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Indicator Species for Interpreting Environmental Variability in the Antarctic Coastal Zone

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ABSTRACT. The Antarctic coastal zone is influenced by natural phenomena associated with the ice sheets and ocean as well as by anthropogenic impacts associated with national programs and commercial activities around the continent. Understanding the complexity of this circumpolar system is essential for both basic and applied science objectives. Indicator species are a fundamental tool for interpreting the sources and dynamics of Antarctic environmental change. The underlying criteria for selecting indicator species include: (1) common in coastal marine habitats around the continent; (2) large, abundant and easy to collect; (3) basic biology is known; (4) available baselines preceding human impacts; (5) contain chemical signatures of environmental impacts; (6) easy to manipulate in field and laboratory experiments; and (7) present in impacted and appropriate control sites. Among the species which fit all of these criteria are two circumpolar bivalve molluscs: the epifaunal scallop (*Adamussium colbecki*) and the infaunal clam (*Laternula elliptica*). The utility of indicator species for assessing environmental variability in the Antarctic coastal zone is discussed in relation to the Antarctic Treaty system and other relevant international programs.

Key Words: Antarctic Treaty, assessment, interdisciplinary, international, marine, molluscs

Distinguishing Natural Variability from Human Impacts

Basic and applied research continuum

It is the combination of basic information from pristine environments and applied information from disturbed environments which is necessary for distinguishing human impacts from natural variability (Fig. 1). Such impact assessment should be based on a range of perspectives from short-term biochemical and physiological responses to relatively long-term population responses. Understanding the interaction between natural phenomena and anthropogenic impacts in Antarctica (Champ *et al.* 1992; Hyland *et al.* 1994; Lenihan and Oliver 1995; Berkman 1997a) is central to the international implementation of environmental management strategies under the *Protocol on Environmental Protection to the Antarctic Treaty* which was signed by the 26 Antarctic Treaty Consultative nations in Madrid in 1991 (*Madrid Protocol*). This paper will discuss biological baselines and responses with indicator species that exist in pristine and disturbed environments that can be used to assess whether human activities in Antarctic coastal areas are impacting local biota and, if so, to what extent.

Human impacts in Antarctic coastal areas

The Antarctic coastal zone can be divided into three regions (Benninghoff and Bonner 1985): shoreline interface between the ocean and the land or ice; enclosed marine habitats (bays, coves and harbors) with restricted circulation; and exposed nearshore habitats with unrestricted circulation. Even though Antarctica is relatively remote, coastal areas can be

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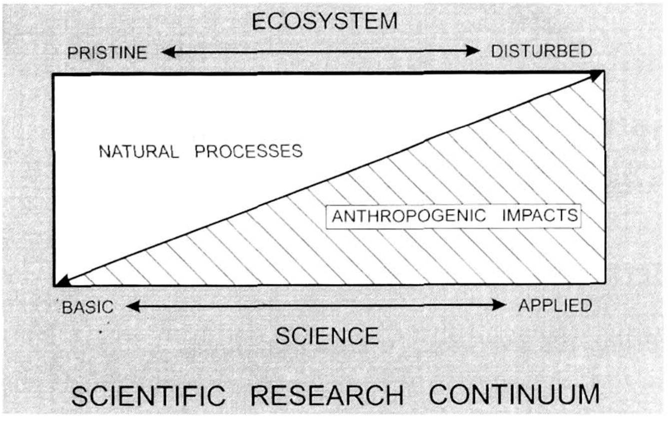

Fig. 1. The Scientific Research Continuum which illustrates: (a) the relationship between natural processes and anthropogenic impacts; and (b) the need for integrating basic and applied science to implement ecosystem management strategies under the Protocol on Environmental Protection to the Antaarctic Treaty. Adapted from Berkman (1992a, 1997a).

influenced by human activities that create: (a) acute short-term lethal impacts or (b) chronic longer-term sub-lethal impacts on the associated biological systems (Giesy and Graney 1989). Acute biological impacts can arise unexpectedly, as with the *Bahia Paraiso* oil spill which occurred in the Antarctic Peninsula region in 1989 and caused the mass mortality of adjacent intertidal limpets (Kennicutt 1990). Chronic impacts can occur from coastal research stations which involve discharges, dumping and habitat modification over time (Dayton 1972) and are distinct from undisturbed reference habitats (Lenihan *et al.* 1990). Chronic impacts also may be cumulative because they occur "*in combination with other activities in the Antarctic Treaty Area*" (Article 3.2, *Madrid Protocol*), such as Antarctic tourism which is fast approaching 10,000 individuals per year (Enzenbacher 1994). Coastal areas with possible cumulative human impacts include Ross Island, King George Island, Northern Antarctic Peninsula, and some sub-Antarctic islands (De Poorter and Dalziell 1997).

