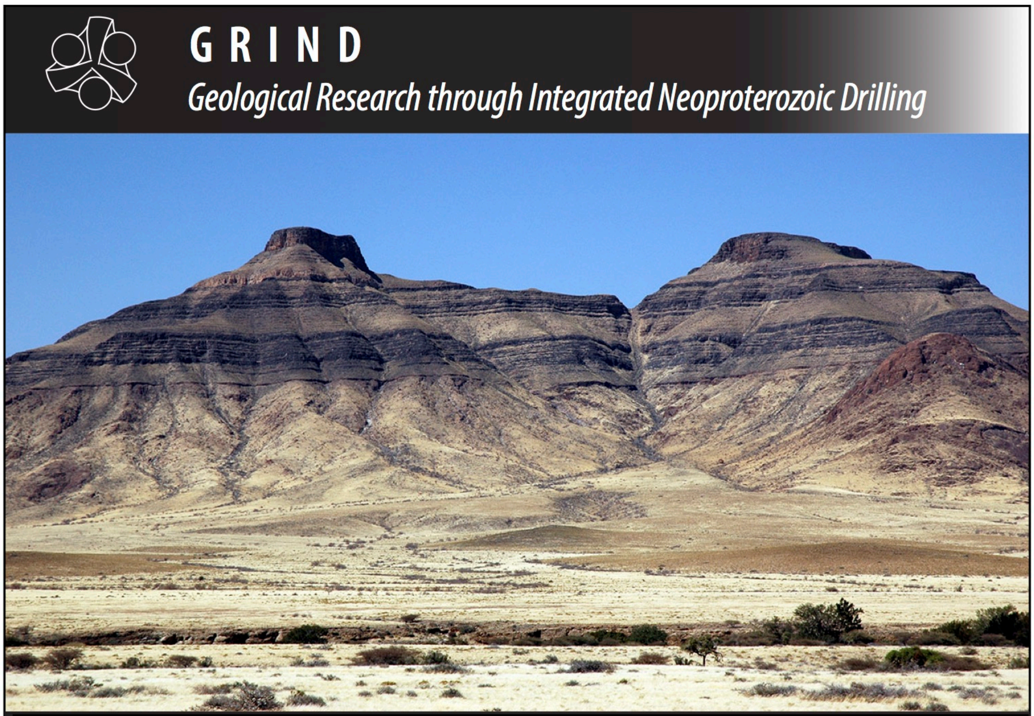

Ediacaran-age Nama Group strata resting unconformably on Proterozoic basement, Namibia.

[1]*GRIND-ECT: Geological Research through Integrated Neoproterozoic Drilling – The Ediacaran-Cambrian Transition (ECT)*

A Proposal submitted to
The International Continental Scientific Drilling Program
15 January 2018

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[1]GRIND-ECT is the first phase of the GRIND initiative: Geological Research through Integrated Neoproterozoic Drilling. GRIND's goal is to create a global archive of cores focussed on enhancing understanding of the 1000 – 520 Ma time interval worldwide, the pivotal period in Earth history during which the planet became oxygen-rich and metazoans evolved. For a full description of GRIND, please read the ICDP/ECORD Workshop Report Condon et al. (2015).

Geological Research through Integrated Neoproterozoic Drilling (GRIND): The Ediacaran-Cambrian Transition (ECT)

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Preamble. In March 2014, an ICDP and ECORD Magellan+ sponsored Workshop was held at the British Geological Survey, Keyworth, England. In attendance were 44 of the world's experts on Neoproterozoic geology representing 14 countries with the aim to define a multi-continent drilling programme to target the Neoproterozoic Era, specifically the Ediacaran-Cambrian transition (ECT). The *unanimous* decision was that Brazil, China and Namibia, countries where the quality and knowledge of the surface and subsurface geology of the ECT is unsurpassed, constituted the key regions for inaugurating that programme; all other areas were identified as either lesser well-documented geologically or having a substandard record of the ECT. This decision led to the GRIND-ECT proposal being submitted to ICDP in January 2016. The ICDP review panel then requested resubmittal in January 2017, followed by an addendum in September 2017. This revised proposal is in response to the ICDP's request for clarification regarding Chinese participation and the Namibian drilling strategy outlined in the addendum. It supplants all previous submissions and: (i) incorporates information provided by the Chinese team that enable reinstating the South China drilling programme, (ii) gives a thorough explanation of the Namibian drilling plan, (iii) informs that drilling in Brazil will commence in 2018 via funding obtained by the Brazilian Team from FAPESP (the federal funding agency of São Paulo Province; note data will be made freely available to GRIND-ECT), and (iv) outlines in detail the organisational and management structure of GRIND-ECT. Please see the Cover Letter for details.

1. Introduction and motivation of GRIND-ECT

The Neoproterozoic Era (1000 - 541 Ma) began with simple eukaryotes that populated Earth during the preceding billion years of the Mesoproterozoic and ended with the oxygenated and diverse ecosystems of the Cambrian. In the interim, some of the most dramatic changes in Earth history occurred (Fig. 1): animals appeared from a world of bacteria and algae (Cohen and Macdonald 2015), the supercontinent Rodinia formed and broke apart (Evans 2013; Li et al. 2008), the carbon cycle underwent high-amplitude fluctuations (Halverson et al. 2005), oxygen concentrations are thought to have risen (Lyons et al. 2014) and climate experienced at least two episodes of prolonged worldwide glaciation (Rooney et al. 2015). However, the fragmented nature of outcrop-based studies and lack of exact age constraints on the timing and durations of those episodes hinders developing quantitatively constrained models of Earth system functioning during that Era.

The GRIND project (Condon et al. 2015) aims to address that shortcoming by creating a global core archive for the Neoproterozoic Era. Fresh, oriented cores will enable constructing continuous high-resolution bio-, chemo- cyclo- and magneto-stratigraphies integrated with geochemical and chronostratigraphic data. The project is an international, community-wide collaborative effort to better understand the nature and drivers of this pivotal time in Earth history and will be achieved via a series of coordinated drilling projects, undertaken sequentially, that target the key localities recording those Earth system transformations. This proposal is for the first phase of GRIND, GRIND-ECT, which focusses on the Ediacaran-Cambrian transition (ECT; Time Slab C, Fig. 2).

Since Darwin's (1859) observation of the seemingly rapid appearance of fossils in Cambrian strata, resolving the causes and tempo of the 'Cambrian Explosion' remains one of science's great challenges (Erwin et al. 2011). GRIND-ECT will obtain sufficient temporal resolution and integration of geological, geochemical and biological data to address the following key questions:

- What was the timing and rates of the advent, expansion and extinction of Ediacaran biota?
- What was the environmental context and timing for changing skeletal mineralogy and diversification of biomineralising metazoa?

- What was the pattern of oxygenation (globally and regionally) and how does it relate to other geochemical patterns? Was there a Neoproterozoic oxygenation event?
- What was the timing, duration, genesis and implications for the global C cycle and the large amplitude C-isotope excursions in late Ediacaran to Cambrian strata?
- Is the Ediacaran-Cambrian boundary a synchronous worldwide biological event or a lengthy episode of biological innovation?

The ECT strata in west Brazil, south China and south Namibia were chosen to answer these questions because their geology from the Marinoan glacial to the early Cambrian is excellent, well understood (Fig. 3) and will guide drilling and supplement core data. Further, each country has expertise and infrastructure for drilling and coring.

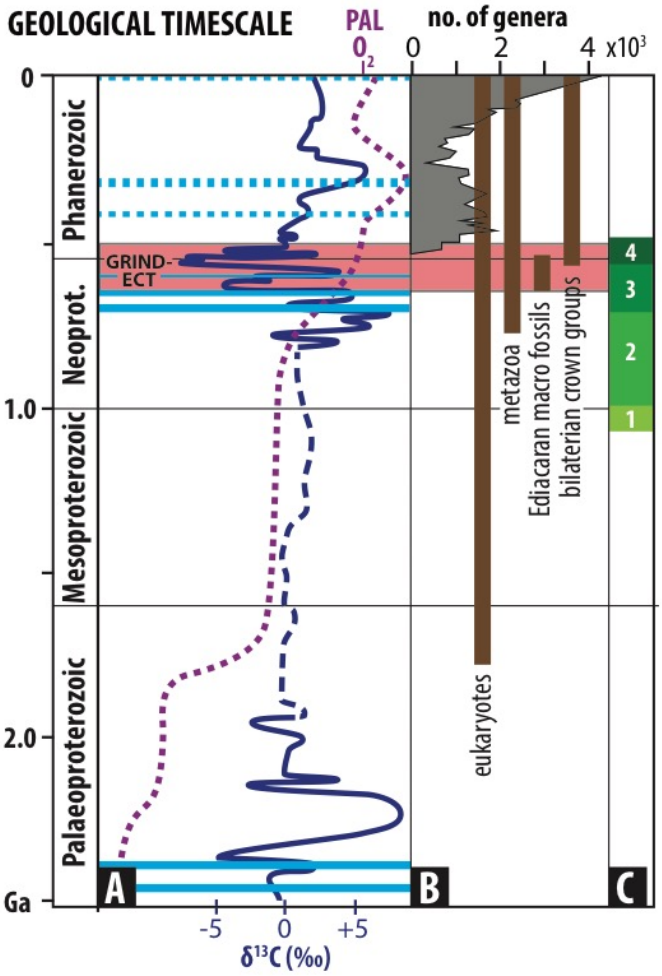

Figure 1. Selected secular trends revealing the distinctiveness of the Neoproterozoic. (A) C cycle and pO_2 (PAL-present atmospheric level). (B) Biospheric evolution. (C) Global tectonics: 1-Grenville orogeny; 2-Rodinia supercontinent; 3-Rodinia rift-to-drift phase; 4-Pan-African orogeny. Solid blue bands represent periods of global glaciations, dashed blue bands denote glaciations restricted to high-latitudes and the red band is the time interval to be targeted by GRIND-ECT. See text for discussion and references for data sources.

Research Foci. GRIND-ECT will be coordinated around three *research foci (RF)*.

RF1: A highly resolved temporal framework. The goal of *RF1* is to obtain precise dates on tuffs and organic-rich shales using U-Pb zircon CA-ID-TIMS and Re-Os geochronology and integrate those with palaeomagnetism and physical stratigraphy to construct age models for the ECT. ECT strata preserve the earliest known phosphatised metazoa embryos, the first appearance datum of *Treptichnus pedum,* and an increase in diversity of metazoa, trace fossils and phytoplankton (Landing 1994; Yin et al. 2007; Narbonne 2005; Grotzinger et al. 1995; Cohen et al. 2009; Marshall 2006). These evolutionary milestones are associated with C-isotope excursions (amplitudes of ≥8‰; *e.g.* Maloof et al. 2010; Smith et al. 2016; Zhu et al. 2017) and, although temporal coincidence is often assumed, their timing and duration remain to be constrained precisely. These data will underpin the work being done in *RF2* and *RF3*.

RF2: Fossil record of early animal evolution. The goal of *RF2* is to refine the patterns of biotic evolution of organic-walled and mineralised microfossils, metazoans and trace fossils and integrate those data with *RF1* and *RF3* to assess the links between and test hypotheses about biological evolution and environment. Documenting changes in morphology and skeletal mineralogy integrated with age data and geochemical and palaeoenvironmental data using the new cores, in conjunction with existing outcrop studies along with CT scanning to reveal ichnofossil assemblages (Appendix A1.1), will inform ideas about the causes of increasing body size and ecological complexity *vis-à-vis* oxygen levels and biological innovation (*e.g.* Butterfield 2017), such as structural defences against predation. Where appropriate, biomarkers will also provide insight into the late Ediacaran and early Cambrian communities (Love et al. 2009; Brocks et al. 2017) using drilling and sampling protocols established during Agouron-funded drilling to recover Archean hydrocarbons (Brocks et al. 2008; Jarrett et al. 2013; Schinteie and Brocks 2014; see French et al. 2015 for details, and Section 4).

