Труды Карельского научного центра РАН
№ 3. 2012. С. 100–109

*УДК 551.72*

# AN IMPORTANT LANDMARK IN THE STUDY OF THE PALAEOPROTEROZOIC WORLD

**V. A. Melezhik[1, 2], A. R. Prave[3]**

[1] *Geological Survey of Norway, N-4791, Trondheim, Norway*
[2] *Centre for Geobiology, University of Bergen, N-5020, Bergen, Norway*
[3] *Department of Earth Science, University of St. Andrews, St Andrews, KY16 9AL, Scotland, UK*

The International Continental Scientific Drilling Program's (ICDP) Expedition (FAR-DEEP) successfully completed drilling operations on the Fennoscandian Shield resulting in recovery of 3650 m of core from 15 holes drilled through sedimentary and volcanic formations recording several global environmental changes spanning the time interval 2500–2000 Ma, including the Great Oxidation Event (GOE). The core has been archived, and sampled by an international team of scientists, and the project has moved to the advanced research phase. The first significant outcome of the FAR-DEEP is a three-volume treatise (ca. 1500 pages) entitled «Reading the Archive of Earth's Oxygenation» scheduled by Springer for printing in August 2012.

K e y  w o r d s: International Drilling Program, Fennoscandian Shield, global environmental changes, Lomagundi-Jatuli, Great Oxidation, Shunga events, glacial episodes.

**В. А. Мележик, А. Р. Прэйв. ВАЖНАЯ ВЕХА В ИССЛЕДОВАНИИ ПАЛЕОПРОТЕРОЗОЯ ЗЕМЛИ**

В статье изложены основные результаты завершившегося в 2012 г. международного бурового проекта, нацеленного на исследование ранней истории Земли на территории российской части Фенноскандинавского щита (FAR-DEEP). Основное внимание участников проекта было сфокусировано на проблеме становления аэробной системы Земли и развития серии взаимосвязанных глобальных событий в переходный период от позднего архея к раннему протерозою (2500–2000 млн лет). Бурение скважин выполнено в 2007 г. финской компанией SMOY, материально-техническое обеспечение осуществляла фирма «Минерал» (С.-Петербург). Проект финансировался фондом ICDP и частично Исследовательскими Советами Норвегии и Германии, институтом Астробиологии NASA, Геологической службой Норвегии, Центром Геобиологии Бергенского университета, Институтом геологии КарНЦ РАН. Получены образцы керна геологических формаций по двум регионам России (по Онежской структуре в Карелии, Печенгскому, Имандра-Варзугскому зеленокаменным поясам Кольского п-ова), общая длина 15 пробуренных скважин – 3650 м. К изучению керна были привлечены научные коллективы из 14 стран. Основные изучавшиеся вопросы истории развития Земли: первое глобальное оледенение, самое раннее и наиболее значимое положительное изменение изотопного состава углерода (Ломагунди-Ятулийское событие), доказательство существования наиболее древнего массового накопления органического вещества и генерации углеводородов (феномен «Шуньга»). Получены новые данные по геохронологии основных событий в ранней истории Земли.
Керн скважин находится в г. Трондхейме, Геологическая служба Норвегии, он доступен для будущих исследований и образования. С обширной коллекцией фото-

графий керна и геохимическими данными можно познакомиться на сайте (http://www.icdp-online.org). Первым значительным результатом проекта являются три тома материалов общим объемом около 1500 страниц (издательство Спрингер). Книги иллюстрированы фотографиями керна и естественных обнажений, геологическими картами, схемами реконструкций условий осадконакопления, в них содержится богатый материал по литологии и геохимии осадочных пород. Описанию общей геологии российской части Фенноскандинавского щита посвящен первый том, глобальных событий переходного периода – второй и третий том издания. В конце статьи авторы приводят список журнальных статей, опубликованных и подготовленных к изданию, в которых приведены основные результаты исследований по темам международного проекта.

Ключевые слова: Международная программа бурения, Фенноскандинавский щит, глобальные изменения окружающей среды, Ломагунди-ятулийское изотопное событие, кислородная катастрофа, феномен «Шуньга», эпизоды оледенения.

## Introduction

The International Continental Scientific Drilling Program (ICDP) supports projects aimed at studying fundamental geological problems of global significance. It helps assemble the best available international scientific teams to examine the best rock formations available in the world. The Fennoscandian Arctic Russia–Drilling Early Earth Project (FAR-DEEP) was one such project, focusing on the emergence of an aerobic Earth System and a series of interrelated global events during the Late Archaean and Early Palaeoproterozoic transition (APT; 2500–2000 Ma). Within the ICDP, the FAR-DEEP with its Deep Time perspective has opened a new window for multidisciplinary research that aims at obtaining fundamental knowledge of the processes that operated on Earth's surface and interior at the dawn of the establishment of an aerobic world. Details of the project idea were presented in Melezhik et al. [2005].

The aim of the FAR-DEEP was to obtain uncontaminated, non-weathered, pristine core material from key geological formations recording a series of hallmark Palaeoproterozoic global events in three separate areas of Russian Fennoscandia (Figs. 1 and 2). The drilling operations were carried out through May–October 2007 by the Finnish operator SMOY, and State Company «Mineral», based in St. Petersburg, provided logistical support. The drilling operations were largely supported by the ICDP and by additional funding from the Norwegian Research Council, the German Research Council, the National Science Foundation, the NASA Astrobiology Institutes, the Geological Survey of Norway (NGU) and the Centre of Excellence in Geobiology, the University of Bergen, Norway. NGU and the Institute of Geology of the Karelian Research Centre of the Russian Academy of Sciences supported onsite geological work.

