Geogr. Fis. Dinam. Quat.
35 (2012), 101-105, 3 figg.

DOI 10.4461/GFDQ.2012.35.10

SHORT COMMUNICATION
Nota Breve

PAOLO GABRIELLI (*), CARLO BARBANTE (**)(***), LUCA CARTURAN (****), GIULIO COZZI (**), GIANCARLO DALLA FONTANA (****), ROBERTO DINALE (*****), GIANFRANCO DRAGÀ (******), JACOPO GABRIELI (**), NATALIE KEHRWALD (**), VOLKMAR MAIR (*******), VLADIMIR MIKHALENKO (********), GIANNI PIFFER (******), MIRKO RINALDI (******), ROBERTO SEPPI (*********), ANDREA SPOLAOR (**********), LONNIE G. THOMPSON (*) & DAVID TONIDANDEL (*******)

DISCOVERY OF COLD ICE IN A NEW DRILLING SITE IN THE EASTERN EUROPEAN ALPS

(*) *School of Earth Sciences, 275 Mendenhall Laboratory, The Ohio State University, 125 South Oval Mall, Columbus, OH 43210, USA.* E-mail: gabrielli.1@osu.edu. *Byrd Polar Research Center, The Ohio State University, 108 Scott Hall - 1090 Carmack Road, Columbus, OH 43210, USA.*

(**) *Istituto per la Dinamica dei Processi Ambientali-CNR and Dipartimento di Scienze Ambientali, University Ca'Foscari of Venice, Dorsoduro 2137 - 30123 Venice, Italy.*

(***) *Accademia Nazionale dei Lincei, Centro B. Segre, via della Lungara 10 - 00196 Rome, Italy.*

(****) *Dipartimento Territorio e Sistemi Agro-forestali, Agripolis, University of Padua, Viale dell'Università 16 - 35020 Legnaro, Italy.*

(*****) *Ufficio Idrografico - Provincia Autonoma di Bolzano, Via Mendola 33 - 39100 Bolzano, Italy.*

(******) *Waterstones geomonitoring, vicolo S. Elisabetta 35 - 39040 Varna, Italy.*

(*******) *Ufficio Geologia e Prove materiali, Provincia Autonoma di Bolzano-Alto Adige, Via Val d'Ega 48 - 39053 Kardano, Italy.*

(********) *Institute of Geography, Russian Academy of Sciences, 29 Statomonetny per - 119017 Moscow, Russia.*

(*********) *Dipartimento di Scienze della Terra e dell'Ambiente, University of Pavia, Via Ferrata 1 - 27100 Pavia, Italy.*

(**********) *Dipartimento di Scienze della Terra, University of Siena, Via del Laterino 8 - 53100 Siena, Italy.*

This work is a contribution to the Ortles project, a program supported by NSF award # 1060115 and by the Ripartizione Protezione antincendi e civile of the Autonomous Province of Bolzano in collaboration with the Ripartizione Opere idrauliche e Ripartizione Foreste of the Autonomous Province of Bolzano and the Stelvio National Park. This is Ortles project publication no. 3 and Byrd Polar Research Center contribution no. 1421. The authors are grateful to the alpine guides of the Alpinschule of Solda, the Institute of Mountain Emergency Medicine of EURAC, the helicopter companies Airway, Air Service Center, Star Work Sky and the Hotel Franzenshöhe for the logistical support. We are also grateful for the valuable contribution of Victor Zagorodnov in the drilling operations and Piero Zennaro in the core processing.

ABSTRACT: GABRIELLI P., BARBANTE C., CARTURAN L., COZZI G., DALLA FONTANA G., DINALE R., DRAGÀ G., GABRIELI J., KEHRWALD N., MAIR V., MIKHALENKO V., PIFFER G., RINALDI M., SEPPI R., SPOLAOR A., THOMPSON L.G. & TONIDANDEL D., *Discovery of cold ice in a new drilling site in the Eastern European Alps*. (IT ISSN 0391-9838, 2012).

During autumn 2011 we extracted the first ice cores drilled to bedrock in the eastern European Alps from a new drilling site on the glacier Alto dell'Ortles (3859 m, South Tyrol, Italy). Direct ice core observations and englacial temperature measurements provide evidence of the concomitant presence of shallow temperate firn and deep cold ice layers (ice below the pressure melting point). To the best of our knowledge, this is the first cold ice observed within a glacier of the eastern European Alps. These ice layers probably represent a unique remnant from the colder climate occurring before ~1980 AD. We conclude that the glacier Alto dell'Ortles is now changing from a cold to a temperate state. The occurrence of cold ice layers in this glacier enhances the probability that a climatic and environmental record is fully preserved in the recovered ice cores.