RF3: Palaeoenvironmental conditions and the rise of oxygen. The goal of *RF3* will be to determine

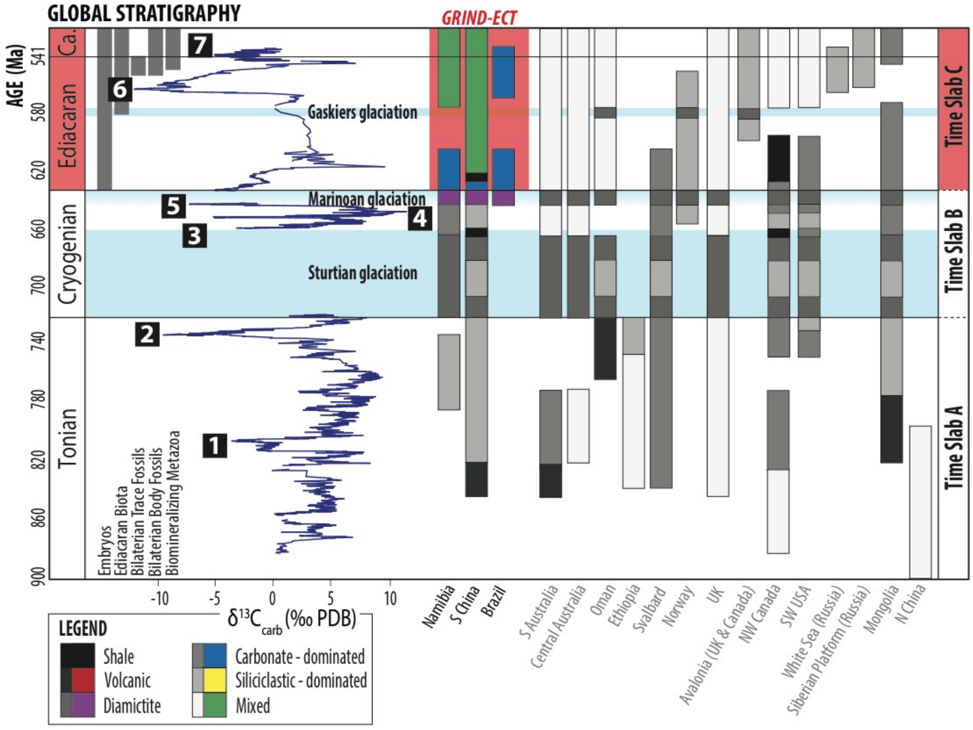

Figure 2. Neoproterozoic time slabs identified for drilling in the GRIND project and stratigraphy and major glacial periods for key successions worldwide. Red highlighted intervals denote the Time Slab C target of GRIND-ECT. Biospheric evolutionary trends are given to the left with a plot of the composite C-isotopic profile and excursions: 1-Bitter Springs; 2-Islay; 3-Keele Peak; 4-Taishir; 5-Trezona; 6-Shuram; 7-BASE. Ca – Cambrian. See text for references providing the sources of data.

palaeoenvironmental conditions using facies interpretations, geochemistry and elemental and stable isotope data integrated into the age model of *RF1* and fossil record of *RF2*. This work will distinguish cause-and-effect relationships and basin-specific versus global-scale secular trends in geochemical and stable isotope patterns. Trace metal abundances, iron speciation and a suite of traditional and non-traditional isotopes will be used to guide hypothesis on weathering and nutrient fluxes (*e.g*. Sr, Os, Li isotopes, P), ocean redox (*e.g.* Mo, δ^{238}U, Fe speciation) and biogeochemistry (*e.g.* δ^{34}S, δ^{15}N, δ^{98}Mo, δ^{13}C isotopes). Perturbations in C and S cycles and studies of redox sensitive elemental ratios (*e.g.* Fe, U) have been used to link the advent of animals with a putative global rise in oxygen, the Neoproterozoic Oxygenation Event (Och and Shields-Zhou 2012). Ediacaran oceans are postulated to have had spatially and temporally varying oxygenation, with ferruginous and anoxic deep waters and variably oxic surface waters but oxic everywhere by the end of the Ediacaran (Lyons et al. 2014). Other workers question this scenario (Butterfield 2009; Sperling et al. 2015). Hence, although temporal coincidence between the advent of skeletonisation and animals and the inference for a rise in oxygen hints at causality, the precise role of oxygen in driving biological evolution remains uncertain. New core data will be compared to and incorporate published geochemical and isotopic data from equivalent outcrop-based studies to create and test ideas linking changing ocean-atmosphere conditions and compositions to the evolution of animals.

Assessing diagenesis. The potential overprinting of original signals by diagenesis is a critical issue to assess for geochemical proxies that are used to inform on ancient environmental conditions. Fresh cores are key because they recover rocks that have been minimally influenced by surface weathering (Appendix A1.2). To identify samples in which geochemical and isotopic signals are preserved, screening protocols will be used that have been applied successfully to Neoproterozoic strata in many areas worldwide (*e.g*. Fantle and Higgins 2014; Kasemann et al. 2005). Screening will first use basic observation (*e.g*. presence/absence of veins, recrystallisation textures, colour alteration), then petrography, SEM and cathodoluminescence imaging, followed by a battery of geochemical tests to assess for diagenetic overprints and distinguish those from primary signals via patterns and trends in selected elements and their ratios (*e.g*. Al, Ba, Ca, Fe, Mg, Mn, P, S, Si, Sr) as well as stable isotope ratios and patterns (C, O, B, Ca, Mg).

In summary, *RF1-3* will enable integration of new core data with published and in-progress outcrop-based studies worldwide. This approach will provide high-resolution sedimentological, geochemical, palaeobiological, palaeomagnetic, geochronological and cyclostratigraphic (Appendix A1.3) data to determine rates of change of biogeochemical processes, evolutionary tempos, and the spatio-temporal record of oxygenation across a spectrum of environmental settings.

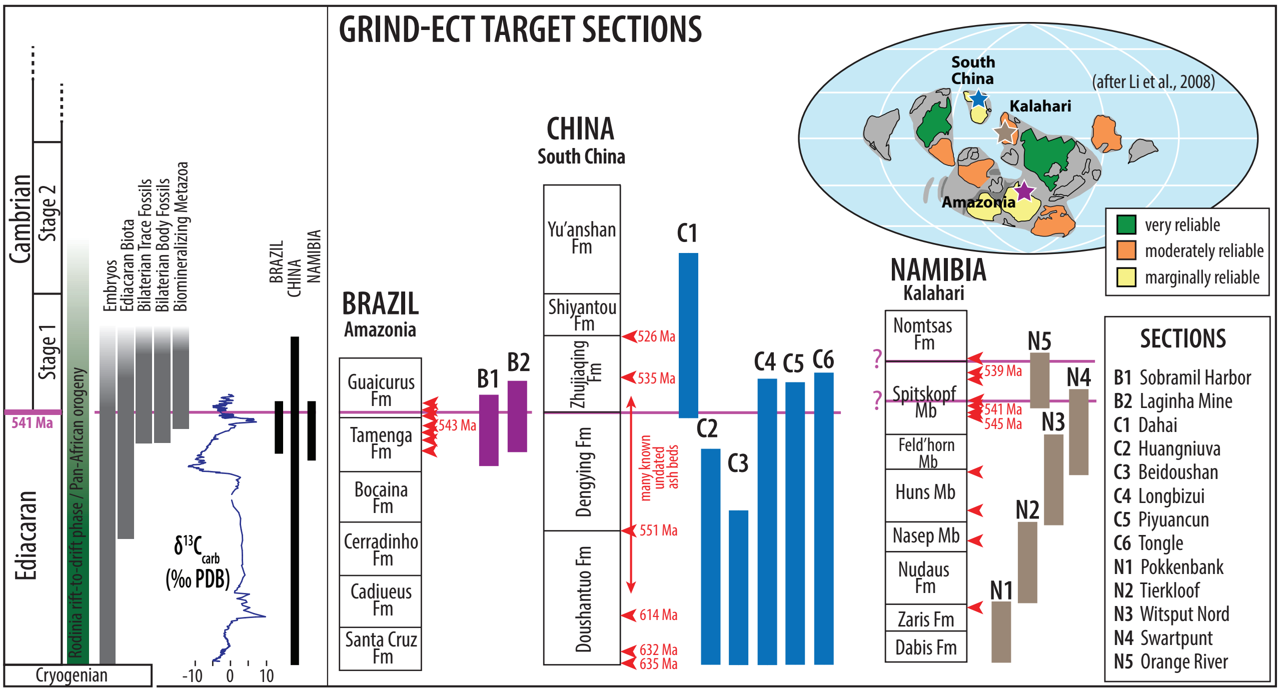

Figure 3: Schematic showing GRIND-ECT target sections in Brazil (B1-2), China (C1-6) and Namibia (N1-5), and their temporal relationship to key evolutionary, C-isotope and tectonic events. Red arrows represent ash beds. Inset map shows locations of drill sites (marked by stars) on a palaeocontinent reconstruction for the formation of Gondwana during the late Ediacaran. See text for references providing these data.

2. The need for multi-craton, multi-site Neoproterozoic scientific drilling

Pristine cores recover complete intervals typically unattainable from outcrops that often have limited continuity of exposure and been modified by weathering. Cores are key to evaluate diagenesis and reduce uncertainty in proxy records, and the value of core networks has been demonstrated by the IODP. In contrast, few core archives exist for Neoproterozoic strata, exceptions being the South Oman Salt Basin and Australia's Centralian Basin and those yielded benchmark works on biospheric evolution (Amthor et al. 2003; Bowring et al. 2007; Fike and Grotzinger 2008; Fike et al. 2006; Pisarevsky et al. 2001; Walter et al. 2000). We expect the same impact and value for the GRIND-ECT core network. Creating a worldwide, integrated network of cores through Neoproterozoic strata will yield unrivalled 3- and 4-D stratigraphies to differentiate global from regional phenomena and create and test hypotheses about, and advance understanding of, the Neoproterozoic Era for scientific as well as natural resource perspectives. Previous experience with ICDP FAR-DEEP (Melezhik et al. 2013) and NASA Agouron Deep Time drilling projects (Schröder et al. 2006) confirms that a continental scientific drilling programme would be decisive in delivering knowledge of the environmental and biogeochemical episodes that record how the Earth System transformed from simple eukaryotes through the ECT to the Cambrian Explosion. GRIND-ECT targets that important transition in Earth history: the advent of animals and the change to a well-oxygenated planet. Each of the three chosen localities has distinct, yet complementary records: fossiliferous organic-rich limestone and shale in west Brazil, microfossil-rich carbonate-dominated strata in south China, and macro- and trace-fossil-rich carbonate-siliciclastic rocks in Namibia. Further, all sections have datable ash beds and organic-rich rocks for high-resolution U-Pb and Re-Os geochronology that will permit age models and correlations at high temporal resolutions to enable quantitative assessments of the mechanisms and rates-of-change leading to and culminating in the Cambrian Explosion.

3. Drilling and drill site selection

Existing detailed geological maps and outcrop-based datasets, structurally simple geology, industry-generated drilling data and in-country skill for drilling and coring provide a solid framework for identifying drill hole locations in west Brazil, south China and south Namibia. FAPESP-funded drilling will commence in 2018 in Brazil and, if this proposal is successful, in 2019 in Namibia and China. The strategy is to core correlative strata within and between nations to test models on the genesis, synchronicity versus diachronicity and global versus regional aspects of early animal evolution and its environmental context. Combined, the core archives will obtain a level of resolution that surpasses all current datasets and will offer rich opportunities for much future research.

Most cores will be between 150-400 m in length, with several approaching 600 m lengths (see below and Appendix 2 for details); such shallow drilling depths combined with the well-understood geology of the drill sites maximise confidence that target strata will be recovered and structural problems avoided. Further, the existing and detailed knowledge from outcrop-based studies will help guide the drilling and supplement the core data. Drilling logistics are also straightforward: drill sites are in relative proximity to necessary infrastructure, roads and access to water, which will reduce costs and maintain a low drilling-operation-cost:post-drilling-research-cost ratio.