The major outcome of the drilling project was the successful recovery of a total of 3650 m of pristine cores from 15 drillholes (Fig. 1). This provided a representative geological record of the most important global events occurring through the APT (Fig. 2). Hence, the chosen approach was a success, and resulted in collection of a rich archive of geological material. Core documentation and associated analytical work were supported by NGU, the Scottish Universities Environmental Research Centre and Penn State University. Facilities and logistical support for international sampling campaigns were provided by NGU. In 2010, the first goal of the project was successfully achieved: a well-characterised, -archived and -illustrated succession of rocks for the 2500–2000 Ma time slice.

The second goal of the FAR-DEEP is to document the changes in the biosphere and the geosphere associated with the emergence of an aerobic Earth System and interrelated global events during the APT, which led to irreversible alteration of Earth's surface environments and rise in atmospheric oxygen. The core archive contains a record of many of the hallmark events of that time and provides the international Earth science community with an exceptional opportunity to study iconic aspects of Palaeoproterozoic Earth history including the first worldwide glaciation, the earliest and one of the largest positive isotopic excursions of the global C cycle, and arguably the world's oldest supergiant oilfield (Fig. 2), and offers the chance for undertaking a wide variety of exciting research and educational activities.

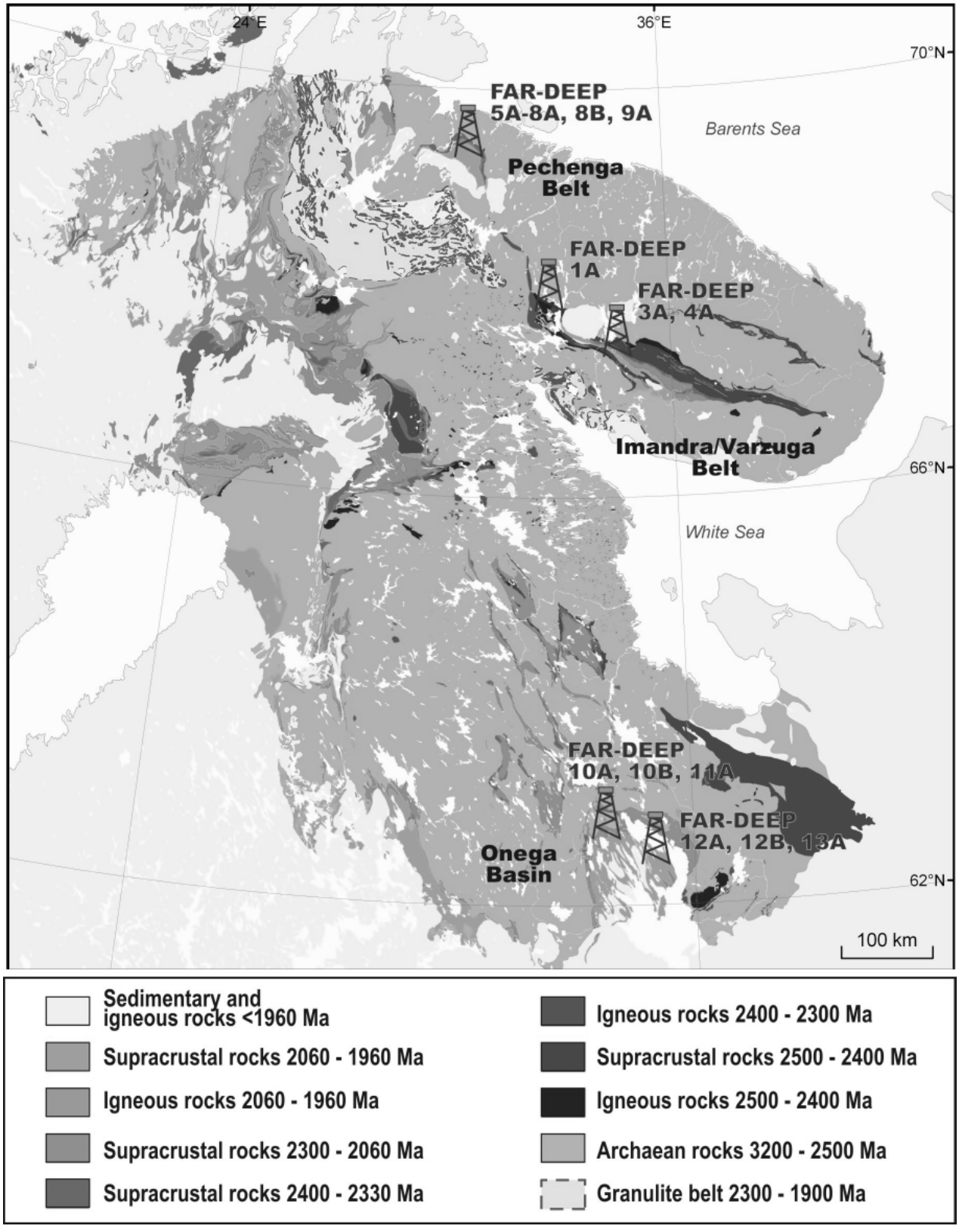


*Fig. 1.* Geological map of the eastern Fennoscandian Shield showing FAR-DEEP drilling sites and drillhole numbers. Geological map is modified by Aivo Lepland from Koistinen et al. [2001]