It has been suggested that Antarctic coastal communities can recover, perhaps within years, after chronic hydrocarbon pollution has abated (Platt 1978). In general, if this conclusion is correct (Clarke and Laws 1981), then chronic sub-lethal contamination should not permanently impact the fitness of Antarctic species. Beyond measuring the exposure of marine populations to contaminants from Antarctic coastal stations, it is important to assess how chronic sub-lethal impacts affect their fitness. Fitness, as measured by individual and population viability, fecundity, and development rates (Dobzhansky *et al.* 1977), is a fundamental feature of evolutionary biology and species' adaptations in the Antarctic marine ecosystem. Such baseline fitness measurements also are central to understanding the capacity of individuals and populations to recover from human impacts (Robinson 1989; EPA 1992).

Basic research: biological baselines and responses

Environmental records which unambiguously reflect natural variability in the absence of any anthropogenic impacts exist in the past. Among the geological, chemical and biological records (Berkman and Yoshida 1994), fossils provide ideal baselines for interpreting historical environmental conditions (Berkman 1997a).

Cores of guano from Adelie penguin (*Pygoscelis adelie*) rookeries around the continent (Goodwin 1993; Baroni and Orombelli 1994; Emslie 1995; Tatur *et al.* 1997) can provide information about occupation-abandonment cycles and periods in Antarctic coastal areas. For example, the continuous occupation of Adelie penguins along the Victoria Land Coast near 74°50' S reflects the persistence of the Drygalski Ice Tongue and its dynamic connection with the East Antarctic Ice Sheet during the last 6,000 years (Berkman 1997a). In other areas along the Victoria Land Coast, Adelie populations regularly appear and disappear over time scales from decades to centuries (Baroni and Orombelli 1994). These baseline data provide insights about natural variability that can be used to assess the environmental factors which are influencing changes in penguin populations this century (Fraser *et al.* 1992).

The persistent scallop population at Explorers Cove in West McMurdo Sound, Antarctica, is another example of a fossil assemblage that reflects natural variability (Berkman 1997a). Based on their spatial distribution (Stuiver *et al.* 1981) and occurrence throughout sediment cores from the Dry Valley Drilling Project (McKelvey 1985) in Explorers Cove, these scallops have lived in this habitat during the last 5,500 years (corrected for the 1,300-year age of the carbonate radiocarbon reservoir in the Southern Ocean as derived by Berkman & Forman (1996)). These data indicate that the habitat conditions have been relatively stable and have not fluctuated beyond the tolerance of the scallop population during this period. Moreover, any marked declines in the scallop population today would reflect environmental changes which have not been experienced over the last 5,500 years. Understanding the basic ecology and biology of representative species is an essential first step in developing baselines for interpreting biological responses associated with natural and anthropogenic impacts in Antarctic coastal areas.

Antarctic coastal marine indicator species

Bivalve molluscs have been identified as ideal indicator organisms (Table 1) and have been used extensively for monitoring pollution in coastal marine systems around the world under the design of the 'Mussel Watch' program (Phillips 1977; Goldberg *et al.* 11978; O'Connor 1996). Two species which meet all of the criteria in Table 1, the ubiquitous epifaunal scallop (*Adamussium colbecki*) and infaunal clam (*Laternula elliptica*), were identified by Berkman & Nigro (1992) as ideal nearshore marine species for extending the 'Mussel Watch' program to the Southern Ocean. These species, which are the largest bivalve molluscs in the Southern Ocean (>90 mm) and have densities that commonly exceed 70 m^{-2} (Berkman 1991; Ahn 1993), were subsequently established as key environmental indicators in the Southern Ocean by the Scientific Committee on Antarctic Research through environmental initiatives associated with the Coastal Shelf - Ecology of the Antarctic Sea Ice Zone (SCAR 1994) and Council of Managers of National Antarctic Programs (SCAR 1996).

Adamussium and *Laternula* have been the focus of more than 65 publications and are among the most studied coastal marine benthic species around Antarctica (Table 2). These studies provide information on the *geology* (e.g. paleoecology and evolution); *ecology* (e.g. competition, predation, evolution and epizoic species); *population biology* (e.g. size frequency, density, biomass, and spatial distributions); *physiology* (e.g. growth, reproduction, mortality, feeding and histology); and *biochemistry* (e.g. toxicology, metabolism and composition). This extensive database of basic and applied information provides an advantage for generating biological baselines and responses to assess anthropogenic impacts in Antarctic coastal areas. These background studies provide an excellent starting point for developing long-term, circumpolar and international studies to integrate population, organismal and cellular responses of these key indicator species for interpreting environmental impacts (both natural and anthropogenic) in Antarctic coastal areas.