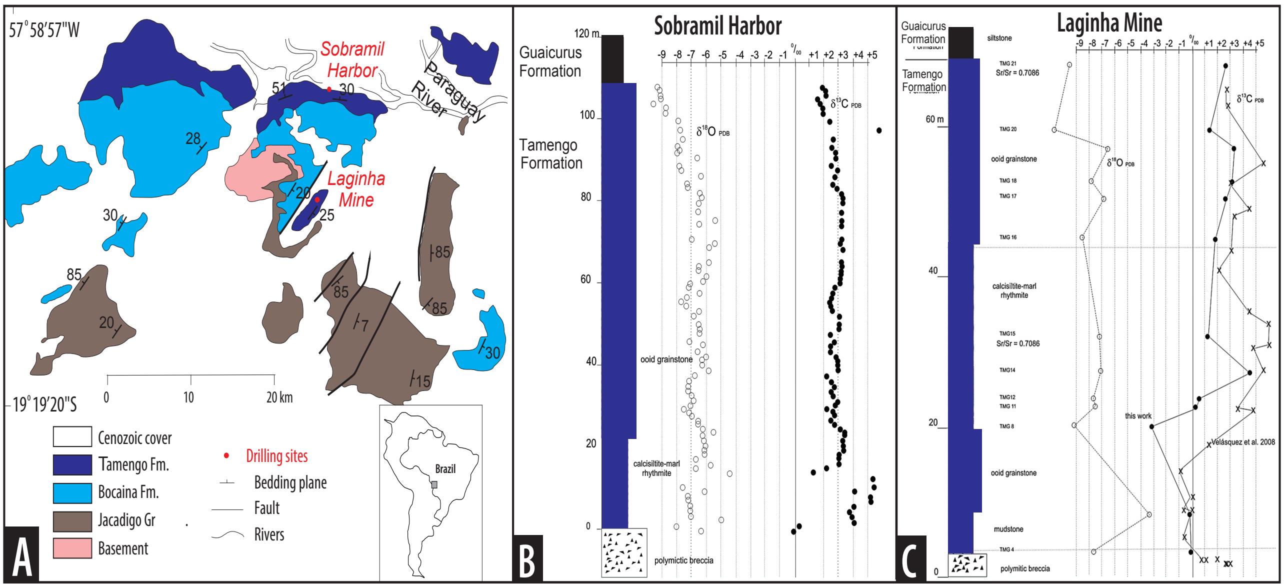

Figure 4. A. Geology map showing drill site locations in Brazil. **B and C.** Chemostratigraphic trends for the Tamengo and Guaicurus formations at Sobramil Harbor and Laginha Mine. Data from references cited in text.

Western Brazil (Corumbá Group). R. Trindade has secured FAPESP funding to obtain two 150-200 m cores of the late Ediacaran-early Cambrian Corumbá Group. The sites are Sobramil Harbour and Laginha Mine, near Corumbá, Mato Grosso do Sul (Figs. 4, 5; Appendix A2.1). The surface and subsurface geology is well understood and simple, marked by the uniformly dipping (≤30º) limbs of the Morros anticline (Fig. 5), which is confirmed by much open-pit mining and drilling. Unfortunately, most cores are proprietary thus the need to obtain new cores. The sites are located close to quarries for additional sampling and comparison to core data.

The Corumbá Group records a marine carbonate platform that fringed the southeast margin of the Amazon Craton and consists of the Cadiueus, Cerradinho, Bocaina, Tamengo and Guaicurus formations (Almeida and Hasui 1984). The drilling targets are the shale and carbonaceous limestone of the latter two formations, which contain the best ECT fossil record in South America (Warren et al. 2012; Pacheco et al. 2015). The Tamengo Formation has *Corumbella werneri*, *Cloudina luceanoi* and conulariids (Walde et al. 2015). The Guaicurus Formation has vendotaenid fossils, including *Eoholynia corumbensis* (Boggiani et al. 2010). These rocks have not experienced metamorphism or severe organic-matter maturation (Spangenberg et al. 2014) and, combined with C-isotope profiles that are interpreted as the rising trend of the Shuram excursion (from -3‰ to +5‰ in $\delta^{13}C_{carb}$; Boggiani et al. 2010; Spangenberg et al. 2014), define a relatively continuous record across the Ediacaran-Cambrian boundary. Tamengo Formation tuffs yielded a U-Pb zircon age of 543 ±3 Ma (Babinski et al. 2008) and 12 other tuffs within that unit and the Guaicurus Formation have been sampled (R. Trindade pers. comm. 2015). These aspects confirm the potential of these rocks to meet the objectives of *Research Foci 1-3*.

Site selection. The target rocks are the Tamengo and Guaicurus formations at Sobramil Harbor and Laginha Mine. This region is a mining district thus all aspects of the logistics are clear: local drilling contractors have operational expertise, electricity and water are accessible, core handling and multi-sensor analysis, core-splitting and preliminary description can be done nearby, and quarries will enable cores to be compared directly to outcrop. As noted, the geology is structurally simple thereby assuring that the drilling targets will be recovered.

Drilling. Drilling operator Geominas will oversee the drilling, coring and permitting; they have a long history of work in the area and can satisfy requirements of obtaining cores of ≥63 mm in diameter, +90% core recovery and minimal to no core contamination. They will also provide core boxes and transportation of cores to Universidade Federal de Mato Grosso do Sul, for temporary storage, preliminary description and multi-sensor logging using a Geotek MSCL shipped from the Universidade de São Paulo to Corumbá.

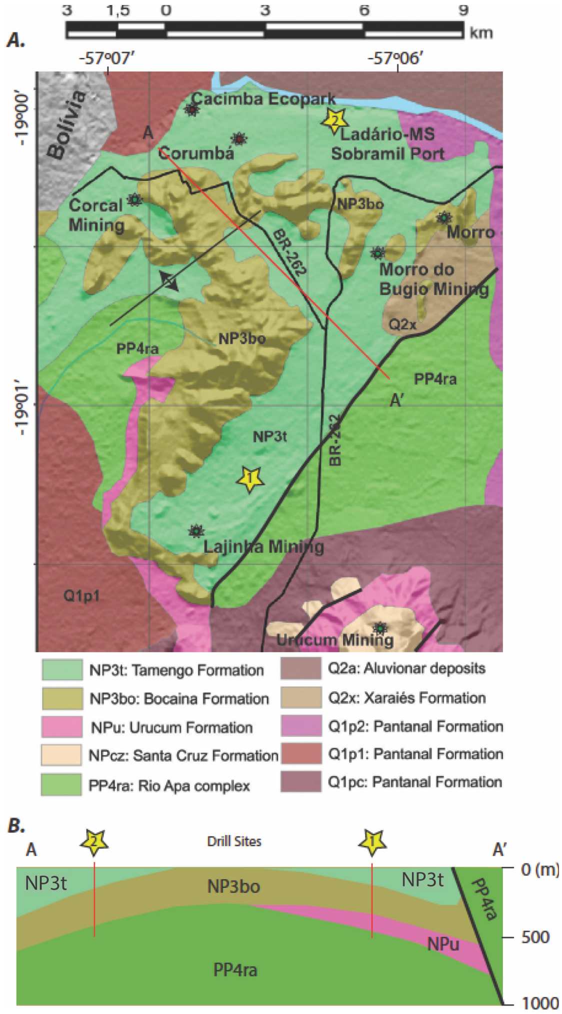

Figure 5. A. Geological map of the Corumba region (after Walde et al. 2015). **B.** Cross section showing position of proposed drill sites on the Morros anticline: 1-Laginha Mine, 2-Sobramil Harbor.

South China (Doushantuo, Dengying and equivalent Formations). Six cores between c. 200-550 m in length will be obtained for the Ediacaran through early Cambrian shallow-marine to deeper slope strata of the Yangtze craton in South China (Figs. 6, 7; Appendix A2.2). The drilling targets are the Doushantuo and Dengying formations and their extraordinary archive of mutlicellular life: silicified leiospheres, macroscopic multi-cellular algae, acanthomorphic acritarchs, and phosphatised embryos and adult fossils (Zhu et al. 2007, 2010, 2013; Jiang et al. 2011; Liu et al. 2013, 2014; Xiao et al. 1998; Yuan et al. 2011; Yin et al. 2015). Hallmark chemostratigraphic features include the Ediacaran cap dolostone, DOUNCE (Shuram) excursion (Lu et al. 2013) and the C-isotope excursions spanning the Ediacaran-Cambrian boundary (Guo et al. 2013). These sections also preserve evidence for multiple Ediacaran oxygenation events from redox metal enrichments (*e.g.* Kendall et al. 2015). Ash beds are abundant and have shown their utility for high-precision U-Pb ID-TIMS geochronology, *e.g.* 635.2 ±0.6 Ma and 632.5 ±0.5 Ma for the Doushantuo Formation and its cap dolostone, respectively (Condon et al. 2005). The carbonate rocks of the overlying Dengying Formation span the Ediacaran-Cambrian boundary and contain a phosphorite-rich and diverse small-shelly-fossil interval (Zhujiaqing Formation, Zhu et al. 2007) with abundant undated ash beds (Li et al. 2007; Steiner et al. 2007; Zhu et al. 2007, 2013; Zhang et al. 2004; Compston et al. 2008) for temporal calibration. Further, slope-basin settings consist of black shale and chert (Liuchapo-Laobao-Piyuancun Fms) that contain the Ediacaran-Cambrian boundary and are ideal for Re-Os geochronology. Combined with the tuffs in Namibia and Brazil, the South China sections will help form an age model for the timing and duration of C-isotope excursions and associated biogeochemical and palaeobiological events to meet the goals of *Research Foci 1-3*.

Site selection. The target areas are the shallow-marine sections of Dahai, Huangniuya and Beidoushan and the deeper slope settings of Longhizui, Piyuancum and Tongle (Figs. 6,7). Their geology is well characterised and subsurface geology is known from previous drilling and coring by local Geological Surveys and mining companies. Those cores, though, are not readily accessible hence new cores are required. All sites are in areas with little to no structural complications. In that each core will be 200-550 m in length, this minimises uncertainty and maximises confidence that the stratigraphic intervals targeted for coring will be recovered.

Drilling. China Continental Scientific Drilling contractors (CCSD-SK), the same company that worked with ICDP in the Songliao basin (SINOPROBE), will be used for the GRIND-ECT cores, thus considerable expertise exists regarding the drilling and coring requirements. CCSD-SK will assure core diameter of ≥80 mm, high drill core recovery and minimal to no contamination. In addition, CCSD-SK will obtain permits, provide temporary on-site core storage, core boxes, multi-sensor logging and core-characterisation, and core transport.

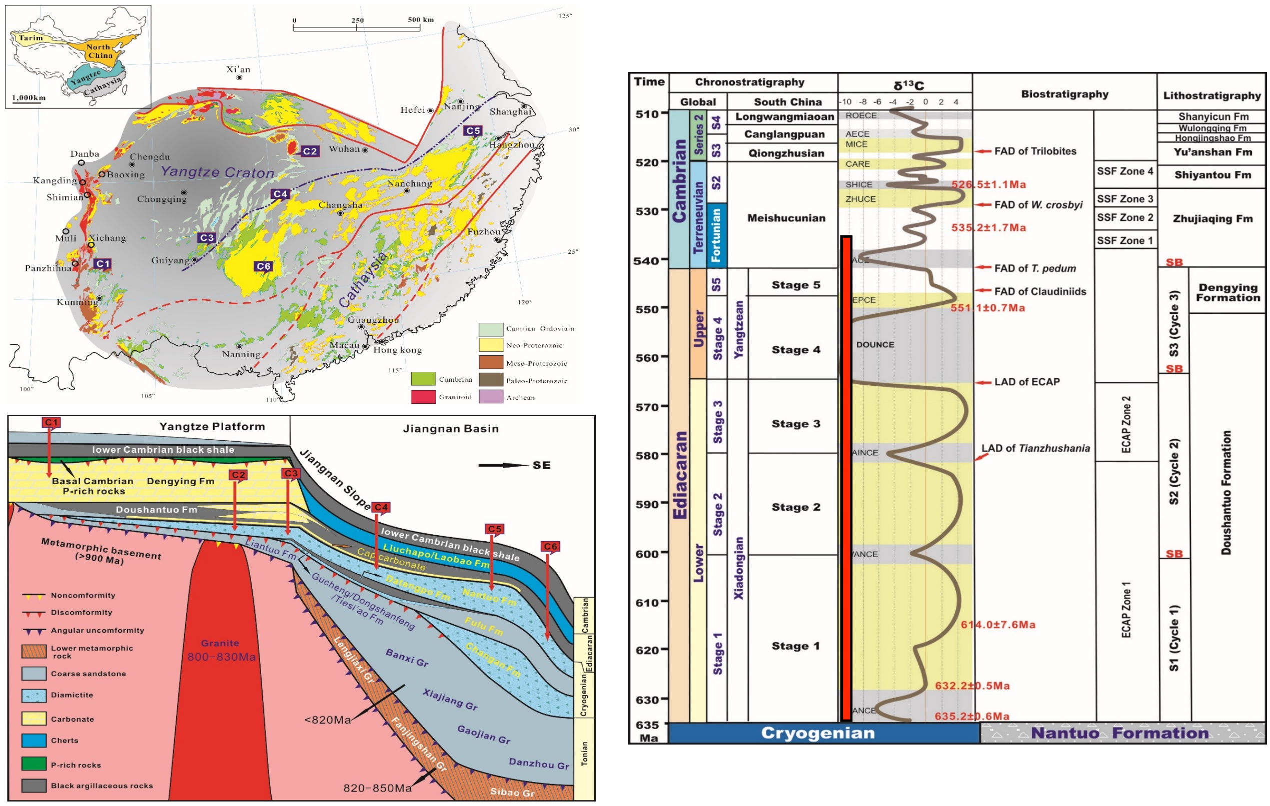

Figure 6. The two figures on the left show the drill site locations on the Yangtze Craton of South China and their stratigraphic positions along the Ediacaran-age shallow-marine platform to slope-basin transect. C1-Dahai, C2-Huangniuya, C3-Beidoushan, C4-Longbizui, C5-Piyuancum, C6-Tongle. Composite stratigraphic section on the left shows the C-isotopic chemostratigraphy and biostratigraphic events that are recorded in the South China succession. Red vertical bar denotes the interval that will be recovered in the proposed drilling and coring programme. Note the dated ash beds; there are many more known datable tuffs that will be readily obtainable in the cores and these will provide the basis for constructing a highly resolved age model spanning the Ediacaran-early Cambrian transition. Information taken