KEY WORDS: Ortles, Ice cores, Eastern Alps.

RIASSUNTO: GABRIELLI P., BARBANTE C., CARTURAN L., COZZI G., DALLA FONTANA G., DINALE R., DRAGÀ G., GABRIELI J., KEHRWALD N., MAIR V., MIKHALENKO V., PIFFER G., RINALDI M., SEPPI R., SPOLAOR A., THOMPSON L.G. & TONIDANDEL D., *Scoperta di ghiaccio freddo in un nuovo sito di perforazione delle Alpi Orientali*. (IT ISSN 0391-9838, 2012).

Durante l'autunno 2011 abbiamo recuperato le prime carote di ghiaccio delle Alpi Orientali perforando, fino al basamento roccioso, un nuovo sito posto sul ghiacciaio Alto dell'Ortles (3859 m, Alto Adige, Italia). L'osservazione diretta delle carote e un profilo di temperatura misurato all'interno del ghiacciaio indicano la contemporanea presenza di firn temperato e di strati profondi di ghiaccio freddo (sotto al punto di fusione). Al meglio delle nostre conoscenze, questi strati rappresentano il primo ghiaccio freddo individuato in un ghiacciaio delle Alpi Orientali. Questo ghiaccio costituisce con ogni probabilità un eccezionale relitto riconducibile al clima più freddo che ha preceduto il ~1980 AD. Possiamo dunque desumere che il ghiacciaio Alto dell'Ortles sta passando da uno stato freddo ad uno temperato. La presenza di strati di ghiaccio freddo in questo ghiacciaio aumenta le possibilità che un record di storia climatica e ambientale sia ben conservato nelle carote di ghiaccio recuperate.

TERMINI CHIAVE: Ortles, Carote di ghiaccio, Alpi Orientali.

INTRODUCTION

Ice cores extracted from polar and low latitude glaciers provide important paleoclimate and paleoenvironmental information (e.g. Thompson & *alii*; 2006a; Wolff & *alii*, 2006). In Europe researchers have only drilled a few glaciers to bedrock and all the drilling sites, including Fiescherhorn (3890 m), Cold du Dome (4250 m) and Colle Gnifetti (4454 m), are located in the western sector of the Alps (Schwikowski & *alii*, 1999; Preunkert & *alii*, 2003; Jenk & *alii*, 2009). A generally accepted criterion to select a drilling site is that the ice body of the glacier is constituted by cold ice where this is defined as ice below the pressure melting point. Cold ice allows the preservation of chemical information, while temperate ice (ice at the pressure melting point) may have been subject to chemical changes. The high elevation (> 4000 m a.s.l.) drilling sites in the western Alps meet the criterion of glaciers comprised of cold ice. In contrast, glaciers in the eastern Alps were assumed to be unsuitable for obtaining interpretable paleoclimatic records due to the lower summit elevations (< 4000 m) and observations of temperate glaciers (Oerter & *alii*, 1985).

During autumn 2011 we retrieved the first ice cores drilled to bedrock in the eastern Alps from a drilling site located on the glacier Alto dell'Ortles (3859 m, South Tyrol, Italy). Using these cores we aim to reconstruct coevolutionary and lead/lag relationships regulating climate, ecosystems and human society (Dearing, 2006) in South Tyrol. Here, we provide evidence that, despite the recent exceptionally warm summer temperatures and the consequent melt water percolation through the firn of Alto dell'Ortles (Gabrielli & *alii*, 2010), cold ice still exists within the deep layers of this glacier.