Table 1. Criteria of key marine indicator species for assessing natural and anthropogenic impacts in Antarctic coastal areas

(a) Common in nearshore habitats around the continent
(b) Large, abundant and easy to collect
(c) Basic biology is known
(d) Available baselines preceding human impacts
(e) Contain chemical signatures of environmental impacts
(f) Easy to manipulate in field and laboratory experiments
(g) Present in impacted sites and appropriate control sites

Applied research: "minor or transitory impacts"

The *Madrid Protocol* creates a comprehensive framework for assessing environmental impacts; conserving Antarctic fauna and flora; managing waste disposal and marine pollution; and protecting Antarctic areas (Lyons 1993). In the United States, the *Madrid Protocol* is being implemented as Amendments to the Antarctic Conservation Act of 1978 (Public Law 104-227). The fundamental principle of the *Madrid Protocol* (Article 3.2) is to ensure that:

> *Activities in the Antarctic Treaty area shall be planned and conducted so as to limit adverse impacts on the Antarctic environment and dependent and associated ecosystems.*

The criteria for planning and conducting these

Table 2. Background data collected for the epifaunal scallop (*Adamussium colbecki*) and the infaunal clam (*Laternula elliptica*) in Antarctic coastal areas

Species	Biochemistry	Physiology	Population	Ecology	Geology
Adamussium colbecki	14, 19, 20, 25, 26, 28, 29, 36, 39, 42, 44, 49, 50, 53, 56, 57, 58, 60, 63, 65	14, 16, 19, 20, 23, 24, 29, 31, 33, 44, 49, 53, 57, 58, 63	4, 5, 10, 16, 18, 23, 25, 28, 29, 33, 34, 38, 41, 44, 53, 54, 55, 59, 66	1, 2, 4, 5, 9, 10, 13, 15, 16, 18, 19, 21, 23, 25, 29, 33, 38, 39, 41, 53, 54, 55, 56, 59, 66	3, 6, 7, 8, 12, 17, 27, 43, 45, 46, 51, 59
Laternula elliptica	26, 37, 42, 44, 47, 52, 58, 60	23, 24, 33, 35, 42, 44, 52, 58, 60, 62, 64	4, 11, 22, 33, 35, 40, 44, 47, 48, 52, 62	1, 2, 4, 11, 21, 22, 33, 35, 40, 60, 62, 64	7, 8, 12, 26, 27, 30, 32, 43, 45, 46, 61

1 Soot-Ryen (1951); **2** Nicol (1966); **3** Stuiver *et al.* (1976); **4** Ralph & Maxwell (1977); **5** Nakajima *et al.* (1982); **6** Stuiver *et al.* (1981); **7** Chapman-Smith (1981); **8** Yoshida (1983); **9** Mullineaux & DeLaca (1984); **10** Stockton (1984); **11** Zamorano *et al.* (1986); **12** Adamson & Pickard (1986); **13** Tucker & Burton (1987); **14** Honda *et al.* (1987); **15** Alexander & DeLaca (1987); **16** Berkman (1988); **17** Denton *et al.* (1989); **18** Berkman (1990); **19** Mauri *et al.* (1990); **20** Barrera *et al.* (1990); **21** Dell (1990); **22** Lenihan *et al.* (1990); **23** Berkman *et al.* (1991); **24** Pearse *et al.* (1991); **25** Berkman (1991); **26** Baroni *et al.* (1991); **27** Berkman (1992b); **28** Berkman *et al.* (1992); **29** Berkman & Nigro (1992); **30** Adamson & Colhoun (1992); **31** Nigro *et al.* (1992); **32** Ingólfsson *et al.* (1992); **33** Brey & Clarke (1993); **34** Nigro (1993); **35** Ahn (1993); **36** Viarengo *et al.* (1993); **37** Marshall *et al.* (1993); **38** Berkman (1994a); **39** Berkman (1994b); **40** Ahn (1994); **41** Hain & Melles (1994); **42** Barrera *et al.* (1994); **43** Hayashi & Yoshida (1994); **44** Nigro *et al.* (1994); **45** Igarashi *et al.* (1995a); **46** Igarashi *et al.* (1995b); **47** Kennicutt *et al.* (1995); **48** Lenihan & Oliver (1995); **49** Viarengo *et al.* (1995); **50** Berkman & Forman (1996); **51** Berkman & Prentice (1996); **52** Ahn *et al.* (1996); **53** Van Bloem (1996); **54** Chiantore *et al.* (1997); **55** Albertelli *et al.* (1997); **56** Regoli *et al.* (1997a); **57** Regoli *et al.* (1997b); **58** Nigro *et al.* (1997); **59** Berkman (1997a); **60** Brey & Mackensen (1997); **61** Hjort *et al.* (1997); **62** Ahn (1997); **63** Regoli *et al.* (1998); **64** Ahn & Shim (1998); **65** Berkman & Ku (1988); **66** Cattaneo-Vietti *et al.* (1998)

activities shall be based on "information sufficient to allow prior assessments of, and informed judgments about, their possible impacts." In addition, "regular and effective monitoring shall take place" (Article 3.2) to

> *allow assessment of the impacts of ongoing activities and to facilitate the early detection of the possible unforeseen impacts...*

Parties to the Antarctic Treaty shall "promote cooperative programs of scientific, technical and educational value" and "provide the appropriate assistance to other Parties" in planning and conducting these environmental assessment activities (Article 6.1). Together, the prior assessments along with the regular and effective monitoring will be used by the Antarctic Treaty nations in making decisions about whether their activities (Article 8.1) have:

> *(a) less than a minor or transitory impact;*
> *(b) a minor or transitory impact; or*
> *(c) more than a minor or transitory impact.*

In one sense, the time frame of a transitory impact is already defined in relation to species recruitment, as in the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) which discusses the prevention of changes (Article 2c) which are not "potentially reversible over two or three decades." In a more general sense, "minor or transitory impacts" should be distinguished from changes which are associated with the natural variability of Antarctic populations (Wolfe *et al.* 1987). To accomplish these objectives, the *Madrid Protocol* (Annex 1: Article 5.2) requires that:

> *"procedures shall be put in place, including appropriate monitoring of key environmental indicators, to assess and verify the impact of any activity..."*

Conclusions

International research collaborations should be designed to generate biological baselines for assessing natural variability and human impacts in

Antarctic coastal areas (Abbott and Benninghoff 1990; Berkman 1997b) . Among the indicator species that can be used to interpret these impacts, special attention should be given to *Adamussium colbecki* and *Laternula elliptica* which have been identified by the Scientific Committee on Antarctic Research for assessing both natural (SCAR 1994) and anthropogenic (SCAR 1996) impacts. From a basic science perspective, this research will produce fundamental data on the biology and ecology of two circumpolar marine species that are ubiquitous throughout the Holocene in the marine ecosystem around Antarctica. From an applied science perspective, experimental responses of these indicator species will reflect their capacity to recover from human impacts. Relevance of this coastal-zone research extends from local to global scales through the Antarctic Treaty System (Lyons 1993), Scientific Committee on Antarctic Research (Benninghoff and Bonner 1985; SCAR 1994, 1996) and the International Geosphere Biosphere Program (Pernetta and Milliman 1995).

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References

Abbott S.B. and Benninghoff W.S. 1990. *In*: Kerry K.R. and Hempel G. (*eds*), *Antarctic Ecosystems: Ecological Change and Conservation.* Springer-Verlag, Heidelberg. pp. 394-403.

Adamson D.A. and Colhoun E.A. 1992. Late Quaternary glaciation and deglaciation of the Bunger Hills, Antarctica. *Antarct. Sci.* **4**: 435-446.

Adamson D. and Pickard J. 1986. Cainozoic history of the Vestfold Hills. *In*: Pickard J. (*ed.*), *Antarctic Oasis: Terrestrial Environments and History of the Vestfold Hills.* Academic Press, New York. pp. 99-139.

Ahn I-Y. 1993. Enhanced particle flux through the biodeposition by the Antarctic suspension-feeding bivalve *Laternula elliptica* in Marian Cove, King George Island. *J. Exp. Mar. Biol. Ecol.* **171**: 75-90.

Ahn I-Y. 1994. Ecology of the Antarctic bivalve *Laternula elliptica* (King and Broderip) in Collins Harbor, King George Island: Benthic environment and an adaptive strategy. *In*: Berkman P.A. and Yoshida Y. (*eds*), *Holocene Environmental Changes in Antarctic Coastal Areas. Mem. Nat. Inst. Polar Res. Spec. Iss.* **50**: 1-10.

Ahn I.-Y. 1997. Feeding ecology of the Antarctic lamellibranch *Laternula elliptica* (Laternulidae) in Marian Cove and vicinity, King George Island, during one austral summer. *In*: Battaglia B., Valencia J. and Walton D.W.H. (*eds*), *Antarctic Communities: Species, Structure, and Survival.* Cambridge Univ. Press, Cambridge. pp. 142-151.

Ahn I.-Y. and. Shim J.H 1998. Summer metabolism of the Antarctic clam, *Laternula elliptica* in Maxwell Bay, King George Island and its implications. *J. Exp. Mar. Biol. Ecol.* **224**: 253-264.

Ahn I.-Y., Lee S.H., Kim K.T., Shim J.H., and Kim D.-Y. 1996. Baseline heavy metal concentrations in the Antarctic clam, *Laternula elliptica*, in Maxwell Bay, King George Island, Antarctica. *Mar. Poll. Bull.* **32**: 592-598.

Albertelli G., Cattaneo-Vietti R., Chiantore M., Pusceddu A., and Fabiano M. 1997. Food availability to an *Adamussium* bed during the austral summer 1993/94 (Terra Nova Bay, Ross Sea). *J. Mar. Syst.* in press.

Alexander S.P. and DeLaca T.E. 1987. Feeding adaptations of the foraminiferan *Cibicides refulgens* living epizooically and parasitically on the Antarctic scallop *Adamussium colbecki. Biol. Bull.* **173**: 136-159.

Baroni C. and Orombelli G. 1994. Abandoned penguin rookeries as Holocene paleoclimatic indicators in Antarctica. *Geology* **22**: 23-26.

Baroni C., Stenni B., and Longinelli A. 1991. Isotopic composition of Holocene shells from raised beaches and ice shelves of Terra Nova Bay (Victoria Land, Antarctica). *Mem. Soc. Geol. Ital.* **46**: 93-102.