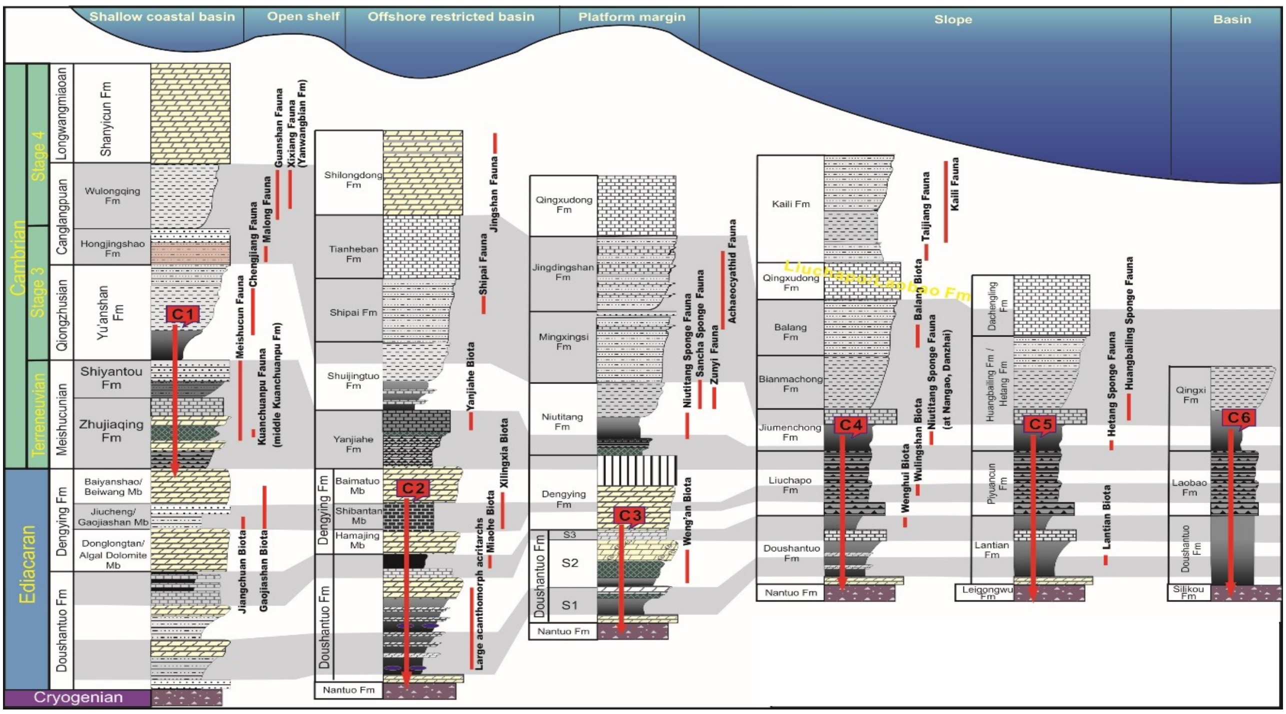

Figure 7. Targets for South China drilling programme: C1-Dahai, C2-Huangniuya, C3-Beidoushan, C4-Longbizui, C5-Piyuancum and C6-Tongle; these will provide a platform-to-basin transect and capture the key biospheric events of the Ediacaran-Cambrian transition on the Yangtze Craton. Data from sources cited in the text.

Southern Namibia (Nama Group). Five cores, 200-450 m in length, will target the lower and middle Nama Group (Fig. 8; Appendix A2.3) with its diverse record of the ECT including the type *Nama assemblage* of Ediacaran rangeomorphs, erniettomorphs, calcified macrofossils and complex trace fossils (Wood and Curtis 2014; Vickers-Rich et al. 2012; Penney et al. 2014). The Kuibis and Schwarzrand Subgroups are the drilling targets (the latter is between 547 ±1 and 540.61 ±0.67 Ma; recalculated from Grotzinger et al. 1995) and consist of mixed carbonate-siliciclastic strata that define outer ramp through nearshore and fluvial-deltaic settings (Germs 1983).

The stratigraphy of the Nama Group is well-documented and is an archetype of the late Ediacaran-early Cambrian (*e.g.* Grotzinger and Miller, 2008). Several C-isotope and redox-sensitive element ratio studies have been done on the Nama rocks, including those that archive the C-isotope excursions and fauna typical of the ECT and in models for postulating patchy ocean oxygenation and ideas that the evolution of animals was driven by varying oxygenation of late Ediacaran oceans (*e.g.* Wood et al. 2015). Further, the presence of abundant undated ash beds (*e.g.* Saylor et al. 2005) offer excellent opportunities for obtaining high-precision U-Pb geochronology, making the Nama Group an ideal target for acquiring precise temporally constrained and detailed geobiological and geochemical data to meet the goals of *Research Foci 1-3*.

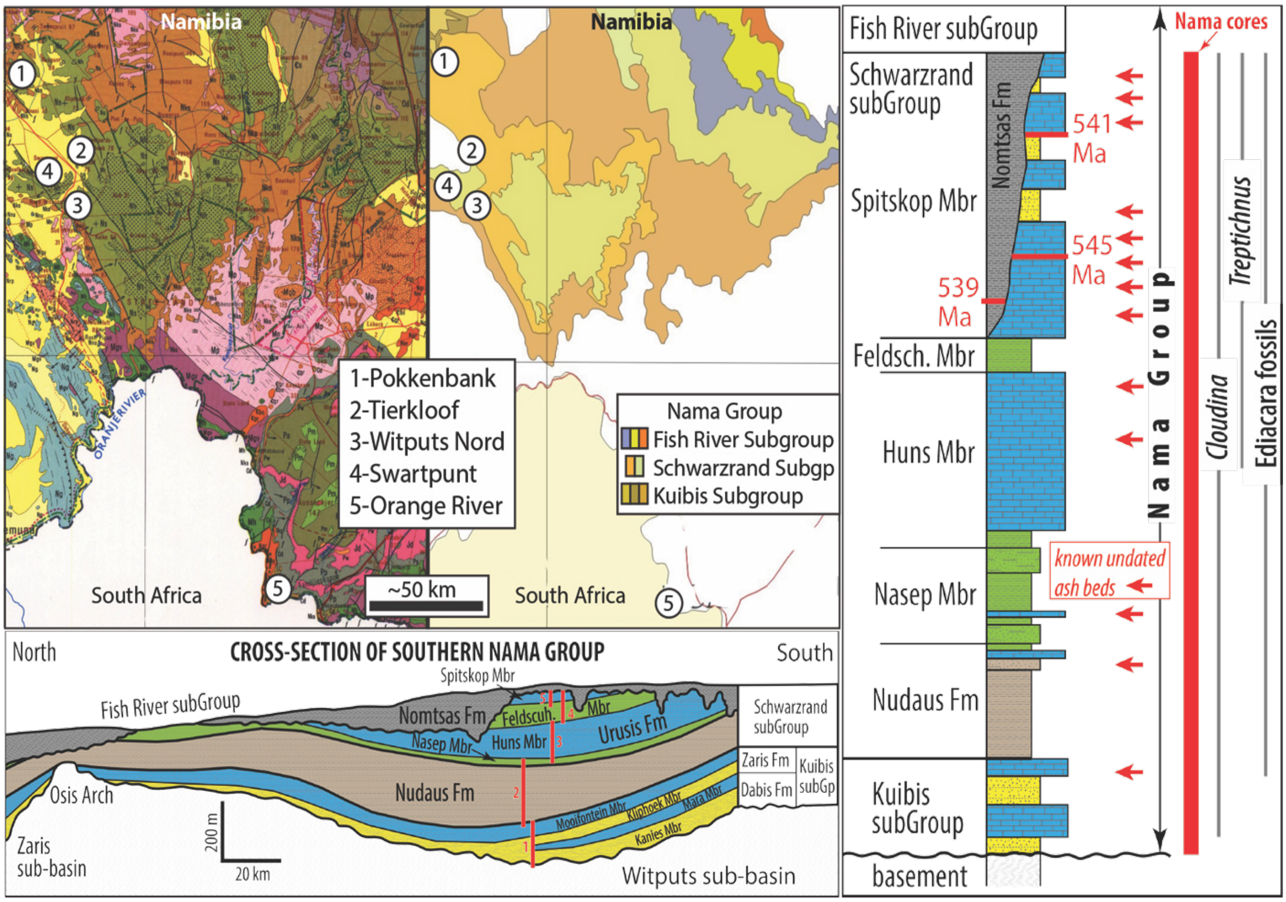

Figure 8. Geological map of southern Namibia (left) and Nama Group outcrop belt (right) showing drill site locations. Cross section of southern portion of Nama basin (Witputs sub-basin) shows the geological simplicity of the basin. Stratigraphic column shows positions of dated ash beds, including many known undated ash beds (red arrows). Red vertical bar indicates targeted coring interval, which captures the entire Ediacaran-Cambrian transition as recorded in the Kuibis and Schwarzand Subgroups (Nama Group). Data obtained from references cited in text.

Site selection. Five sites were chosen in geologically well-understood areas (Witsput and Orange River) near to roads and water sources thus mobilisation-demobilisation logistics are simple: Pokkenbank, Tierkloof, Witputs Nord, Swartpunt and Orange River (Fig. 8). Exposure is excellent and the stratigraphy of the Nama rocks has been established by decades of detailed mapping. The rocks are everywhere flat-lying to low-angle dipping (<20º), there are few faults, none at the target sites, and most are sub-vertical and occur in clearly identifiable narrow zones (100s of m in width); the frontal thrust faults of the Gariep orogen are well to the west of the sites and their subsurface projections readily known. Previous drilling confirms that the Nama rocks retain a layer-cake geology in the subsurface but these cores failed to capture the oldest stratigraphy that GRIND-ECT is targeting. Reconnaissance surveys of the sites corroborate the accuracy of the existing geological mapping, providing strong confidence that the stratigraphic intervals targeted for coring will be recovered.

Drilling. Günzel Drilling will do the drilling and coring, obtain permits, provide core boxes and temporary on-site core storage, multi-sensor logging equipment to enable initial characterisation of the cores, and core transportation. The Namibian Geological Survey will assist with all customs and shipping permits. Günzel Drilling has operated for almost two decades in Namibia and has ample experience in meeting the drilling and coring requirements of GRIND-ECT: core diameter of ≥56 mm, high drill core recovery, minimal or no contamination, and low cost.