STUDY AREA

The ice core drilling campaign was conducted on Mt. Ortles (3905 m, South Tyrol, Italy), the highest mountain of the eastern Alps, during September and October 2011. The northwestern slope of Mt. Ortles is covered by the glacier Alto dell'Ortles which gently slopes (8° - 9°) from near the summit for ~300 m, and then flows on steeper bedrock into two major «tongues» down to its lowest elevation of 3018 m (fig. 1). The total surface area is 1.34 km^2 (Carturan & *alii*, 2012) of which ~10% constitutes the upper, gentle slopes. The drilling site was located on a small col (3859 m; 10°32"34, 46°30"25) between the summit of Mt. Ortles and the Vorgipfel (3845 m) (fig. 1, 2). During our previous 2009 survey at this location, we estimated a bedrock depth of ~75 m, the firn/ice transition below ~24 m and a current snow accumulation rate of ~ 800 mm of water equivalent per year (Gabrielli & *alii*, 2010). Over the last three decades (1980-2009) the reconstructed average summer air temperature was –1.6 °C (~2 °C higher than during the previous 115 years), with an exceptional maximum peak of 2 °C during the 2003 summer heat wave (Gabrielli & *alii*, 2010).

DRILLING CONDITIONS

Four cores were drilled within 20 m of each other using a lightweight electromechanical drill installed in a dome tent (fig. 2) and powered by a 1.5 kw diesel generator (Zagorodnov & *alii*, 2000). Three ice cores reached bedrock at final logged depths of 75.5 m (#1), 76.1 m (#2) and 75.1 m (#3). A fourth core reached 61.0 m (#4), presumably ~15 m above bedrock. Preliminary density measurements on core #2 point to a firn/ice transition at approximately 30 m of depth, with a measured average ice density of 870 ± 30 kg m^{-3} down to bedrock. In general, the retrieved firn cores were wet until a depth of ~30 m, suggesting the presence of temperate firn. The presence of cold ice below ~30 m was immediately evident during the drilling operations because the diameter of the borehole began to narrow as melt water flowing from the upper

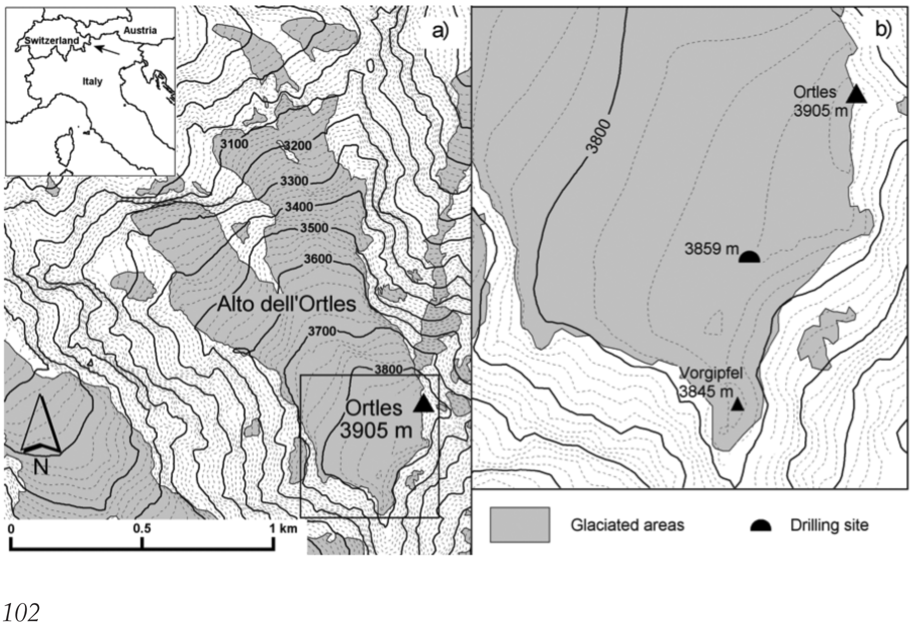

FIG. 1 - (a) Map of the Alto dell'Ortles glacier (South Tyrol, Italy); (b) Detail of the boxed area in (a) indicates the position of the drilling site where four cores were extracted within 20 m from each other (adapted from Gabrielli & *alii*, 2010).

FIG. 2 - The drilling dome built at 3859 m near the summit of Mt. Ortles (3905 m) (Photo by Paolo Gabrielli).

temperate firn portion (< 30 m depth) into the lower part of the borehole re-froze. No antifreeze was used at any time during the drilling operations. Ice accretion was directly observed to occur at a refreezing rate of ~ 0.7 mm/h in an ice cross section retrieved at a depth of 56 m in borehole #1 (fig. 3). This rate was calculated as the thickness of newly formed ice accreted overnight to the borehole divided by the time interval occurred between the last and the first drilling runs over two consecutive working days.