Barrera E., Tevesz J.S., and Carter J.G. 1990. Variations in oxygen and carbon isotopic compositions and microstructure of the shell of *Adamussium colbecki* (Bivalvia). *Palaios* **5**: 149-159.

Barrera E., Tevesz M.J.S., Carter J.G., and McCall P.L. 1994. Oxygen and carbon isotopic composition and shell microstructure of the bivalve *Laternula elliptica* from Antarctica. *Palaios* **9**: 275-287.

Benninghoff W.S. and Bonner W.N. 1985. *Man's Impact on the Antarctic Environment.* Scientific Committee on Antarctic Research, Cambridge.

Berkman P.A. 1988. *Ecology of the Circumpolar Antarctic Scallop,* Adamussium colbecki *(Smith 1902).* Doctoral Dissertation, University of Rhode Island, Narragansett, Rhode Island.

Berkman P.A. 1990. The population biology of the Antarctic scallop, *Adamussium colbecki* (Smith, 1902) at New Harbor, Ross Sea. *In*: Kerry K.R. and Hempel G. (*eds*), *Antarctic Ecosystems: Ecological Change and Conservation.* Springer-

Verlag, Heidelberg. pp. 281-288.

Berkman P.A. 1991. Holocene meltwater variations recorded in Antarctic coastal marine benthic assemblages. *In*: Weller G., Wilson C.L., and B.A.B. Severin (*eds*), *Proceedings of the International Conference on the Role of the Polar Regions in Global Change.* Univ. Alaska, Fairbanks. pp. 440-449.

Berkman P.A. 1992a. The Antarctic marine ecosystem and humankind. *Rev. Aquat. Sci.* **6**: 295-333.

Berkman P.A. 1992b. Circumpolar distribution of Holocene marine fossils in Antarctic beaches. *Quatern. Res.* **37**: 256-260.

Berkman P.A. 1994a. Epizoic zonation on growing scallop shells in McMurdo Sound, Antarctica. *J. Exp. Mar. Biol. Ecol.* **179**: 49-67.

Berkman P.A. 1994b. Geochemical signatures of meltwater in Antarctic coastal marine molluscs during the Holocene. *In*: Berkman P.A. and Yoshida Y. (*eds*), *Holocene Environmental Changes in Antarctic Coastal Areas. Mem. Nat. Inst. Polar Res. Spec. Iss.* **50**: 11-33.

Berkman P.A. 1997a. Ecological variability in Antarctic coastal environments: Past and present. *In*: Battaglia B., Valencia J. and Walton D.W.H. (*eds*), *Antarctic Communities: Species, Structure, and Survival.* Cambridge Univ. Press, Cambridge. pp. 349-357.

Berkman P.A. 1997b. Biological baselines and responses for assessing environmental impacts in Antarctic coastal areas. *In*: De Poorter M. and Dalziell J.C. (*eds*), *Cumulative Environmental Impacts in Antarctica: Minimisation and Management.* International Union for the Conservation of Nature, Washington, D.C. pp. 117-123.

Berkman P.A. and Forman S.L. 1996. Pre-bomb radiocarbon and the reservoir correction for calcareous marine species in the Southern Ocean. *Geophys. Res. Lett.* **23**: 363-366.

Berkman P.A. and Ku T.-H. 1998. $^{226}Ra/Ba$ ratios for datine Holocene biogenic carbonates in the Southern Ocean: Preliminary evidence from coastal mollusc shells. *Chem. Geol.* in press.

Berkman P.A. and Nigro M. 1992. Trace metal concentrations in scallops around Antarctica: Extending the Mussel Watch Programme to the Southern Ocean. *Mar. Poll. Bull.* **24**: 322-323.

Berkman P.A. and Prentice M.L. 1996. Pliocene extinction of Antarctic Pectinid Mollusks. *Science* **271**: 1606-1607.

Berkman P.A. and Yoshida Y. (*eds*) 1994. *Holocene Environmental Changes in Antarctic Coastal Areas. Mem. Nat. Inst. Polar Res. Spec. Iss.* **50**: 1-107.

Berkman P.A., Waller T.R., and Alexander S.P. 1991. Unprotected larval development in the Antarctic scallop, *Adamussium colbecki* (Mollusca: Bivalvia: Pectinidae). *Antarct. Sci.* **3**: 151-157.

Berkman P.A., Foreman D.W., Mitchell J.C., and Liptak R.J. 1992. Scallop shell mineralogy and crystalline characteristics: Proxy records for interpreting Antarctic nearshore marine hydrochemical variability. *In*: Elliot D.H. (*ed.*), *Contributions to Antarctic Research III, Antarct. Res. Ser. Vol.* 57. American Geophysical Union, Washington, D.C. pp. 27-38.

Brey T. and Clarke A. 1993. Population dynamics of marine benthic invertebrates in Antarctic and subantarctic environments: Are they unique adaptations? *Antarct. Sci.* **5**: 253-266.

Brey T. and Mackensen A. 1997. Stable isotopes prove shell growth bands in the Antarctic bivalve *Laternula elliptica* to be formed annually. *Polar Biol.* **17**: 465-468.