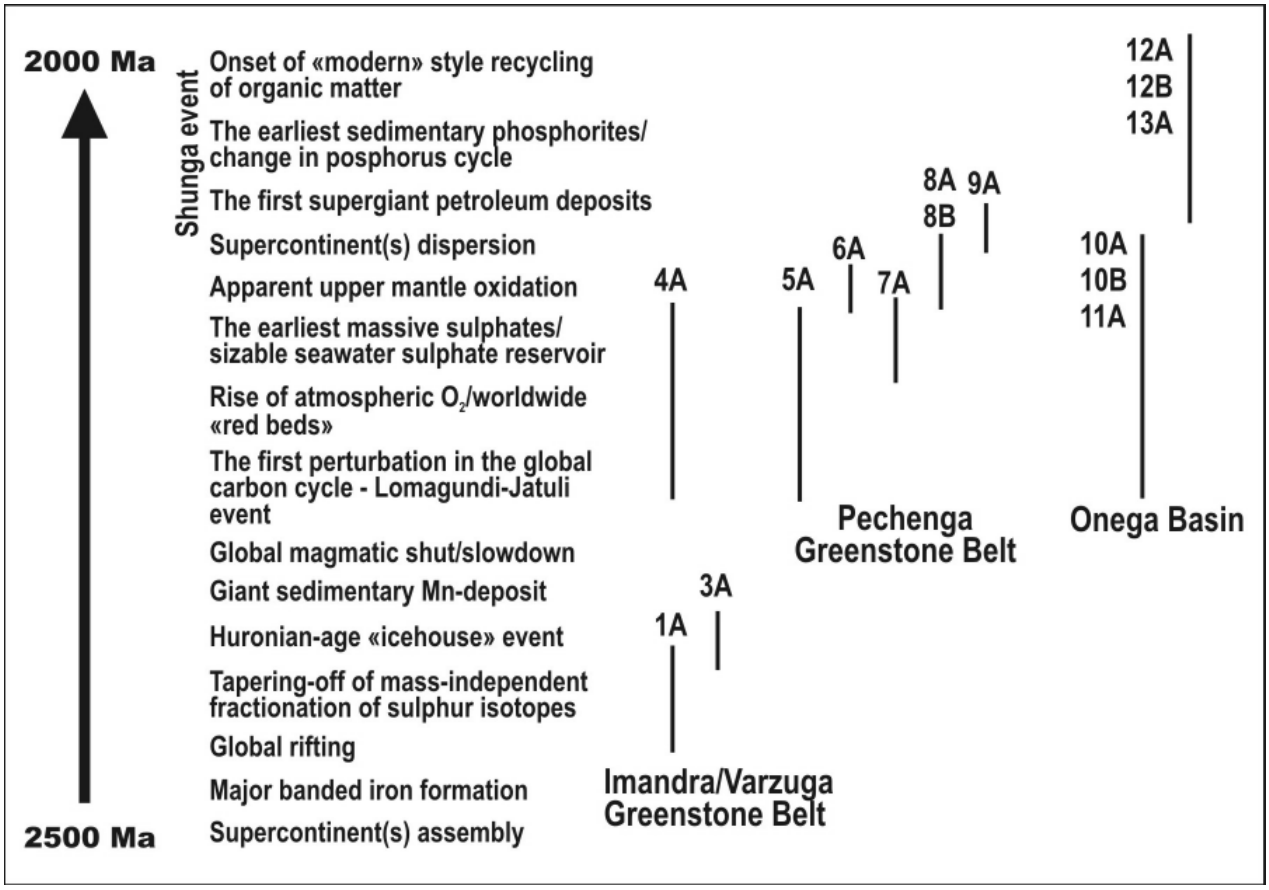


*Fig. 2.* FAR-DEEP drillholes projected against major global events through the Archaean-Palaeoproterozoic transition. Note that precise position of events relative each other on the chronological scale remains to be constrained

Currently, an international team of scientists from 14 countries is undertaking an ambitious and successful FAR-DEEP research program. Several research grants, eight PhD and four postdoctoral projects supported by various funding agencies in Austria, Finland, Germany, Great Britain, Norway and USA are involved in the FAR-DEEP research program. A large group of scientists from the USA has received support from the National Science Foundation and NASA. Several research groups from Belgium, Czech Republic, Estonia and Russia have been also successful in obtaining research grants.

**FAR-DEEP – current research**

Selected research areas and directions, which are being actively developed by various research groups are briefly highlighted below. This section does not aim to review the abundant published material on the APT, instead it focuses on on-going FAR-DEEP core-based work, and articles recently published by the FAR-DEEP international community.

*Geochronology*

The construction of stratigraphic frameworks, inter-regional correlations, the assessment of geochemical, geobiological and development of basin evolution models demand geochronological control. Furthermore, no definition of the timing, rates and durations of geological processes and events could be made without precise and accurate radiometric ages. Currently, only a few robust ages exist to bracket the events of the Palaeoproterozoic time slice. FAR-DEEP cores and associated material offer new opportunities. One new, robust age-constraint is on the termination of the Lomagundi-Jatuli isotopic excursion in Imandra/Varzuga and Pechenga belts [Martin et al., 2012a]. Another example is tightening the age of glacial deposits documented in Core 3A in the Imandra/Varzuga Belt. Ash beds associated with diamictites are yielding a precise date linking them to the Huronian-age glaciations [Brasier et al., 2012c]. Trial projects on dating of organic matter from Palaeoproterozoic $C_{org}$- and S-bearing rocks by the Re-Os technique have also proven to be successful [e.g., Hannah et al., 2006, 2008].

Future projects could explore U-Pb dating techniques on igneous baddelyite and diagenetic phosphate and xenotime, and may offer geochronological constraints on regional and global correlations, assess the synchronicity or diachronicity of isotopic excursions, the timing and duration of climatic events and volcanism, and the temporal (in)completeness of the sedimentary record. Oxidising processes could be dated by a (U-Th)/He series programme on haematite-bearing rocks [e.g., Lippolt et al., 1995, 1998; Shuster et al., 2005]. FAR-DEEP Core 6A, 8A, 8B offer a varied suite of igneous and volcaniclastic «red beds» and haematite-rich lithofacies such as haematite-cemented sandstones and jaspers to undertake such work.

Advanced work on provenance analysis of Paleoproterozoic siliciclastic sediments based on age and geochemistry of detrital zircons is in progress [Gärtner et al., 2012a–c].