While a significant influx of melt water in borehole #1 kept the water level close to or above the firn/ice transition, the other boreholes contained less (boreholes #2 and #4) to almost no (#3) input of water originating from the temperate firn. We explain this difference by assuming sub-glacial streams of water flow on the slightly tilted and impermeable surface of the firn/ice transition. In this case, sub-glacial streams might have affected boreholes #1, #2 and #4 while borehole #3 was essentially not subject to

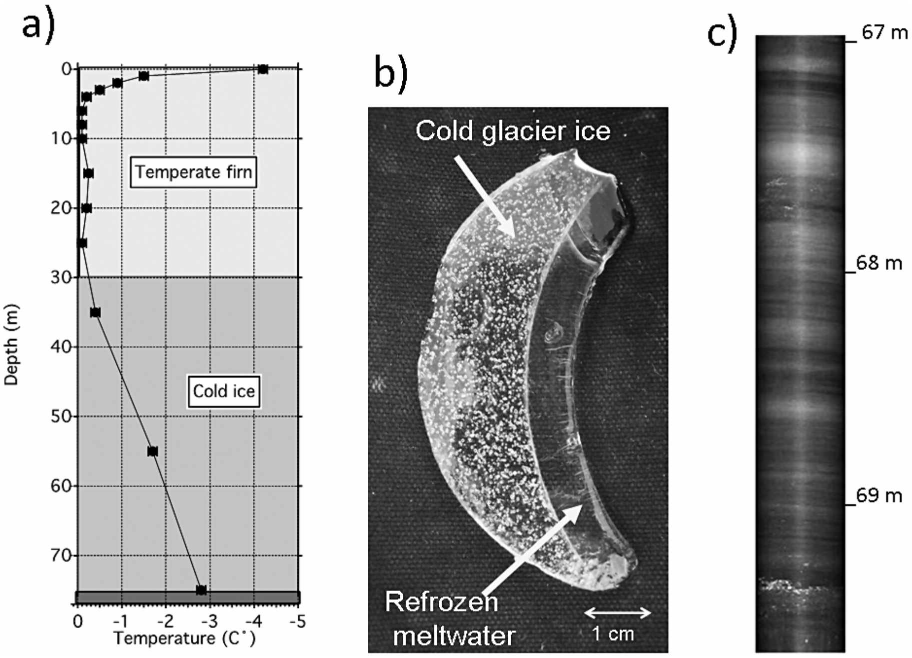

FIG. 3 - a) Borehole #3 temperatures recorded 43 days after the end of the drilling operations; b) Borehole #1 cross section extracted at 56 m of depth after the partial refreezing occurred overnight. The newly formed ice (refrozen meltwater that is free of air bubbles) is accreted to the cold glacier ice of the borehole walls (rich of air bubbles); c) Virtual image of core #1 between 67 and 70 m of depth (obtained from a 360-degrees continuous imaging scan of the borehole) displaying thin ice layers near bedrock.

such flow. An alternative explanation is that unobserved crevasses beneath the glacier surface might have efficiently drained the firn portion only next to borehole #3.

BOREHOLE TEMPERATURES

Two thermistor strings (Negative Temperature Coefficient, YSI 4403110 10 kOhm, precision 0.1 °C) using data loggers MDL-8/3 were installed in borehole #3 on October 5, 2011, immediately after the completion of the drilling operations. The first thermistor string was equipped with temperature sensors at 0, 1, 2, 3, 4, 6, 8, 10, 15, 20, 25 m of depth while the second one contained the sensors at 15, 35, 55 and 75 m (fig. 3). We could read the first thermistors data only 43 days after their installation and thus we assume that any thermal disturbance linked to the drilling operations had become negligible. The shallowest thermistors, between depths of 0-3 m, depict negative temperatures that simply reflect the initiation of the winter season. The lower thermistors (3-25 m depth) located within the firn indicated temperatures at or near the pressure melting point, which agree with the wet firn observations at these depths. Thermistors positioned in the lower ice portion clearly demonstrate negative temperature at 35 m (–0.4 °C), 55 m (–1.8 °C) and at 75 m close to bedrock (–2.8 °C) confirming the occurrence of cold ice. The depth of the transition between the temperate and the cold parts of the glacier remain uncertain and is only estimated to be close to the firn/ice transition at ~30 m of depth.