4. Core handling: DIS data acquisition, core characterisation, archiving and sampling

Drilling Information System data acquisition. Core data acquisition will use ICDP's Drilling Information System (DIS) for real-time capture of information at the drill site and for all subsequent data-gathering activities. DIS will form a reference framework for use by all project scientists and the platform for integrating the varied data (lithological, palaeobiolgical, geochemical, geochronological) to ensure a consistent and uniform data management-integration-recording protocol is maintained and coordinated across GRIND-ECT. Overseeing and coordinating the core data is a key job and we have requested funding to support a DIS Core Manager. We are fortunate in that Ms Melanie Mesli, the DIS Core Manager for ICDP's FAR-DEEP programme, has agreed to accept that role for GRIND-ECT. Ms Mesli has over a decade of experience running DIS and maintaining the FAR-DEEP core repository; she resides in Germany and is ideally placed to work for GRIND-ECT and be available to aide researchers at the core repository of the Federal Institute for Geosciences and Natural Resources (BGR) in Berlin-Spandau, Germany (see below and Appendix 4). Further, Central Science Team member Dr Catherine Rose along with in-country scientists from each nation will be sent for training by ICDP in the use of DIS. This training will ensure that DIS will be ready for use by the Core-characterisation Units (see below) at each drilling site and at each core repository.

Core archiving and repositories. A total of *c*. 0.4, *c*. 2.6 and *c*. 1.5 km of core will be obtained for the Brazilian, Chinese and Namibian targets, respectively. As described below, once on-site and initial core characterisation work is completed, cores will be transported to core repositories. One half of all cores will be retained in-country for research and educational training purposes and the other half will be shipped to the Federal Institute for Geosciences and Natural Resources (BGR) in Berlin-Spandau, Germany, for permanent archiving (Fig. 9; Appendix 4). The BGR repository has technical staff and a suite of analytical equipment including multi-sensor and high-resolution XRF and CT scanners that will be available for use by project scientists. In Brazil, the core repository will be at the Instituto de Geociências and de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, São Paulo; in China, it will be at the China Geological Sample Center of Land and Resource (CGSC), China Geological Survey, Beijing; in Namibia, it will be at the Ministry of Mines and Energy, Namibian Geological Survey, Windhoek. Both the Instituto and the CGSC have dedicated staff to handle cores, including high-resolution XRF and CT scanning capabilities. The

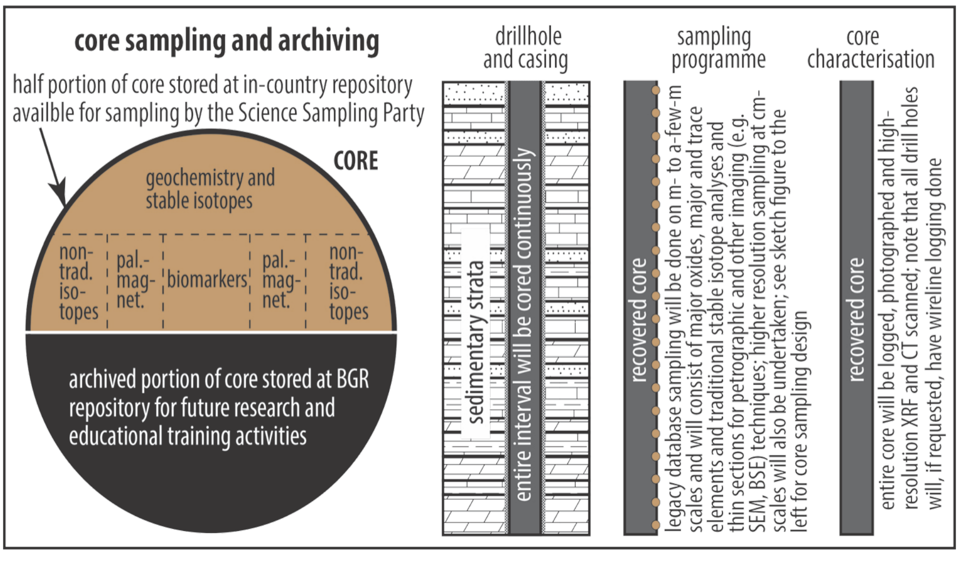

Figure 9. Core sampling and archiving design. Cores will be slabbed in half with one half being kept in-country for use by the Science Sampling Party and for in-country research, educational training and capacity-building purposes. The other half will be shipped for archiving and future studies at the BGR core repository in Berlin-Spandau, Germany. Prior to sampling, cores will be photographed and undergo high-resolution XRF and CT scanning. Samples will be for geochemical, isotopic, biomarker, and palaeomagnetism analyses.

Namibian Survey core shed does not have dedicated staff but the Survey and Günzel Drilling will help arrange for core-handling assistants and, if needed, ICDP's core scanning equipment can be hired (these costs have been budgeted). At each core repository, accessing the cores is free-of-charge. When the agreed-GRIND-ECT moratorium restrictions end, the cores at both the in-country and BGR repositories will become freely available to the Earth Science community for study and educational training purposes. Importantly, having centralised, open access and easily accessible repositories will mark the first step towards meeting the goal of creating a global core archive for on-shore continental scientific drilling that will match in scope and scale that of the IODP.

Core activities Phase 1: On-site management and Core-characterisation Unit. Drilling activities will be directed by a country-specific Head of Operations (HoO; Fig. 10) and once drilling is about to commence a Core-characterisation Unit (CcU) will arrive on-site. The CcU will consist of four to six persons: the HoO and/or 1-2 Central Science Team (CST) members (see Section 5), 1-2 in-country experts who are project scientists and 1-2 in-country students for capacity building and training; at least one of the CcU members will be an ICDP-trained DIS operator. The CcU will ensure quality control during the drilling operations, such as marking core orientation and way-up, and providing preliminary core descriptions. All cores will be placed in plastic boxes for shipment to in-country storage facilities where the CcU will supervise the slabbing of cores, photographing them and DIS recording of information such as composition, bedding, colour, presence/absence of body and trace fossils, sedimentary structures, diagenetic textures, faults-fractures-veins and performing wire-line logging and multi-sensor XRF and CT scanning. The Central Science, Data Management and Outreach Teams (see Section 5) will be updated regularly on the drilling and coring progress.

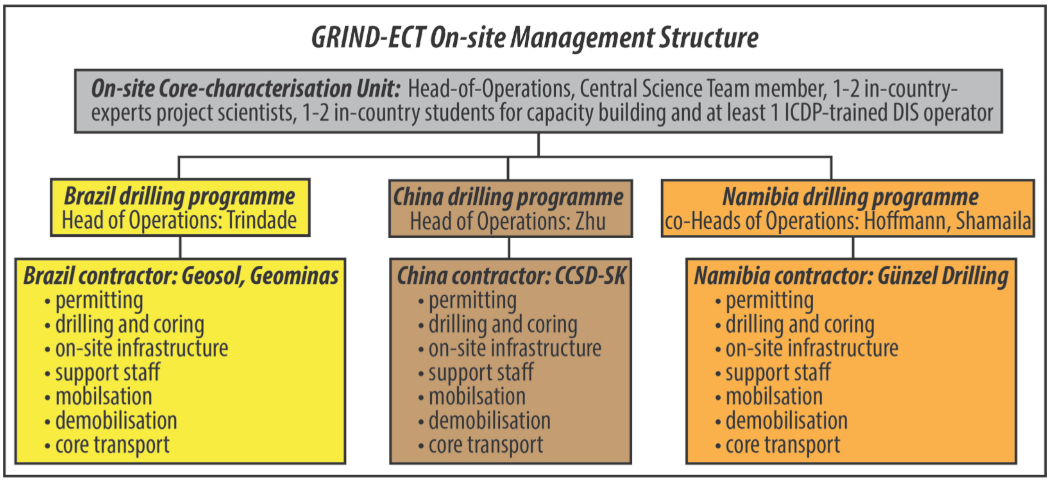

Figure 10. Organisation and management of the on-site drilling and coring activities. The country-specific Head-of-Operations will liaise directly with drilling contractors and provide overall management and coordination between them and the on-site Core-characterisation Unit. The ICDP's Data Information System (DIS) will be used to record and manage all coring, logging, sampling and analytical data.

Biomarker analysis. Care needs to be taken to minimise contamination to the rocks identified for biomarker analysis (*e.g*. French et al. 2015). Water will be used where possible for drilling but if other fluids are used they will be pre-screened and characterised for their hydrocarbon content before drilling commences. Core intervals and samples identified for biomarker studies will be bagged in ultra-clean Teflon bags and two blank samples per core will be taken for exterior/interior experiments to monitor and assess if surficial contamination penetrated the rock interior.

Oriented palaeomagnetic samples. All drill sites have sedimentary rocks that dip consistently with no to minimal structural disruption, no thermal or metamorphic overprints, and are in areas of good outcrop thus absolute bed orientations can be constrained by the bedding attitude measured in exposures adjacent to the drill sites. Cores will be oriented *in-situ* and careful core barrel retrieval and core marking will assure that core orientation errors are avoided. Where possible, *in-situ* orientation of cores will be done using coupled three-axis magnetometers and accelerometers.

Core activities Phase 2: Science Sampling Party. Core sampling will be subject to stringent controls to assure that duplication and overlap is avoided within and between projects. These data gathering activities will be recorded, integrated and maintained using DIS, in conjunction with other appropriate federated databases to provide open-access data, and unique sample identifiers assigned (Fig. 11). It is estimated that within 3 months of the cores being transferred to repositories, the Science Sampling Party (SSP) will begin detailed core description and sampling; this will require between one to three weeks (depending on amount of core) to complete for each nations' cores. The SSP will consist of representatives from each Science Theme (see Section 5) and 1-2 Central Science Team members. Before sampling begins in earnest, the Depositional Frameworks Theme will first do detailed sedimentological descriptions and stratigraphic work to provide a basis for the sampling. Once this work is completed, the SSP will begin its work following the design in which certain portions of the core will be earmarked for specific analyses (Fig. 9).

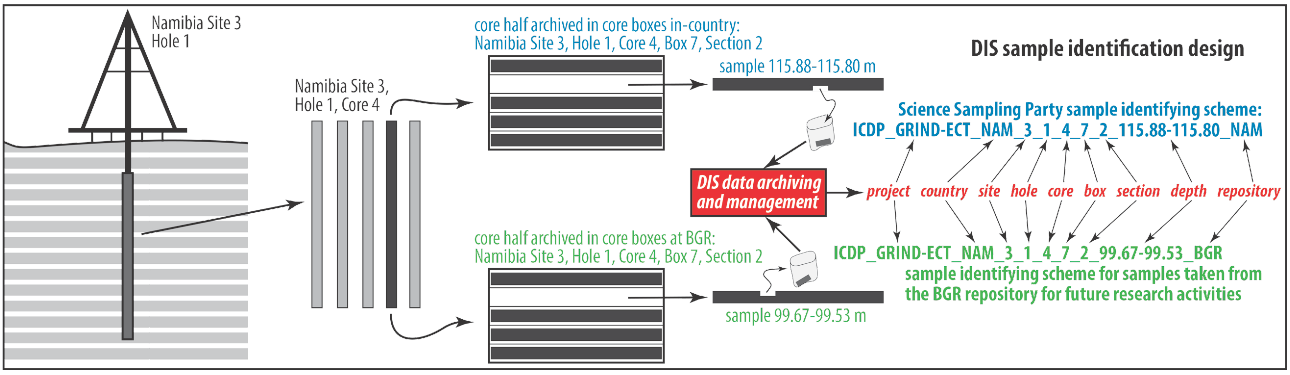

Figure 11. Example of a DIS-assignable numbering scheme for obtaining a unique identifier for samples taken from in-country cores by the Science Party Team; this example uses a hypothetical core from a Namibian drill site but is applicable to all GRIND-ECT cores. Any future research samples that may be requested from cores stored at the BGR in Berlin-Spandau, Germany, will have a matching identifier differentiated by its repository code, i.e. the ending 3-digit identifier: BRA – Brazil, CHN – China, NAM – Namibia, and BGR for the Berlin-Spandau repository.

A legacy dataset will be obtained at several-m-scale sampling density to geochemically characterise the cores, identify intervals of interest (isotope excursions, changes in faunal trends, extinctions, first occurrences) and sample for thin-sections and imaging analyses (*e.g.* SEM, BSE). Sampling at higher-resolution, commonly at cm-scale spacing, will then be needed to characterise any high-frequency isotopic and biogeochemical patterns. In addition to standard geochemical analyses (major and trace oxides and elements), all samples will be analysed for $\delta^{13}C_{bulk}$, $\delta^{18}O_{bulk}$, $\delta^{13}C_{org}$, organic C/N, TOC, and $CaCO_3$. Biogenic carbonate $\delta^{18}O$, $\delta^{13}C$ and Sr isotopes will also be measured on carbonate rocks, and ICP-MS and automated mineral analysis calibration of core-scan XRF will be undertaken on selected samples. Sampling of ash beds for U-Pb geochronology and organic-rich intervals for Re-Os dating will be done jointly with the geochemistry sampling. All samples will be available for use by all GRIND-ECT scientists. Once the GRIND-ECT moratorium ends, cores (both in-country and at the BGR) will be made available for study to any researcher worldwide.