*Change in sulphur cycle and the advent of the progressive oxidation of the atmosphere*

In the Imandra/Varzuga Belt, the FAR-DEEP Hole 1A (Figs. 1 and 2) intersected c. 120-m of tidal sandstone-siltstone-shale, quartzite and marine dolostones. These rocks accumulated at c. 2442 Ma during a transitional period in atmosphere evolution, from largely anoxic to a state of incipient oxidation. The continuous core allows obtaining high-resolution carbon and multiple sulphur isotope measurements and is a great opportunity to resolve the internal structure of the termination of mass-independent fractionation of sulphur isotope [Reuschel et al., 2012c] and ultimately a quantitative understanding of the related environmental changes. The study of the core will also contribute to better understanding of the global carbon cycle and seawater chemistry [Melezhik et al., 2012a] at the dawn of progressive atmospheric oxidation and prior to the global Huronian glaciations.

*Palaeoclimate*

The FAR-DEEP Core 3A obtained from the Imandra/Varzuga Belt (Figs. 1 and 2) contains a record of one of the Palaeoproterozoic glacial episodes but unlike anywhere else in the world, the diamictic units are interbedded with high-Sr, marine limestones and varves. The C isotopic composition of marine carbonates may record seawater chemistry and can be used as proxies for atmospheric composition informing on driving forces that caused the first global icehouse [Brasier et al., 2012]. Ash beds associated with the glacial deposits have shown a great potential for precise radiometric dating [Brasier et al., 2012c] and will provide a robust time constraint on the Palaeoproterozoic glaciations in the Fennoscandian Shield.

*Palaeoproterozoic perturbation of the global carbon cycle, the Lomagundi-Jatuli event*

The earliest, and one of the largest in Earth history, positive excursion of $\delta^{13}C$ in sedimentary carbonates, the Lomagundi-Jatuli Event, lasted more than 160 myr. This is one of several other prominent Palaeoproterozoic environmental events whose causative mechanism(s) remain intriguing and unresolved. The possible role of local factors in amplification of a global signal remains unconstrained. Cause-and-effect relationships of the Lomagundi-Jatuli Event with other global palaeoenvironmental changes in the APT remain only partially understood.

FAR-DEEP cores 5A, 10A, 10B and 11A (Figs. 1 and 2), together with previously published data, offer an opportunity to construct two- and three-dimensional isotopic models in the Pechenga [Salminen et al., 2012a] and Onega basins; these may inform on basinal $\delta^{13}C$ variations associated with local amplifying factors [e.g., Brasier et al., 2011]. Providing that high-precision age constraints are obtainable [e.g., Martin et al., 2012a], the FAR-DEEP holes 4A, 5A, 10A, 10B and 11A (Fig. 2) have a potential for comparison of time-equivalent successions accumulated in lacustrine (Core 5A), open marine (Core 4A) and restricted evaporitic (Cores 10A, 10B and 11A) environments. More $\delta^{13}C_{org}$ data covering the Lomagundi-Jatuli-age interval will help shed light on the merits of competing hypotheses and on inherent assumptions, and this will be addressed in future studies [e.g., Illing et al., 2012]. A detailed geochemical investigation of carbonate formations transitional from the Lomagundi-Jatuli to Shunga events is also in progress [Salminen et al., 2012b].

*Oxidised ocean, abundant Ca-sulphates and Palaeoproterozoic seawater sulphate reservoir*

Progressive oxygenation of Earth's surface environments resulted in increased sulphide oxidation during continental weathering and concomitant increase in the concentration of marine sulphate. To date, the database on $\delta^{34}S$ of Palaeoproterozoic sulphate remains limited and shows a large range from +5.1 ‰ to +42.3 ‰ (VCTD) [Schröder et al., 2008 and references therein; Guo et al., 2009; Крупеник и др., 2011]. In the Onega Basin, several FAR-DEEP drillholes

(10A, 10B and 11A; Figs. 1 and 2) specifically and successfully targeted sedimentary formations that contain abundant seawater sulphates in the form of pseudomorphs after gypsum and anhydrite. Reuschel et al. [2012a] generated data on the sulphur isotopic composition based on analyses of carbonate-associated and breccia-hosted sulphate, and *in situ* analyses of anhydrite and barite relicts in quartz-pseudomorphed Ca-sulphate nodules. All range in $\delta^{34}S$ between +7.8 and +11.3 ‰ (one outlier is at +15.8 ‰) over c. 500 m of stratigraphy and suggest seawater sulphate concentration >2.5 mM. Abundant relicts of sulphates preserved in dolomite- and quartz-pseudomorphed chicken-wire and enterolithic structures, concretions, crystals and rosettes in FAR-DEEP cores are rich material for further detailed mineralogical, petrographic, sedimentological and isotopic studies.

*Enhanced accumulation of organic carbon, petrified supergiant oil field and the Shunga event*

FAR-DEEP cores 12A, 12B and 13A obtained from the Onega Basin (Figs. 1 and 2) hold information on the enhanced accumulation of organic matter (the Shunga event) and an associated petrified supergiant oil field. Despite many years of research, numerous geological, geochemical and petrological features of this unique rock formation remain understudied. The cause(s) of such unprecedented global accumulation of organic matter and pervasive oil generation remains unknown.

FAR-DEEP core-based results show a stratigraphic trend in $\delta^{13}C_{org}$ from –22 ‰ to –40 ‰ in a c. 600-m-thick succession, and a two-step, stratigraphic shift by 15 ‰ within the upper 200 m of the succession. Kump et al. [2011] interpreted this negative excursion as a temporary but massive reversal of the long-term global carbon cycle. This reversal event is known as the 2.0 Ga Shunga Event [e.g., Melezhik et al., 2005], and it was the time when oxidation of organic carbon from the crust dominated the global carbon cycle [Kump et al., 2011].

Coupling carbon and sulphur isotopic systems [Meister et al., 2012; Illing et al., 2012], involving paired organic carbon [Qu et al., 2012a] and carbonate carbon isotopic studies on primary and diagenetic carbonate phases [Črne et al., 2012a, b], may reveal additional and crucial information on evolution of primary producers of organic matter and its recyclers. Other ongoing research includes structural organisation of organic material [van Zuilen et al., 2012; Qu et al., 2012b] and possible link of the Shunga event with an extraterrestrial impact [Hubert et al., 2011, 2012a–c]. A sulphur isotope study combined with iron speciation has been performed to elucidate redox-state conditions of the Shunga-event depositional system [Reuschel et al., 2012b]. Brasier et al. [2011b] have addressed a silica source in organosiliceous rocks. The FAR-DEEP cores warrant a series of other fascinating research projects on $C_{org}$-rich rocks.