Cattaneo-Vietti R., Chinatore M., and Albertelli G. 1997. The population structure and ecology of the Antarctic scallop, *Adamussium colbecki*, at Terra Nova Bay (Ross Sea, Antarctica). *Scient. Mar.* in press.

Champ M.A., Flemer D.A., Landers D.H., Ribic C., and DeLaca T. 1992. The roles of monitoring and research in polar environments: A perspective. *Mar. Poll. Bull.* **25**: 220-226.

Chapman-Smith M. 1981. The Taylor Formation (Holocene) and its macrofaunas, Taylor Dry Valley, Antarctica. *In*: McGinnis L.D. (*ed.*), *Dry Valley Drilling Project. Antarctic Research Series, Volume 33.* American Geophysical Union, Washington, D.C. pp. 365-378.

Chiantore M., Cattaneo-Vietti R., Povero P., and Albertelli G. 1997. The population structure and ecology of the Antarctic scallop, *Adamussium colbecki*, in Terra Nova Bay. *In*: Faranda F., Gguglielmo L., and Ianora A. (*eds*), *Ross Sea Ecology: Italian Antarctic Expeditions (1987-1995).* Springer-Verlag, Berlin. in press.

Clarke A. and Laws R. 1981. Aliphatic and aromatic hydrocarbons in benthic invertebrates from two sites in Antarctica. *Mar. Poll. Bull.* **12**: 10-14.

Dayton P.K. 1972. Toward an understanding of community resilience and the potential effect of enrichment to the benthos at McMurdo Station, Antarctica. *In*: Parker B.C. (*ed.*), *Proceedings of the Colloquium on Conservation Problems in Antarctica.* Allen Press, Laurence, Kansas. pp. 81-95.

Dell R.K. 1990. *Antarctic Mollusca: With Special Reference to the Fauna of the Ross Sea. Royal Society of New Zealand, Bulletin 27.* Royal Society of New Zealand, Wellington.

Denton G.H., Bockheim J.G., Wilson S.C., and Stuiver M. 1989. Late Wisconsin and Early Holocene glacial history, inner Ross Embayment, Antarctica. *Quartern. Res.* **31**: 151-182.

de Poorter M. and Dalziell J.C. (*eds*) 1997. *Cumulative Environmental Impacts in Antarctica; Minimisation and Management.* International Union for the Conservation of Nature, Washington, D.C.

Dobzhandsky T., Ayala F.J., Stebbins G.L., and Valentine J.W. 1977. *Evolution.* W.H. Freeman, San Francisco.

Emslie S.D. 1995. Age and taphonomy of abandononed penguin rookeries in the Antarctic Peninsula region. *Polar Rec.* **179**: 409-418.

Enzenbacher D.J. 1994. Antarctic tourism: An overview of the 1992-93 season, recent activity and emerging issues. *Polar Rec.* **30**: 105-116.

EPA 1992. *Framework for Ecological Risk Assessment.* U.S. Environmental Protection Agency, Risk Assessment Forum, Washington, D.C. EPA/630/R-92/001.

Fraser W.R., Trivelpiece W.Z., Ainley D.G., and Trivelpiece S.G. 1992. Increases in Antarctic penguin populations: Reduced competition with whales or a loss of sea ice due to environmental warming? *Polar Biol.* **11**: 525-531.

Giesy J.P. and Graney R.L. 1989. Recent development in and intercomparison of acute and chronic biassays and bioindicators. *Hydrobiologia* **188**: 21-60.

Goldberg E.D., Bowen V.T., Farrington J.W., Harvey G., Martin J.H., Parker P.L., Risebrough R.W., Robertson W., Schneider E., and Gamble E. 1978. The mussel watch. *Environ. Conserv.* **5**: 101-125.

Goodwin I.D. 1993. Holocene deglaciation, sea-level change, and the emergence of the Windmill Islands, Budd Coast, Antarctica. *Quatern. Res.* **40**: 70-80.

Hain S. and Melles M. 1994. Evidence for a marine molluscan fauna beneath ice shelves in the Lazarev and Weddell Seas, Antarctica, from shells of *Adamussium colbecki* and *Nacella* (*Patinigera*) cf. *concinna*. *Antarct. Sci.* **6**: 29-36.

Hayashi M. and Yoshida Y. 1994. Holocene raised beaches in the Lutzhow-Holm Bay Region, East Antarctica. *In*: Berkman P.A. and Yoshida Y. (*eds*), *Holocene Environmental Changes in Antarctic Coastal Area. Mem. NIPR, Spec. Iss.* **50**: 49-84.

Hjort C., Ingólffson Ô., Möller P., and Lirio J.M. 1997. Holocene glacial history and sea-level changes on James Ross Island, Antarctic Peninsula. *J. Quatern. Sci.* **12**: 259-273.

Honda K., Yamamoto Y., and Tasukawa R. 1987. Distribution of heavy metals in the Antarctic marine ecosystem. *Proc. NIPR Symp. Polar Biol.* **1**: 184-197.