5. Project organisation, management, execution and Science Teams

The organisation and management of GRIND-ECT will be overseen by a Central Science Team (CST) composed of GRIND-ECT PIs (headed by a Chair) and country-specific Heads-of-Operations (HoO, Fig. 12). The CST will have oversight over the managing, drilling, research and archiving work, coordinating proposals to national and international funding agencies (*e.g.* ERC, DFG, NSF, NERC), and Outreach activities. Country-specific experts as HoOs will coordinate their respective in-country drilling operations. Because GRIND-ECT is broader in scope than most ICDP projects (*i.e.* multiple drill sites in three countries), an Advisory Board will be constituted to assist in managing and planning and consist of two *ex-officio* scientists with considerable experience in the delivery of large-scale projects: Dr Aivo Lepland, Norwegian Geological Survey, who co-coordinated the ICDP FAR-DEEP project, and Professor Bruce Levell, Oxford University, who was Exploration Manager at Petroleum Development Oman (on secondment from Shell) during the opening up of the Precambrian to Cambrian transition Huqf (Ara) oil play,(which was a very successful example of an industry-academia partnership) and went on to be "Chief Scientist: Geology" at Shell.

Research will be via five Science Themes (Figs. 12, 13; Appendices 5-7), each with a designated Coordinator and headed by an overall Coordinator. Each Theme is designed to address the three Research Foci defined in Section 1. The overall Theme Coordinator will ensure that there is effective inter-Theme integration and communication, including to the CST who have ultimate responsibility in ensuring the effective flow of information between each nation's project; this will be aided by the fact that CST members are themselves members of a Science Theme. Note that some Theme members will work across more than one country's drilling project whereas others will be tied to country-specific research projects.

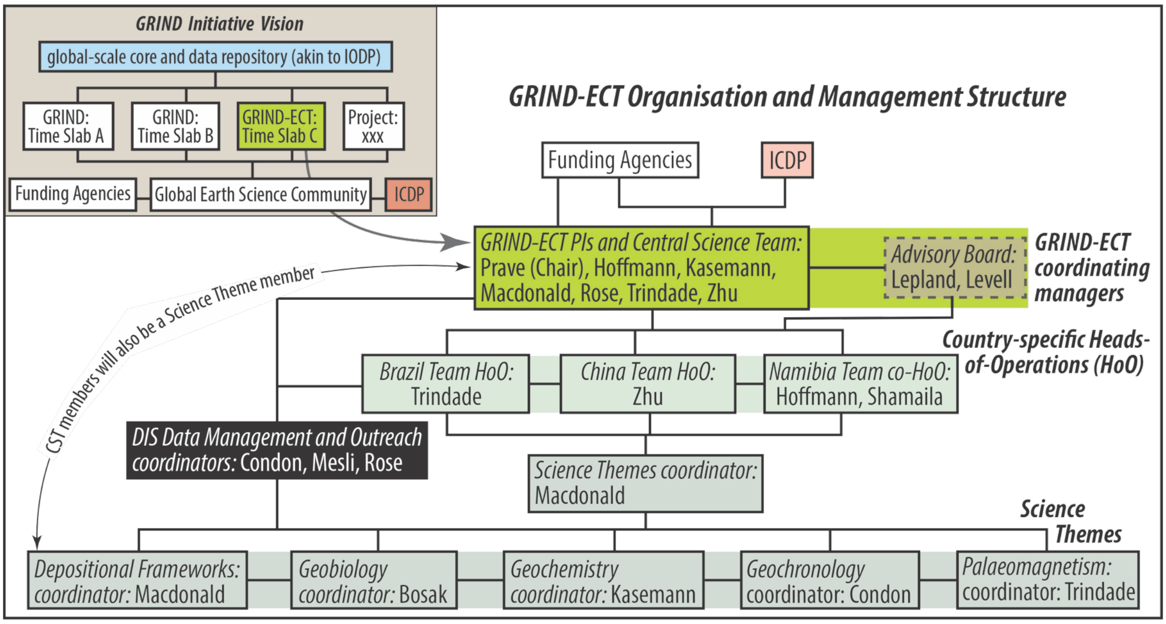

Figure 12. GRIND-ECT organisation and management. A Central Science Team (CST) will consist of the main PIs and country-specific Heads of Operations; the CST will be responsible for overall project coordination and communication activities and will be aided by an Advisory Board. The bulk of researchers will be organised into five Science Themes, based on their area of expertise, and research will be organised and managed by an overall Theme Coordinator and Coordinators for individual Themes. DIS database management and outreach activities, inclusive of all public, scientific and educational efforts, will be coordinated through a Data and Outreach Team. Inset in upper left shows the overall vision for the GRIND (Geological Research through Integrated Neoproterozoic Drilling) initiative, of which this proposal, GRIND-ECT, constitutes the inaugural project. See text for details.

The management of a large project such as GRIND-ECT is a challenge (Appendix 7). Success, though, will be facilitated by the rich record of collaborative engagement already present within the GRIND-ECT community (since its inception at the 2014 Workshop, GRIND-ECT participants have grown to +50; Appendices 6 and 8). Further, two organisational aspects will guarantee that the intra- as well as inter-country research and data management are coordinated and integrated effectively: (i) the three national Heads of Operations are members of the CST (see Figs. 11-13); and (ii) DIS will be used for data acquisition and archiving (see Section 4) across the entire GRIND-ECT project. Such a matrix of managerial and organisational integration will ensure consistent and efficient information exchange and delivery of the science, as well as coordinated planning and implementation of the drilling, coring and archiving activities.

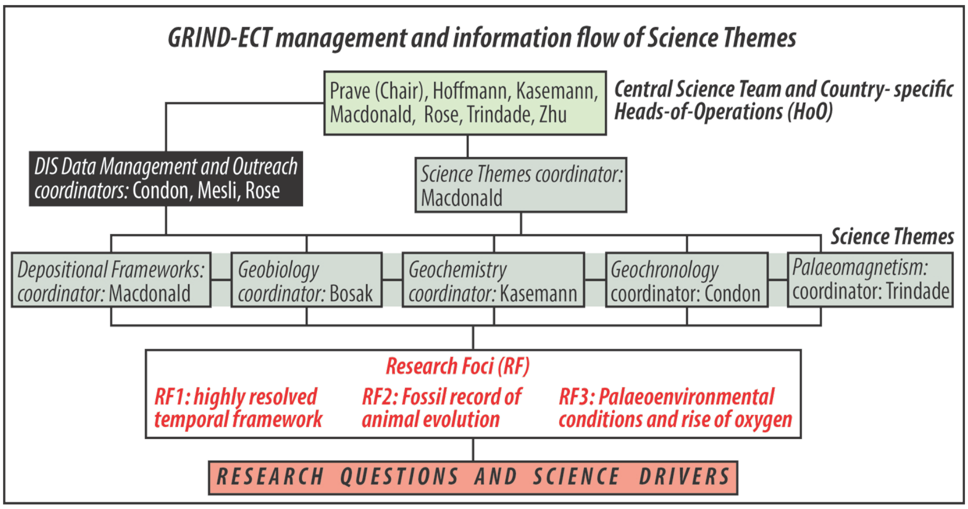

Figure 13. GRIND-ECT research structure is coordinated around 5 Science themes that address each Research Foci. Science Themes will be organised and managed by their respective Coordinators who will liaise with the Themes Coordinator and Heads of Operations and, ultimately, the Central Science Team to ensure clear communication both within and between Themes and national drilling projects. DIS data management and Outreach are integral throughout.

6. Expected scientific and societal benefits, education and Outreach

All the described activities below will be replicated as much as possible within the individual nations of project scientists, as likely mandated by their funding agency requirements for Outreach.

Scientific benefits. GRIND-ECT is the inaugural project of what we envisage will become an ICDP programme comparable to IODP. The goal is to deliver a worldwide network and archive of time-calibrated cores for open-access sharing and state-of-the-art research. The archive will be an educational resource for teaching and training early-career researchers and a catalyst for multinational, multidiscipline collaborations. It will form the intellectual hub to encompass future research and education undertaken by the Earth science community to resolve the fundamental questions regarding circumstances that led to the advent and expansion of metazoans and inception of equable climates in the aftermath of the environmental extremes of the Neoproterozoic. The project team is well represented in professional bodies (*e.g.* ICS, Geological Society's Stratigraphy Commission) and will ensure that GRIND-ECT data are integral with community initiatives such as EARTHTIME and NIGPAS's Geobiodiversity Database. Neoproterozoic and Cambrian Earth System science is a major focus at international meetings (*e.g.* Goldschmidt AGU, GSA, EGU) and these venues will be used for holding Workshops and dissemination of results.

Societal benefits. Knowledge of how Earth evolved over its 4.5-billion-year history captures the public's curiosity and can be publicised via public-focussed educational programmes in all countries to ensure that citizens are informed about how natural processes and feedbacks influence the environments we live in, and the response and recovery times of environments from natural perturbations. GRIND-ECT will provide insights into the most extraordinary climatic (Snowball Earth) and biospheric changes (Cambrian Explosion) ever, as well as improved knowledge about potential mineral and hydrocarbon resources and its relevance for societal wealth creation.

Education and Outreach. This will be organised into two main components.
Training early-career geoscientists and in-country capacity building. This training will involve engagement with contacts in Brazilian, Chinese and Namibian universities and institutions. Members of GRIND-ECT already have established links with in-country Surveys and Universities in Brazil, China and Namibia and will work to develop opportunities for staff and BSc/MSc students and postgraduates for top undergraduate and postgraduate students to participate in the GRIND-ECT project and become involved with training in core logging, core characterisation activities and research projects. The budget will include support for two BSc or MSc students for 1-month internships. It is also envisaged that relevant, early-career researcher training Workshops will be taught by GRIND-ECT members (*e.g.* Rocks-and-Clocks: stratigraphic frameworks and geochronology; Earth System Science: geochemistry, palaeobiology and modelling).

Public information and Open-day activities. This will involve:

- project scientists visiting local schools and public fora to deliver talks to a broad cross-section of people about GRIND-ECT and its key findings; these talks could occur concurrent with drilling and initial core work and will be organised by the in-country Heads of Operations;
- holding in-country Open days at the drill sites and core repositories with information materials, including core samples and photographs, rock samples and a video about the GRIND-ECT project (this can be given to schools for teaching and educational use);
- develop teaching packages for teacher training that will cover Earth system climate, biotic evolution and modelling, as well as drilling and geoengineering techniques to complement STEM subjects and highlight careers in Geoscience;
- deployment of 'Virtual information boards' at key outcrops for self-guided geological tours; these will use a web-based infrastructure and a QR code system; and
- developing museum exhibits at the Namibian Geological Survey's museum in Windhoek, at the Universidade's de São Paulo and de Mato Grosso do Sul in São Paolo Province, and at NIGPAS in China.

Press releases and social media. Project scientists will work with their respective press offices to issue releases and social media communications for project milestones and publications. Progress reports will also be posted on the GRIND-ECT website that will include field photos and daily to weekly status updates that can be followed by colleagues as well as the general public.

7. Timetable for GRIND-ECT

Figure 14 shows GRIND-ECT's planned schedule. Central Sceince Team member and Brazilian Head-of-Operations R Trindade has successfully secured funding by FAPESP; this requires that drilling in Brazil be initiated by early 2018. If this GRIND-ECT proposal is successful, and pending outcomes by national funding bodies, drilling operations in Namibia and China would be planned to commence sequentially in 2019.

