307	sand, cobbles	Gorgonians	HIGH	64
Cape Russell	74°50'.2	164°05'.5	R 4	216-174	sand, cobbles	Bryozoans and Pterobranchia	MEDIUM	74
Cape Russell	74°49'.9	164°05'.3	R 4bis	156-135	sand, cobbles	Gorgonians	MEDIUM	
Terra Nova Bay	74°43'.6	164°13'.6	SMN	366-363	sand, cobbles	Polychaetes	LOW	75

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TABLE 3. MULTIBEAM SURVEYS ALONG VICTORIA LAND, ANTARCTICA, FROM THE 2004 R/V "ITALICA" CRUISE (FIG. 3)				
SITE	**SURVEY LINES**	**LINEAR DISTANCE (km)**	**TOTAL AREA (km^2)**	**TOTAL SOUNDINGS**
Cape Hallett	92	197.0	37.27	20,418,059
Cape Adare	27	96.9	23.78	8,389,464
Cape Russell	22	72.6	11.30	7,564,900
TOTAL	141	366.5	72.35	36,372,423