Hyland J., Laur D., Jones J., Shrake J., Cadian D., and Harris L. 1994. Effects of an oil spill on the soft-bottom macrofauna of Arthur Harbour, Antarctica, compared with long-term natural change. *Antarct. Sci.* **6**: 37-44.

Igarashi A., Numanami H., Tsuchiya Y., Harada N., Fukuchi M., and Saito T. 1995a. Radiocarbon ages of molluscan shell fossils in raised beach deposits along the east coast of Lützow-Holm Bay, Antarctica, determined by accelerator mass-spectrometry. *Proc. NIPR Symp. Polar Biol.* **8**: 154-162.

Igarashi A., Harada N., and Moriwaki K. 1995b. Marine fossils of 30-40 ka in raised beach deposits and late Pleistocene glacial history around Lützow-Holm Bay, East Antarctica. *Proc. NIPR Symp. Antarct. Geosci.* **8**: 219-229.

Ingólffson Ô., Hjort C., Björck S., and Lewis Smith R.I. Late Pleistocene and Holocene glacial history of James Ross Island, Antarctic Peninsula. *Boreas* **21**: 209-222.

Kennicutt M.C. 1990. Oil spillage in Antarctica. *Environ. Sci. Technol.* **24**: 620-624.

Kennicutt M.C., McDonald S.J., Sericano J.L., Boothe P., Oliver J., Safe S., Presley B.J., Liu H., Wolfe D., Wade T.L., Crockett A., and Bockus D. 1995. Human contamination of the marine environment - Arthur Harbor and McMurdo Sound, Antarctica. *Environ. Sci. Technol.* **29**: 1279-1287.

Lenihan H.S. and Oliver J.S. 1995. Anthropogenic and natural disturbances to marine benthic communities in Antarctica. *Ecol. Appl.* **5**: 311-326.

Lenihan H.S., Oliver J.S., Oakden J.M., and Stephenson M.D. 1990. Intense and localized benthic marine pollution around McMurdo Station, Antarctica. *Mar. Poll. Bull.* **9**: 422-430.

Lyons D. 1993. Environmental impact assessment in Antarctica under the Protocol on Environmental Protection. *Polar Rec.* **29**: 111-120.

Marshall J.D., Pirrie D., and Nolan C. 1993. Oxygen stable isotope composition of skeletal carbonates from living Antarctic marine invertebrates. *In*: Heywood R.B. (*ed.*), *University Research in Antarctica, 1989-1992*. British Antarctic Survey, Cambridge. pp. 81-84.

Mauri M., Orlando E., Nigro M., and Regoli F. 1990. Heavy metals in the Antarctic scallop, *Adamussium colbecki. Mar. Ecol. Prog. Ser.* **67**: 27-33.

McKelvey B.B. 1985. The lithologic logs of DVDP cores 10 and 11, Eastern Taylor Valley. *In*: McGinnis L.D. (*ed.*), *Dry Valley Drilling Project. Antarctic Research Series, Vol. 33.* American Geophysical Union, Washington, D.C. pp. 63-94.

Mullineaux L.S. and DeLaca T.E. 1984. Distribution of Antarctic benthic foraminifera settling on the pecten *Adamussium colbecki. Polar Biol.* **3**: 185-189.

Nakajima Y., Watanabe K., and Naito Y. 1982. Diving observations of the marine benthos at Syowa Station, Antarctica. *Mem. Nat. Inst. Polar Res. Spec. Iss.* **23**: 44-54.

Nicol D. 1966. Descriptive ecology and geographic distribution of some Antarctic pelecypods. *Bull. Amer. Paleontol.* **51**: 1-102.

Nigro M. 1993. Nearshore population characteristics of the circumpolar Antarctic scallop *Adamussium colbecki* (Smith, 1902) at Terra Nova Bay (Ross Sea). *Antarct. Sci.* **5**: 377-378.

Nigro M., Orlando E., and Regoli F. 1992. Ultrastructural localization of metal binding sites in the kidney of the Antarctic scallop, *Adamussium colbecki. Mar. Biol.* **113**: 637-643.

Nigro M., Mauri M., Orlando E., and Regoli F. 1994. Ecology and metal distribution in Antarctic molluscs. *In*: Battaglia B., Bisol P.M., and Varotto V. (*eds*), *Proceedings of the 2nd Meeting on Antarctic Biology*. Edizioni Universitarie Patavine, Padova. pp. 235-256.

Nigro M., Regoli F., Rocchi R., and Orlando E. 1997. Heavy metals in Antarctic molluscs. *In*: Battaglia B., Valencia J., and Walton D.W.H. (*eds*), *Antarctic Environmental Change and Conservation*. Scientific Committee on Antarctic Research. pp. 409-412.

O'Connor T.P. 1996. Trends in chemical concentrations in mussels and oysters collected along the US coast from 1986 to 1993. *Mar. Environ. Res.* **41**: 201-221.

Pearse J.S., McClintock J.B., and Bosch I. 1991. Reproduction of Antarctic benthic marine invertebrates: Tempos, modes and timing. *Amer. Zool.* **31**: 65-80.