*Ferric iron rich volcanic rocks: upper mantle oxidising event versus regional surface oxidation*

Why, how and when did atmospheric oxygen levels rise remains a fundamental problem: was it related to increased dioxygen due to evolution of oxygen-producing organisms or was it controlled by a decrease in oxygen sinks. A hypothesis has been proposed that the predominant sink for oxygen in the Archaean by chemically reduced gasses emitted in connection with submarine volcanism era was abruptly and permanently diminished during the APT [Kump, Barley, 2007]. FAR-DEEP cores 6A and 8 obtained in the Pechenga Belt (Figs. 1 and 2) contain information, which may test such ideas.

The drillholes 4A and 6A recovered more than 300 m of oxidised lavas that represent an unusual phenomenon and require explanation. Such rocks may either be evidence for relatively oxidised mantle material (e.g., recycled banded iron formations) or a large-scale alteration of Earth's surface by oxidised meteoric and/or groundwaters [Kyle et al., 2012]. Either outcome will represent a significant contribution to our knowledge on the oxidation of terrestrial environments.

*Subaerial and subaqueous hydrothermal systems*

Two types of compositionally different hydrothermal products have been documented in the FAR-DEEP drillcores. The first is represented by jasper, which appears in a large variety of occurrences in the cores, these include: numerous amygdales, veinlets and veins in volcanic rocks; layers, beds and feeder-veinlets in dolostones and siliciclastic sediments; and redeposited clasts in fluvial, deltaic and marine sediments. The jasper occurrences thus represent a complex history of fluid migration and redox alteration in magmatic processes, ground-, surface-, and hydrothermal waters, weathering crusts, and diagenetic processes. FAR-DEEP Cores 6A, 7A, 8A and 8B (Figs. 1 and 2) provide researchers with excellent material for studying the complex «iron story» which is tightly linked to the progressive oxidation of terrestrial

environments. Ongoing research on amygdales aims to constrain the origin of silica-precipitated fluids [Martin et al., 2012b].

The second type of hydrothermal products is travertine, which occurs in great abundances as thin crusts and feeder-veinlets in $^{13}C$-rich lacustrine dolostones intersected by Hole 5A in the Pechenga Belt. These are the earliest documented travertines and may signify a radical change in Earth surface environments to ones allowing the precipitation of hydrothermal carbonates in subaerial conditions. Detailed petrographic and geochemical work on the earliest known travertine-precipitating hydrothermal systems by Salminen [2012c] is in progress.

*Revolution in biological cycling of phosphorous and organic matter*

At around 2000 Ma, sedimentary formations record the first known appearance (if siderite in banded iron formations is excluded), and then worldwide development, of diagenetic carbonate concretions significantly depleted in $^{13}C$. These are varied in size and composition, and abundant in sedimentary successions <2000 Ma where they are associated with other diagenetic products, such as phosphorites, all of which are seemingly absent in older rocks. This could be attributed to the shift of recycling of organic matter by obligate anaerobes from the water column into the sediment column due to progressive oxidation of the terrestrial hydrosphere [e.g., Fallick et al., 2008].

In the Onega Basin, FAR-DEEP Holes 12A, 12B and 13A (Figs. 1 and 2) recovered hundreds of meters of cores containing abundant carbonate nodules and diagenetic phosphates. These c. 2000 Ma old sediments have geochemical signatures that indicate intensive diagenetic mineralisation of organic matter within the sedimentary column, perhaps reflecting increased rates in dissimilatory sulphate reduction and associated increased concentration of interstitial phosphate. Detailed petrographic and geochemical work on diagenetic carbonates [Črne et al., 2012a, b] and diagenetic phosphates is in the progress.

## FAR-DEEP core archive – a unique basis for the education of Earth-science researchers

FAR-DEEP core is readily accessible in its current stored location with NGU, Trondheim. The cores will be transferred in the future to the ICDP storage in Berlin, Germany. The FAR-DEEP core and database offer an unprecedented opportunity for future research, geological training and education. The 3650 m of cores represent palaeoenvironmental settings ranging from lacustrine to deep marine, and from rifted-margins to continental slopes. The cores contain exceptionally well-preserved spinifex-textured komatiitic lavas, pillowed basalts, alkaline amygdaloidal lavas, felsic lava breccias, Earth's first red beds, stromatolitic dolostones, lacustrine travertines, jaspers, abundant sulphates, tidalites, glacigenic rocks, organic-rich oil shales and pyrobitumens of ancient oil seeps, abundant diagenetic concretions and Earth's earliest phosphorites. All of these rocks can be cross-referenced to detailed geochemical data. The FAR-DEEP website (http://www.icdp-online.org) is the gateway to a vast collection of core photos and geochemical data, organised by hole, core box and easy-to-follow spreadsheet arrays.

The educational aspects associated with FAR-DEEP cores could accompany research activities involving educators, students and researchers. The well-preserved core material can be successfully employed for targeting several unresolved sedimentological, petrological and geochemical problems associated with the emergence of the aerobic Earth system. The core material enables defining and undertaking research activities ranging from focused master programmes and doctoral studies to large-scale multidisciplinary projects.