ICE CORES STRATIGRAPHY

Here, we provide a summary of the field-logged stratigraphy. We observed horizontal to tilted (10-20°) ice lenses through the entire length of the cores, where the angle probably reflects the slight tilt of the basal slope. Firn alternates with ice lenses and ice glands of various thicknesses down to a depth of ~30 m. The cumulative thickness of these ice features constituted ~20% of the entire length of the firn portion when the firn length is expressed in ice equivalents. The ice lenses constituted ~15% of the glacier ice between 30 and 55 m, however, these lenses only constituted ~5% of the cumulative length between 55 and 65 m depth. Variations in the relative occurrence of the ice lenses over the length of the Ortles cores may indicate changes in summer temperatures through time (Koerner & *alii*, 1977). Borehole images obtained from a 360-degree continuous-imaging scan suggest ice layers substantially thinned beginning at ~60 m and continuing until the bedrock contact (fig. 3). For this reason, it was more difficult to discriminate ice with and without bubbles in the lowest core sections during field logging. However, we can roughly estimate a bubble-free ice frequency of greater than 20% between 65 and 75 m depth.

The diameters of the air bubbles entrapped within the ice layers ranged from a few mm to less than 1 mm. We observed elongated air bubbles (up to ~10-15 mm) at various depths indicating that horizontal ice flow might be a component of the dynamic of the drilling site. Various black particles, filaments, and mm-scale fragments were observed in the four cores. Rock particles of various diameters (from a few mm to a few cm) were observed in the deepest sections of ice cores #1, #2 and #3 within 1 m above the bedrock. In core #2 we observed a single pebble 2.5 m above bedrock.

DISCUSSION

To the best of our knowledge Alto dell'Ortles is the first glacier with documented cold ice in the eastern Alps. However, researchers found cold ice at a similar elevation and exposure at Fiescherhorn (3890 m), located on the northern slope of the western Alps in Switzerland (Jenk & *alii*, 2003). The concomitant presence of temperate firn and cold ice in Alto dell'Ortles demonstrates that this glacier is now out of thermal equilibrium. However, the occurrence of ice lenses in the cold deep layers indicates that Alto dell'Ortles had once been within the «cold infiltration recrystallization zone», where surface snow melted by the influence of solar radiation and high temperatures refreezes always within a few centimeters below the surface (Shumskii, 1964). Under these conditions, over time, atmospheric temperatures are transferred and conserved into the deep layers of cold glaciers, and thus the lower cold portion of the Alto dell'Ortles glacier probably represents a unique remnant of a past colder climate in this region. The recorded sub-freezing englacial temperatures and observations of less frequent melting episodes recorded in the deep ice layers are consistent with the suggestion that before AD ~1980 summer air temperatures were ~2 °C colder than those observed during the last three decades in this region (Gabrielli & *alii*, 2010). We conclude that Alto dell'Ortles glacier is probably rapidly changing from a cold to a temperate state.

To explain how cold ice survived below 30 m depth during such recent warm summer conditions, we assume that the recent percolation of melt water through the firn portion of Alto dell'Ortles must have laterally drained at the firn/ice transition. The presence of the largest observed ice lens (~50 cm) occurred at ~29 m of depth in all four cores. This ice lens correlates with the temperate firn/cold ice transition and suggests that lateral drainage affected all drilled sections of the glacier at about this depth. This idea is supported by field observations demonstrating similar processes occurring in other locations such as on the Quelccaya ice cap in the Peruvian Andes (Thompson & *alii*, 2006b).

The preservation of at least part of the seasonal chemical-physical features in the uppermost firn layers of Alto dell'Ortles during the recent warm years 2005-2009 (Gabrielli & *alii*, 2010; Gabrieli & *alii*, 2011), suggests that a climatic record is still preserved in the lower cold ice, probably formed before AD ~1980. Drainage of melt water at the firn/ice transition should have preserved the underlying climate record from overprinting caused by the recent excess of melt water percolation. In conclusion, the new observations and data collected during the autumn 2011 drilling campaign strongly support the idea that the glacier ice fields near the summit of Mt. Ortles may have retained much of their physical, chemical and biological records.

REFERENCES

CARTURAN L., FILIPPI R., SEPPI R., GABRIELLI P., NOTARNICOLA C., BERTOLDI L., PAUL F., RASTNER P., CAZORZI F. & DALLA FONTANA G. (2012) - *Analysis of the current deglaciation of the Ortles-Cevedale massif: climatic causes, controls and impacts*. To be submitted to Cryosphere.