Pernetta J.C. and Milliman J.D. 1995. *Land-Ocean Interactions in the Coastal Zone: Implementation Plan. IGBP Global Change Report 33*. International Council of Scientific Union, Stockholm.

Phillips D.J.H. 1977. The use of biological indicator organisms to monitor trace metal pollution in marine and estuarine environments - A review. *Environ. Pollut.* **13**: 281-317.

Platt H.M. 1978. Assessment of the macrobenthos in an Antarctic environment following recent pollution abatement. *Mar. Poll. Bull.* **9**: 149-153.

Ralph R. and Maxwell J.G.H. 1977. Growth of two Antarctic lamellibranchs: *Adamussium colbecki* and *Laternula elliptica*. *Mar. Biol.* **42**: 171-175.

Regoli F., Principato G.B., Bertoli E., Nigro M., and Orlando E. 1997a. Biochemical characterization of the antioxidant system in the scallop *Adamussium colbecki*, a sentinel organism for monitoring the Antarctic environment. *Polar Biol.* **17**: 251-258.

Regoli F., Nigro M., Bertoli E., Principato G.B., and Orlando E. 1997b. Defenses against oxidative stress in the Antarctic scallop, *Adamussium colbecki* and effects of acute exposure to metals. *Hydrobiologia* **355**: 139-144.

Regoli F., Nigro M., and Orlando E. 1998. Lysosomal and antioxidant responses to metals in the Antarctic scallop, *Adamussium colbecki*. *Aquat. Toxicol.* in press.

Robinson R.M. 1989. Environmental impact assessment: The growing importance of science in government decision making. *Hydrobiologia* **189**: 137-142.

SCAR 1994. *Coastal and Shelf Ecology of the Antarctic Sea-Ice Zone. Science Plan and Implementation Plan.* Scientific Committee on Antarctic Research (SCAR) Rept. 10: 1-20.

SCAR 1996. Environmental Monitoring in Antarctica. Draft Report. Scientific Committee on Antarctic Research (SCAR), Council of Managers of National Antarctic Programs (COMNAP). May 1996.

Soot-Ryen T. 1951. Antarctic pelecypods. *Scient. Res. Norw. Antarct. Exped.* **32**: 1-46.

Stockton W.L. 1984. The biology and ecology of the epifaunal scallop *Adamussium colbecki* on the west side of McMurdo Sound, Antarctica. *Mar. Biol.* **78**: 171-178.

Stuiver M.L., Denton G.H., and Borns H.W. 1976. Carbon-14 dates of *Adamussium colbecki* (Mollusca) in marine deposits at New Harbor, Taylor Valley. *U.S. Antarct. J.* **11**: 86-88.

Stuiver M.L., Denton G.H., Hughes T.J., and Fastook J.L. 1981. History of the marine ice sheet in West Antarctica during the last glaciation: A working hypothesis. *In*: Denton G.H. and Hughes T.J. (*eds*), *The Last Great Ice Sheets*. John Wiley and Sons, New York. pp. 319-436.

Tatur A., Myrcha A., and Niegodzisz J. 1997. Formation of abandoned penguin rookery ecosystems in the maritime Antarctic. *Polar Biol.* **17**: 405-417.

Tucker M.J. and Burton H.R. 1987. A survey of the marine fauna in shallow coastal waters of the Vestfold Hills and Rauer Island, Antarctica. *Austral. Nat. Antarct. Res. Exp. Res. Notes* **55**: 1-24.

Van Bloem S.J. 1996. *Exploring the Biomass-Productivity Paradox: The Case of the Long-Lived Antarctic Scallop.* Masters Thesis, Ohio State Univ., Columbus. 76 pp.

Viarengo A., Canesi L., Mazzucotelli A., and Ponzano E. 1993. Cu, Zn and Cd content in different tissues of the Antarctic scallop *Adamussium colbecki*: Role of metallothionein in heavy metal homeostatis and detoxication. *Mar. Ecol. Prog. Ser.* **95**: 163-168.

Viarengo A., Cameso L., Garcia Martinez P., Peters L.D., and Livingstone D. 1995. Pro-oxidant and antioxidant defense systems in the tissues of the Antarctic scallop (*Adamussium colbecki*) compared with the Mediterranean scallop (*Pecten jacobaeus*). Comp. *Biochem. Physiol.* **111B**: 119-126.

Wolfe D.A., Champ M.A., Flemer D.A., and Mearns A.J. 1987. Long-term biological data sets: Their role in research, monitoring, and management of estuarine and coastal marine systems. *Estuaries* **10**: 181-193.

Yoshida Y. 1983. Physiography of the Prince Olav and the Prince Harald Coasts, East Antarctica. *Mem. Nat. Inst. Polar Res.* **13C**: 1-83.

Zamorano J.H., Duarte W.E., and Moreno C.A. 1986. Predation upon *Laternula elliptica* (Bivalvia, Anatinidae): A field manipulation in South Bay, Antarctica. *Polar Biol.* **6**: 139-143.

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