## Springer-published FAR-DEEP three-volume treatise on Earth's Oxygenation

The first significant outcome of the FAR-DEEP is a three-volume treatise (ca. 1500 pages) entitled «Reading the Archive of Earth's Oxygenation». This, scheduled by Springer for publication in July 2012, will: (*i*) provide a comprehensive review of the Palaeoproterozoic Eon with an emphasis on the Fennoscandian Shield geology; (*ii*) serve as an initial report of the preliminary analysis of one of the finest lithological and geochemical archives of early Palaeoproterozoic Earth history, created under the auspices of the International Continental Scientific Drilling Program (ICDP); and (*iii*) synthesise the current state of our understanding of aspects of early Palaeoproterozoic events coincident with and likely related to Earth's progressive oxygenation, with an emphasis on still-unresolved problems ready to be addressed by future research. Combining this information in three coherent volumes offers an unprecedented cohesive and comprehensive study of the progressive oxidation of the terrestrial environments and related global upheavals that eventually led to the emergence of the modern aerobic Earth System.

The format of these books centres on high-quality photo-documentation of FAR-DEEP cores and natural exposures of the Palaeoproterozoic rocks of the Fennoscandian Shield. The photos are linked to geochemical data sets, summary figures and maps, and time-slice reconstructions of basinal and palaeoenvironmental settings that document the response of the Earth system to the Great Oxidation Event. The emphasis on a thorough, well-illustrated characterisation of rocks reflects the importance of sedimentary and volcanic structures that form a basis for interpreting ancient depositional environments, and chemical, physical and biological processes operating on Earth's surface. Most of the structural features are sufficiently complex as to challenge the description by other than a visual representation and high-quality photographs are themselves a primary resource for presenting essential information. Although nothing can replace the wealth of information that a geologist can obtain from examining an outcrop first-hand, the utility of photographs offers the next best source of data for assessing and evaluating palaeoenvironmental reconstructions. This three-volume treatise will, thus, act as an information source and guide to other researchers, help them to identify and interpret such features elsewhere, and will serve as an illustrated guidebook to the Precambrian for geology students.

Finally, the three-volume treatise provides a link to the FAR-DEEP core collection archived at the Geological Survey of Norway. These drillcores are a unique resource that can be used to solve the outstanding problems in understanding the causes and consequences of the multiple processes associated with the progressive oxygenation of terrestrial environments. It is anticipated that the well-archived core will provide the geological foundation for future research aimed at testing and generating new ideas about the Palaeoproterozoic Earth. The three-volume treatise will be of interest to researchers involved directly in studying this hallmark period in Earth history, as well as professionals and students interested in Earth System evolution in general.

Volume 1, «The Palaeoproterozoic of Fennoscandia as Context for the Fennoscandian Arctic Russia – Drilling Earth Project» [Melezhik et al., 2012b], describes the implementation of the FAR-DEEP drilling project in Arctic Russia. It summarises the knowledge of more than 50 years of largely Russian-led fieldwork, information hitherto virtually unavailable in the West, and provides geological description of drilling areas with an overwhelming illustration of rocks by high-quality, representative photographs. The volume offers a comprehensive review and photo-illustration of palaeotectonic, palaeogeographic and magmatic evolution of the Fennoscandian Shield in the early Palaeoproterozoic, and links the evolution of the Shield to the emergence of an aerobic Earth system. The volume unfolds the event-based Fennoscandian chronostratigraphy and discusses the chronology of the Palaeoproterozoic global events as the base for a new subdivision of Palaeoproterozoic time.

Volume 2, «The Core Archive of the Fennoscandian Arctic Russia – Drilling Early Earth Project» [Melezhik et al., 2012c], provides a description of the newly generated archive hosting ICDP's FAR-DEEP drill cores through key geological formations in Russian Fennoscandia. The book contains several hundred high-quality, representative photographs illustrating 3650 m of fresh, uncontaminated core documenting the series of global palaeoenvironmental upheavals linked to the Great Oxidation Event. The core exhibits sedimentary and volcanic formations that record a transition from anoxic to oxic Earth surface environments, the first global glaciation (the Huronian glaciation), an unprecedented perturbation of the global carbon cycle (the Lomagundi-Jatulian Event), a radical increase in the size of the seawater sulphate reservoir, an apparent upper mantle oxidising event, the Earth's earliest documented sedimentary phosphates, one of the greatest accumulations of organic matter (the Shunga Event) and generation of the Earth's earliest supergiant petroleum deposit. The volume highlights the potential of the FAR-DEEP core archive for future research of the Great Oxidation Event and the biogeochemical cycles operating during that time.

Volume 3, «Global Events and the Fennoscandian Arctic Russia – Drilling Earth Project» [Melezhik et al., 2012d], represents another kind of illustrated journey through the early Palaeoproterozoic, provided by syntheses, reviews and summaries of the current state of our understanding of a series of global events that resulted in a fundamental change of the Earth System from an anoxic to an oxic state. The book discusses traces of life, possible causes for the Huronian-age glaciations, addresses radical changes in carbon, sulphur and phosphorus cycles during the Palaeoproterozoic, and provides a comprehensive description and a rich photo-documentation of an early Palaeoproterozoic supergiant, petrified oil-field. Terrestrial environments are characterised through a critical review of available data on weathered and calichified surfaces and travertine deposits. Potential implementation of Ca, Mg, Sr, Fe, Mo, U and Re-Os isotope systems for deciphering Palaeoproterozoic seawater chemistry and a

change in the redox-state of water and sedimentary columns are discussed. The volume considers in detail the definition of the oxic atmosphere, possible causes for the oxygen rise, and the oxidation of terrestrial environment not as a single event, but a more stately process lasting over hundreds of millions of years. Finally, the book provides a roadmap as to how the FAR-DEEP cores may facilitate further interesting science and a new foundation for education in the Earth-science community.

## References


*Крупеник В. А., Ахмедов А. М., Свешникова К. Ю.* Изотопный состав углерода, кислорода и серы в породах людиковийского и ятулийского надгоризонтов // Онежская палеопротерозойская структура (геология, тектоника, глубинное строение и минерагения) / Отв. ред. Л. В. Глушанин, Н. В. Шаров, В. В. Щипцов. Петрозаводск: Карельский НЦ РАН, 2011. С. 250–255.