DEARING J.A. (2006) - *Climate-human-environment interactions: resolving our past*. Climate of the past, 2, 187-203.

GABRIELI J., CARTURAN L., GABRIELLI P., KEHRWALD N., TURETTA C., COZZI G., SPOLAOR A., DINALE R., STAFFLER H., SEPPI R., DALLA FONTANA G., THOMPSON L.G. & BARBANTE C. (2011) - *Impact of Po' Valley emissions on the highest glacier of the Eastern European Alps*. Atmospheric Chemistry and Physics, 11, 8087-8102.

GABRIELLI P., CARTURAN L., GABRIELI J., DINALE R., KRAINER K., HAUSMANN H., DAVIS M., ZAGORODNOV V.S., SEPPI R., BARBANTE C., DALLA FONTANA G. & THOMPSON L.G. (2010) - *Atmospheric warming threatens the untapped glacial archive of Ortles mountain, South Tyrol*. Journal of Glaciology, 56, 843-853.

JENK T.M., GAGGELER H.W., SCHWERZMANN A.A. & SCHWIKOWSKI M. (2003) - *Recovery of a 150 m ice core down to bedrock from the Fiescherhorn glacier*. 2003 PSI Internal Report.

JENK T.M., SZIDAT S., BOLIUS D., SIGL M., GAGGELER H.W., WACKER L., RUFF M., BARBANTE C., BOUTRON C.F. & SCHWIKOWSKI M. (2009) - *A novel radiocarbon dating technique applied to an ice core from the Alps indicating late Pleistocene ages.* Journal of Geophysical Research 114, DOI: 10.1029/2009JD011860.

KOERNER R.M. (1977) - *Devon Island ice cap: core stratigraphy and paleoclimate*. Science, 196, 15-18.

OERTER H., BAKER D., STICHLER W. & RAUERT W. (1985) - *Isotope studies of ice cores from a temperate Alpine glacier (Vernagtferner, Austria) with respect to the meltwater flow*. Annals of Glaciology, 7, 90-93.

PREUNKERT S., WAGENBACH D. & LEGRAND M. (2003) - *A seasonally resolved alpine ice core record of nitrate: comparison with anthropogenic inventories and estimation of preindustrial emissions of NO in Europe*. Journal of Geophysical Research, 108, 4681-4690.

SCHWIKOWSKI M., BRUTSCH S., GAEGGELER H.W. & SCHOTTERER U. (1999) - *A high-resolution air chemistry record from an Alpine ice core: Fiescherhorn glacier, Swiss Alps*. Journal of Geophysical Research 104, 13709-13719.

SHUMSKII P.A. (1964) - *Principles of structural glaciology*. Dover Inc.: Dover, New York.

THOMPSON L.G., YAO T., DAVIS M., THOMPSON E.M., LIN P.N., MASHIOTTA T.A., MIKHALENKO V.N. & ZAGORODNOV V.S. (2006a) - *Holocene climate variability archived in the Puruogangri ice cap from the central Tibetan Plateau*. Annals of Glaciology 43, 61-69.

THOMPSON L.G., THOMPSON E.M., BRECHER H.H., DAVIS M., LEON B., LES D., LIN P.N., MASHIOTTA T.A. & MOUNTAIN K. (2006b) - *Abrupt tropical climate change: Past and present*. Proceedings of the National Academy of Science 103, 10536-10543.

WOLFF E.W., FISCHER H., FUNDEL F., RUTH U., TWARLOH B., LITTOT G.C., MULVANEY R., ROTHLISBERGER R., DE ANGELIS M., BOUTRON C.F., HANSSON M.E., JONSELL U., HUTTERLI M.A., LAMBERT F., KAUFMANN P., STAUFFER B., STOCKER T., STEFFENSEN J.P., BIGLER M., SIGGAARD-ANDERSEN M.L., UDISTI R., BECAGLI S., CASTELLANO E., SEVERI M., WAGENBACH D., BARBANTE C., GABRIELLI P. & GASPARI V. (2006) - *Southern Ocean sea-ice extent, productivity and iron flux over the past eight glacial cycles*. Nature, 440, 491-496.

ZAGORODNOV, V.S., THOMPSON, L.G. & THOMPSON, E.M. (2000) - *Portable system for intermediate-depth ice-core drilling*. Journal of Glaciology, 46, 167-172.

(Ms. received 29 February 2012; accepted 30 April 2012)