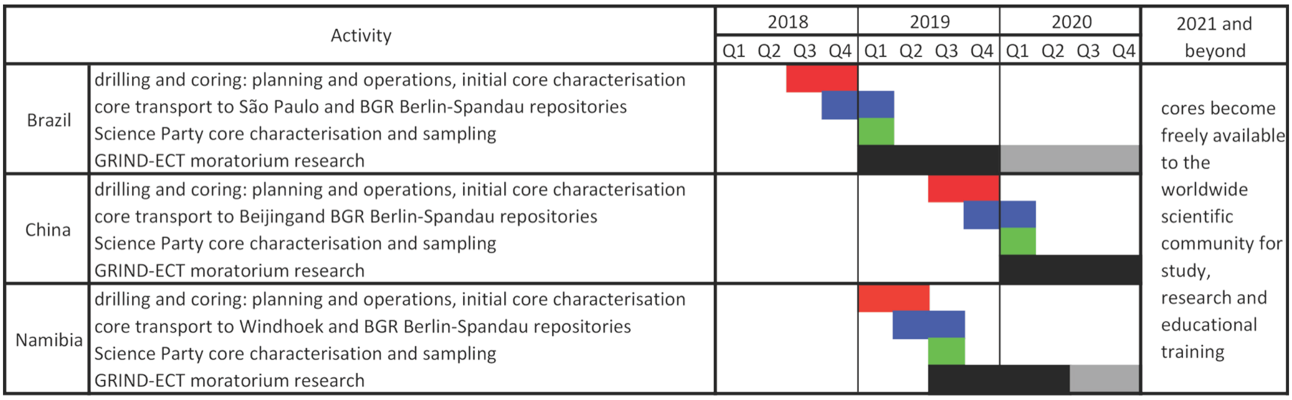

Figure 14. Planned schedule of GRIND-ECT drilling, coring, sampling, archiving and research activities. Note that, post-moratorium research will be open to all scientists; it is envisaged that the moratorium will end simultaneously for all three projects, hence why the Brazilian and Namibian moratoriums are shown extended with the grey bars.

8. Budget Plan

The budget shown on the next page summarises the costs of drilling and coring operations in Brazil, China and Namibia (see Appendix 3 for details) and associated costs, including for shipping core to the BGR repository in Berlin-Spandau, Germany. The operations will acquire a total of 4.5-5 km of core and funds requested from ICDP are ~$638,210, which would support 50% of the costs. Funds already secured by Professor R Trindade from FAPESP total $492,461, which includes $62,000 for drilling and coring operations in Brazil and $120,000 to help offset drilling costs in Namibia. Proposals to funding agencies (NERC UK, NASA and NSF USA, DFG, NSFChina) will be submitted to request support to cover remaining costs. Estimates of costs for post-drilling Science Party and associated research costs are also given, based on a Science Party of 20-25 project scientists and their linked research activities (Appendix 3). Clearly, success with ICDP will help the success of those proposals and ensure that the full programme of drilling is achieved.

GRIND-ECT summary budget		
Total pre-drilling planning meetings and ICDP training	$	16,375.00
Total drilling costs (Brazil, China, Namibia)	$	1,032,250.00
Total on-site core characterisation costs	$	118,950.00
Total other costs (Core manager, internships, core shipping to BGR, hire of ICDP equipment, etc.)	$	108,845.00
Total cost estimate for costs linked directly to drilling and coring activities	**$**	**1,276,420.00**

n.b.: FAPESP has already provided a grant to Prof R Trindade to cover Brazilian research costs that totals $492,461.00

Request to ICDP for 50%	$	638,210.00
FAPESP support already obtained for Brazilian drilling	$	62,000.00
FAPESP support already obtained for Namibian drilling	$	120,000.00
Request to NSF for 10% (or greater)	$	127,642.00
Request to NASA for 10% (or greater)	$	127,642.00
Request to DFG for 10% (or greater)	$	127,642.00
Request to NSFChina for 10% (or greater)	$	127,642.00
Request to NERC for 10% (or greater)	$	127,642.00

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Appendix 1. Proof-of-concept stratigraphic methodologies

A1.1 Computed Tomography (CT) imaging of trace fossils. Recent proof-of-concept work between researchers in Bristol, Manchester, BGS and São Paulo on rocks from near Corumbá, Brazil, reveals a spectacularly preserved assemblage of small, pyrite-filled burrows that are some of the earliest known in the fossil record (Parry et al. 2017). Non-destructive X-ray CT-scanning of hand specimens has permitted 3-D digital reconstruction of burrow morphologies as small as 50 µm width (Fig. A1) and creates a novel opportunity for identifying the activity of meiofaunal organisms. It would facilitate obtaining high-resolution records of complex metazoan behaviour in GRIND-ECT cores, opening a previously unexplored window into animal evolution during Neoproterozoic time and potentially extending the known fossil record of animals by several tens of millions of years. The sites offer a wide range of palaeogeographic and depositional environmental settings for sampling, permitting meaningful and rigorous characterisation of the available Neoproterozoic record.

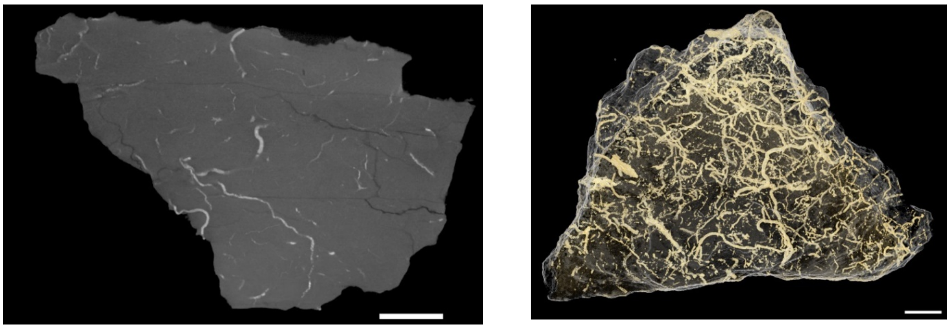


Figure A1. CT scan data from a bioturbated siltstone from the latest Ediacaran Guaicurus Formation, Corumba, Brazil. Left: CT scan slice through rock, burrows are picked out in lighter tones. Right: A 3D reconstruction of burrows within the hand specimen using Drishti software. Scale bars = 10 mm.

A1.2 Subsurface drill core for magnetic mineralogy. Scientific drilling provides material that has not experienced surface weathering that can modify redox-sensitive geochemical proxies and magnetic minerals. This is illustrated by a study using outcrop and drill core samples of a Neoproterozoic limestone (Swanson-Hysell et al. 2012). Rock magnetic changes at low temperature provide insight into the mineralogy of iron oxides and iron sulphides in geological materials. Figure A2 shows experimental results of the magnetisation of samples as they were cycled downward from room temperature to 10ºK. The outcrop sample is dominated by the iron-oxyhydroxide goethite (FeO(OH)) and its behaviour is similar to pure goethite (Rochette and Fillion 1989). Palaeomagnetic analysis indicates that the goethite holds a present-day local geomagnetic field direction, which indicates it formed as the result of recent surface weathering. In contrast, the drill core sample shows

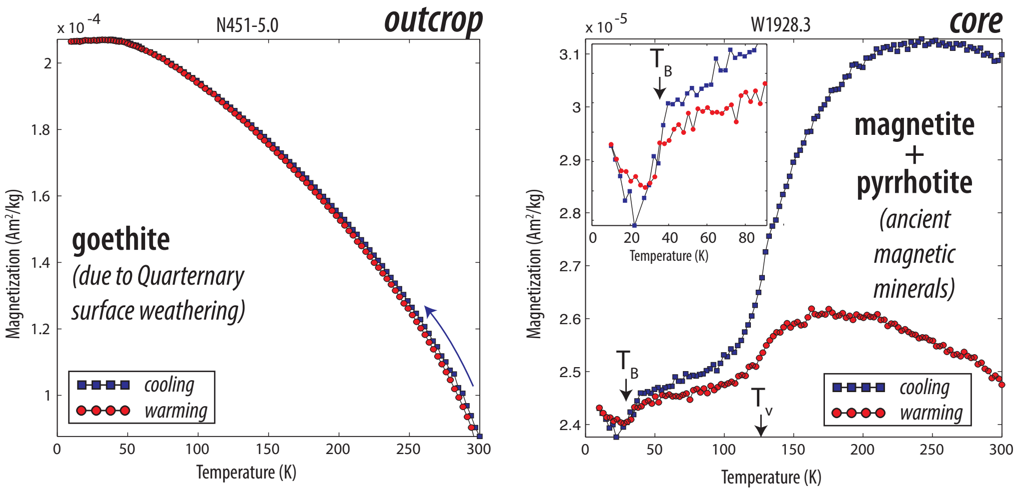


Figure A2. Results from low temperature rock magnetic experiments reveal magnetic mineralogy differences between outcrop and core; Love's Creek Mbr Bitter Springs Fm (1928m Wallara-1 core; Swanson-Hysell et al. 2012). The large increase in magnetisation upon cooling in outcrop sample is diagnostic of goethite formed via surface weathering. In contrast, the core retains ancient magnetite and pyrrhotite through the decrease in magnetisation at the crystallographic Verwey transition of magnetic, labeled as T_V (Verwey 1939) and Besnus transition of pyrrhotite, labeled as T_B (Dekkers et al. 1989).

two distinct decreases in magnetisation upon cooling, indicative of magnetite and pyrrhotite. These results show that ancient magnetic mineralogy is obscured in the surface samples and that goethite formed under surficial processes gives rise to starkly different behaviour, likely at the expense of pre-existing iron-oxides and iron-sulphides.

A1.3 Cyclostratigraphic environmental analyses using rock magnetic parameters. High-resolution rock magnetic data (*i.e.* cm-level data acquisition) are useful in informing about cyclostratigraphy and have been used for calibrating the Mesozoic and Cenozoic. Deeper in time, Earth's astronomical parameters have been applied to rocks as old as 2500 Ma (Berger et al. 1989; Berger and Loutre 1994; Franco and Hinnov 2008) and, apropos to GRIND-ECT, good results have been obtained for a core of the Doushantuo Formation in South China (Wu et al. 2013). A proof-of-concept study using multi-taper spectral analysis of the volume-specific susceptibility revealed spectral peaks, which can be interpreted as astronomically-forced cycles Figs. 1, 2). However, to test and calibrate this method, new core is required but these results conform the utility of the approach for assessing durations of events during Ediacaran time.

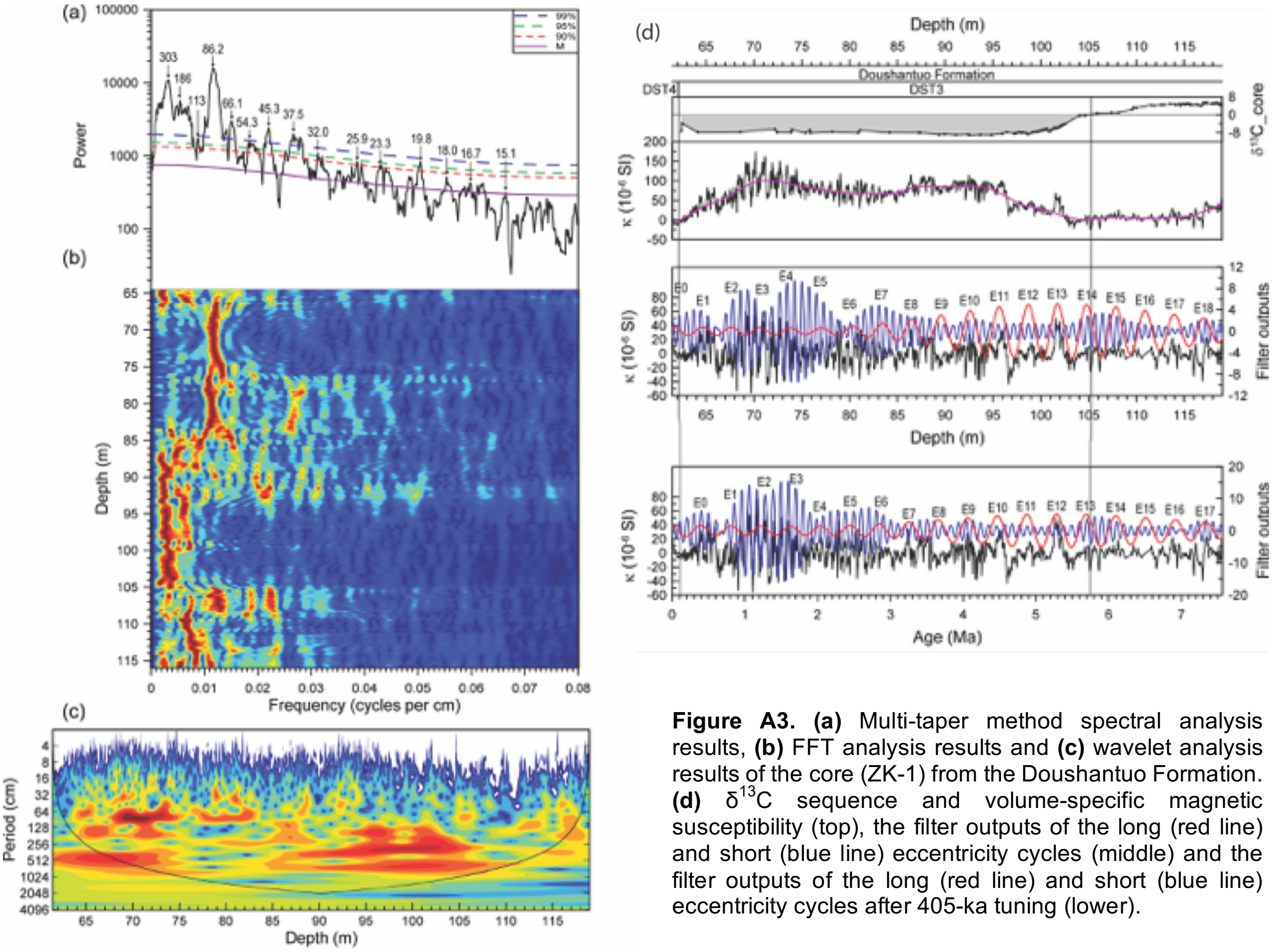


Figure A3. (a) Multi-taper method spectral analysis results, **(b)** FFT analysis results and **(c)** wavelet analysis results of the core (ZK-1) from the Doushantuo Formation. **(d)** $\delta^{13}C$ sequence and volume-specific magnetic susceptibility (top), the filter outputs of the long (red line) and short (blue line) eccentricity cycles (middle) and the filter outputs of the long (red line) and short (blue line) eccentricity cycles after 405-ka tuning (lower).