*Brasier A. T., Fallick A. E., Prave A. R., Melezhik V. A., Lepland A. and FAR-DEEP Scientists.* Coastal sabkha dolomites and calcitised sulphates preserving the Lomagundi-Jatuli carbon isotope signal // Precambrian Research. 2011a. 189. P. 193–211.

*Brasier A. T., Lepland A., Melezhik V. A. et al.* Oil in sediments and sediments in oil: the origin of silica in the enigmatic 2.0 Ga Palaeoproterozoic petrified oilfield of Karelia, Russia // 7th international Cambridge diagenesis conference, 15th–16th September 2011. 2011b.

*Brasier A. T., Martin A. P., Fallick A. E. et al.* Earth's earliest global glaciation: geochronology and geochemistry of the Polisarka Sedimentary Formation, Kola Peninsula, Russia // Precambrian Research. 2012 (in preparation).

*Črne A. E., Melezhik V. A., Lepland A. et al.* Negative C-isotope excursion in carbonates during 2.0 Ga Shunga Event // Goldschmidt Conference, Montréal, Canada, June 24–29, 2012. 2012a.

*Črne A. E., Melezhik V. A., Lepland A. et al.* Organic diagenesis recorded in geochemistry of carbonates associated with the Shunga Event // Chemical Geology. 2012b (in preparation).

*Fallick A. E., Melezhik V. A., Simonson B.* The ancient anoxic biosphere was not as we know it // N. Dobretsov, N. Kolchanov, A. Rozanov, G. Zavarzin (Eds.). Biosphere origin and Evolution. Springer Science+Business Media, 2008. P. 169–188.

*Gärtner C., Bahlburg H., Martin A. et al.* Time constraints for Archean-Paleoproterozoic events of the Fennoscandian Shield from detrital zircon geochronology // Precambrian Research. 2012a (in preparation).

*Gärtner C., Bahlburg H., Berndt J., Gerdes A.* Provenance analysis of Paleoproterozoic siliciclastic sediments from Fennoscandia – Indications for source regions and crustal evolution // Sedimentary Geology. 2012b (in preparation).

*Gärtner C., Bahlburg H., Martin A. et al.* Investigating Fennoscandian Paleoproterozoic stratigraphy – New insights from detrital zircon geochronology and provenance of the Kolosjoki Sedimentary Formation, the Pechenga Greenstone Belt, Russia // Precambrian Research. 2012c (in preparation).

*Guo Q., Strauss H., Kaufman A. J. et al.* Reconstructing Earth's surface oxidation across the Archean-Proterozoic transition // Geology. 2009. 37. P. 399–402.

*Hannah J. L., Stein H. J., Zimmerman A. et al.* Precise 2004 ± 9 Ma Re-Os age for Pechenga black shale: Comparison of sulfides and organic material // Geochim. Cosmochim. Acta. 2006. 70. Supplement, A-228.

*Hannah J. L., Stein H. J., Zimmerman A. et al.* Re-Os geochronology of a 2.05 Ga fossil oil field near Shunga, Karelia, NW Russia // Abstract, the 33rd International Geological Congress, Oslo, 2008, 6–14 August. 2008.

*Huber M. S., Crne A. E., Lepland A., Melezhik V. A., Koeberl C., FAR DEEP Science Team.* Possible Occurrence of Distal Impact Ejecta from the Vredefort Impact Event in Drill Cores from the Onega Basin, Russia // Lunar and Planetary Science Conference XLII, The Woodlands, Texas, USA, March 7–11. Abstract #1487. 2011.

*Huber M. S., Crne A. E., Lepland A., McDonald I., Melezhik V. A., Koeberl C., FAR DEEP Science Team.* Chemical analysis of impact spherules from the Zaonega Formation, Karelia, Russia, and implications for Vredefort origin // Lunar and Planetary Science Conference XLIII, The Woodlands, Texas, USA, March 19–23, 2012. Abstract #1970. 2012a.

*Huber M. S., Crne A. E., Lepland A. et al.* Probable Vredefort ejecta from Karelia, Russia: A key to understanding Precambrian impact spherules // Nature Geoscience. 2012b (in preparation).

*Huber M. S., Crne A. E., Lepland A. et al.* Petrography and geochemistry of Vredefort-age impact spherules from Karelia, Russia // Precambrian Research. 2012c (in preparation).

*Illing C. J., Strauss H., Summons R. E. et al.* Insights into the carbon cycle at the Archean Proterozoic Transition from Fennoscandia // Precambrian Research. 2012 (in preparation).

*Koistinen T., Stephens M. B., Bogatchev V. et al. (comps.).* Geological Map of the Fennoscandian Shield, Scale 1 : 2 000 000. Espoo, Trondheim, Uppsala, Moscow, 2001.

*Kump L. R., Barley M. E.* Increased subaerial volcanism and the rise of atmospheric oxygen 2.5 billion years ago // Nature. 2007. 448. P. 1033–1036.

*Kump L. R., Junium Ch., Arthur M. A. et al.* Isotopic evidence for massive oxidation of organic matter following the Great Oxidation Event // Science. 334. P. 1694–1696.

*Lippolt H. J., Wernicke R. S., Bähr R.* Paragenetic specularite and adularia (Elba, Italy): Concordant (U+Th)-He and K-Ar ages // Earth and Planet. Sci. Letters. 1995. 132. P. 43–51.

*Lippolt H. J., Brander T., Mankopf N. R.* An attempt to determine formation ages of goethites and limonites by (U+Th)-$^4$He dating // Neues Jahrb Mineral Monatsh. 1998. 11. P. 505–528.

*Martin A. P., Condon D. J., Prave A. R. et al.* Dating the termination of the Palaeoproterozoic Lomagundi-Jatuli carbon isotopic Event in the North

Transfennoscandian Greenstone Belt // Precambrian Research. 2012a (submitted).

*Martin A. P., Brasier A. T., Fallick A. E. et al.* Oxygen isotope ratios in amygdaloidal silica from the 2058 Ma Kuetsjärvi Volcanic Formation, Russia // Chemical Geology. 2012b (submitted).

*Meister D., Strauss H., Melezhik V. A.* A record of sedimentary sulfur and carbon cycling during the Shunga Event – implications from sulfur isotopes of the 2.0 Ga Zaonega Formation, NW Russia // Precambrian Research. 2012 (in preparation).

*Melezhik V. A., Fallick A. E., Hanski E. J. et al.* Emergence of the aerobic biosphere during the Archean-Proterozoic transition: Challenges of future research // GSA Today. 2005. 15. P. 4–11.

*Melezhik V. A., Prave A. R., Lepland A.* Depositional framework and C-isotopic composition of the Palaeoproterozoic (pre-Huronian-age) Seidorechka Sedimentary Formation in the Imandra-Varzuga Greenstone Belt, NE Fennoscandia, Russia // Precambrian Research. 2012a (in preparation).

*Melezhik V., Prave A., Hanski E. et al. (eds.).* Reading the Archive of Earth's Oxygenation. Vol. 1: The Palaeoproterozoic of Fennoscandia as Context for the Fennoscandian Arctic Russia – Drilling Earth Project. Springer, Heidelberg, 2012b (accepted).

*Melezhik V., Prave A., Fallick A. et al. (eds.).* Reading the Archive of Earth's Oxygenation. Vol. 2: The Core Archive of the Fennoscandian Arctic Russia – Drilling Early Earth Project. Springer, Heidelberg, 2012c (accepted).

*Melezhik V., Kump L., Fallick A. et al. (eds.).* Reading the Archive of Earth's Oxygenation. Vol. 3: Global Events and the Fennoscandian Arctic Russia – Drilling Earth Project. Springer, Heidelberg, 2012d (accepted).

*Qu Yu., Črne A. E., Lepland A., van Zuilen M.* Methanotrophy in a Paleoproterozoic oil field ecosystem, Zaonega Formation, Karelia, Russia // Geobiology. 2012a (submitted).

*Qu Yu., van Zuilen M., Lepland A. et al.* Structural variation of metamorphosed carbonaceous matter in the 2.0 Ga Zaonega Formation, Karelia, Russia // Earth and Planet. Sci. Letters. 2012b (in preparation).

*Reuschel M., Melezhik V. A., Lepland A. et al.* Isotopic evidence for a sizeable seawater sulfate reservoir at 2.1 Ga // Precambrian Research. 2012a. 192. P. 78–88.

*Reuschel M., Melezhik V. A., Strauss H.* Sulfur isotopic trends and iron speciation from the c. 2.0 Ga Pilgujärvi Sedimentary Formation, NW Russia // Precambrian Research. 2012b. P. 196–197, 193–203.

*Reuschel M., Martin A. P., Lepland A. et al.* The decline of mass-independent sulfur isotopic fractionation recorded on the Fennoscandian Shield // Nature. 2012c (in preparation).

*Rybacki K., Hanski E. J., Melezhik V. A., Kump L. R.* Evidence for extensive oxidation weathering of subaerial lava flows following the «Great Oxidation Event» // Earth and Planet. Sci. Letters. 2012 (in preparation).

*Salminen P. E., Karhu J. A., Melezhik V. A.* Tracking lateral $\delta^{13}C_{carb}$ variation in the Paleoproterozoic Kuetsjärvi basin, the Pechenga Greenstone Belt, the north-eastern Fennoscandian Shield // Precambrian Research. 2012a (submitted).

*Salminen P. E., Karhu J. A., Melezhik V. A.* Kolosjoki Sedimentary Formation: a record of the aftermath of the Paleoproterozoic global positive $\delta^{13}C$ excursion of sedimentary carbonates // Precambrian Research. 2012b (in preparation).

*Salminen P. E., Brasier A. T., Karhu J. A., Melezhik V. A.* Various carbonate precipitates in the Paleoproterozoic Kuetsjärvi Sedimentary Formation // Chemical Geology. 2012c (in preparation).

*Schröder S., Bekker A., Beukes N. J. et al.* Rise in seawater sulphate concentration associated with the Paleoproterozoic positive carbon isotope excursion: evidence from sulphate evaporites in the ~2.2–2.1 Gyr shallow-marine Lucknow Formation, South Africa // Terra Nova. 2008. 20. P. 108–117.

*Shuster D. L., Vasconcelos P. M., Heim J. A., Farley K. A.* Weathering geochronology by (U-Th)/He dating of goethite // Geochim. Cosmochim. Acta. 2005. 69. P. 659–673.

*van Zuilen M., Fliegel D., Wirth R. et al.* Mineral-templated growth of natural graphite films // Geochim. Cosmochim. Acta. 2012. 83. P. 252–262.

## СВЕДЕНИЯ ОБ АВТОРАХ:

**Мележик Виктор**
Геологическая служба Норвегии
п./я. 6315, Слуппен, Тронхейм, Норвегия, N-7491
эл. почта: victor.melezhik@ngu.no
http://www.ngu.no
http://far-deep.icdp-online.org
тел.: +47 – 73 90 40 00 (прямой 241)
факс: +47 – 73 92 16 20

**Melezhik, Victor A.**
Geological Survey of Norway, Postboks 6315 Sluppen,
N-7491 Trondheim, Norway
e-mail: victor.melezhik@ngu.no
http://www.ngu.no
http://far-deep.icdp-online.org
tel.: +47– 73 90 40 00 (direct 241)
fax: +47 – 73 92 16 20

**Прэйв Энтони**
Факультет науки о Земле, Университет Сент-Эндрюс,
С. Эндрюс, KY16, 9AL, Шотландия, Великобритания
эл. почта: ap13@st-andrews.ac.uk
тел.: +44 133 4462481

**Prave, Anthony R.**
Reader in Earth Sciences
Department of Earth Science, University of St. Andrews, St
Andrews, KY16, 9AL, Scotland, UK
e-mail: ap13@st-andrews.ac.uk
office telephone: +44 133 4462481