Appendix 2. Site geology and objectives

In total, 13 drill sites have been identified that will recover the ECT successions on three different cratons: Sobramil Harbour and Laginha Mine in west Brazil; Dahai, Huangniuya, Beidoushan, Longhizui, Piyuancum and Tongle in south China; and Pokkenbank, Tierkloof, Witputs Nord, Swartpunt and Orange River. The targets were identified based on the scientific objectives they could deliver (Table A1) and their central role in enabling creation of a network of time-equivalent strata to obtain highly resolved age models integrated with the palaeontological record of Ediacaran-early Cambrian biospheric evolution, oxygenation and biogeochemical cycling (Fig. A4).

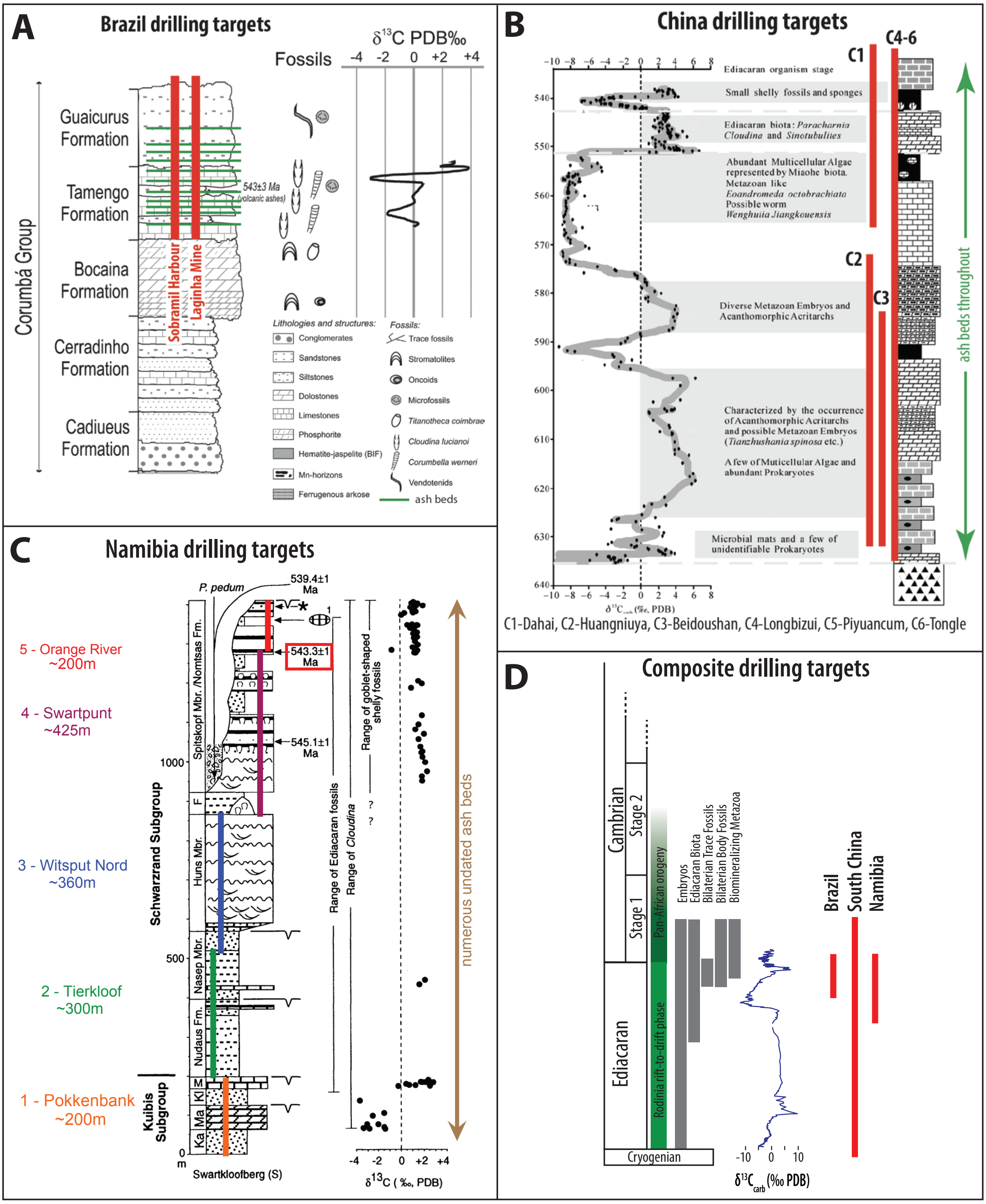


Figure A4. Schematics showing GRIND-ECT drilling target sections in Brazil (**A**), China (**B**) and Namibia (**C**), and their stratigraphic context. **D**. A composite of the drilling targets on three continents and their temporal relationship to key evolutionary, C-isotope and tectonic events.

Drill core	***Length***	***Time interval***	***Science target***	***Research Foci Objectives***
Brazil: Sombramil Harbour	*c. 180 m*	*>555 to <540 Ma*	*Corumbella and Cloudina fossils, biomarkers, and redox proxies in a shallow-water environment.*	*RF1-RF3. Biomineralisation, biomarkers, high-resolution bio-, magneto-, and chemo-stratigraphy.*
Brazil: Laginha Mine	*c. 150 m*	*>555 to <540 Ma*	*Corumbella and Cloudina fossils, biomarkers, and redox proxies in a shallow-water environment.*	*RF1-RF3. Biomineralisation, biomarkers, high-resolution bio-, magneto-, and chemo-stratigraphy.*
China: Dahai	*c. 550 m*	*~545 to 525 Ma*	*Precambrian-Cambrian boundary, early Cambrian geochemical change, Meishucun and Kuanchuanpu Fauna with abundant ash beds.*	*RF1-RF3. Geochemistry of platform shale integrated with fossil record to assess Ediacaran-early Cambrian oxygenation.*
China: Huangniuya	c. 550 m	*~635 to 550 Ma*	*Ediacaran platform with mixed carbonate and shale, LOEMs, Miohe and Xilingzia Biota, Shuram excursion, and abundant ash beds.*	*RF1-RF3. Geochemistry of Ediacaran shale deposited on platform integrated with fossil record in geochronological framework.*
China: Beidoushan	*c. 200 m*	*~635 to 550 Ma*	*Ediacaran carbonate platform margin with Weng'an Biota and Shuram excursion.*	*RF1-RF3. Geochemistry of platform margin integrated with fossil record in a high-resolution geochronological framework.*
China: Longbizui	*c. 500 m*	*~635 to 540 Ma*	*Ediacaran slope section, mixed carbonate & shale, with Wenghui Biota, Shuram excursion, and Precambrian-Cambrian boundary.*	*RF1-RF3. Geochemistry of slope sections integrated with fossil record in a high-resolution geochronological framework.*
China: Piyuancun	*c. 400 m*	*~635 to 540 Ma*	*Ediacaran slope section, mixed carbonate & shale, with Lantian Biota, Shuram excursion, Precambrian-Cambrian boundary.*	*RF1-RF3. Geochemistry of slope sections integrated with fossil record in a high-resolution geochronological framework.*
China: Tongle	*c. 400 m*	*~635 to 540 Ma*	*Ediacaran deep-water basinal shale section with Laobao Formation for micropaleontology, and organic-rich shale for redox geochemistry.*	*RF1-RF3. Compare chemistry of deep-water succession to slope and platform successions.*
Namibia: Pokkenbank	*c. 275 m*	*~550 to ~545 Ma*	*End of Shuram excursion and Cloudinid-rich rocks with interbedded ashes in proximal mid-ramp setting.*	*RF1-RF3. Integrate new geochemical records for end of Shuram excursion, fossil record and oxygenation.*
Namibia: Tierkloof	*c. 300 m*	*~550 to 540 Ma*	*Mixed siliciclastic-carbonate strata with shelly fossils and Cloudina in shallow-marine-shoreline settings.*	*RF1-RF3. New geochemistry integrated with paleontology to assess oxygenation in high-resolution geochronological framework.*
Namibia: Witputs Nord	*c. 360 m*	*~550 to 540 Ma*	*Carbonate ramp-shelf settings with reefal buildups and small shelly fossils and Cloudinids.*	*RF1-RF3. New geochemistry integrated with paleontology to assess oxygenation in high-resolution geochronological framework.*
Namibia: Swartpunt	*c. 425 m*	*~541 to >539 Ma*	*Bioturbated strata of upper Nama Group with last Ediacaran fauna in more shallow water setting.*	*RF1-RF3. Geochemistry of platform sections and fossil record to assess Ediacaran-Cambrian oxygenation in high-resolution geochronological framework.*
Namibia: Orange River	*c. 200 m*	*~541 to >539 Ma*	*Bioturbated strata of upper Nama Group with last Ediacaran fauna in more shallow water setting.*	*RF1-RF3. Geochemistry of platform sections and fossil record to assess Ediacaran-Cambrian oxygenation in high-resolution geochronological framework.*

Table A1. Summary of the core strategy and science objectives for Brazil, China and Namibia

A2.1 Western Brazil. Two drill cores will target the Tamengo and Guaicurus Formations for a total core recovery of *c*. 0.4 km; both are known to contain tuff beds and fossiliferous intervals and span the Ediacaran-Cambrian boundary. The sites are Sobramil Harbor and Laginha Mine near Corumbá (Table A2, Fig. A5), a mining town in the State of Mato Grosso do Sul. Adjacent quarries will enable direct comparison of cores to outcrop. FAPESP has already agreed funding to start drilling and coring operations in early 2018 and contractor Geominas will undertake the drilling and attend to all core requirements. Local storage and initial core description will be performed at the Universidade Federal do Mato Grosso do Sul, Corumbá. As noted in Section 3, the surface and subsurface geology of the area is well documented: the sites occur on the northwest and southeast limb of the gently plunging near symmetric Morros anticline (Fig. 5 and A5) and given the short length of the cores (<200m) recovery of target intervals is assured.

Table A2. Summary of core details for drilling sites Sobramil Harbor and Laginha Mine.

drill site	location; elevation	target interval	core length	geology	access	water
Sobramil Harbor	19°00'01" S 57°37'11" W 110 m	lower part of Guaicurus Fm; complete Tamengo Fm	c.180m	30° uniform dips; volcanic ash beds and metazoan fossil in shallow-marine facies.	adjacent to main road	on-site
Laginha Mine	19°07'07" S 57°38'43" W 196 m	lower part of Guaicurus Fm; complete Tamengo Fm	c.150m	30° uniform dips; organic limestone in deeper-marine facies.	adjacent to mine access	200m from site

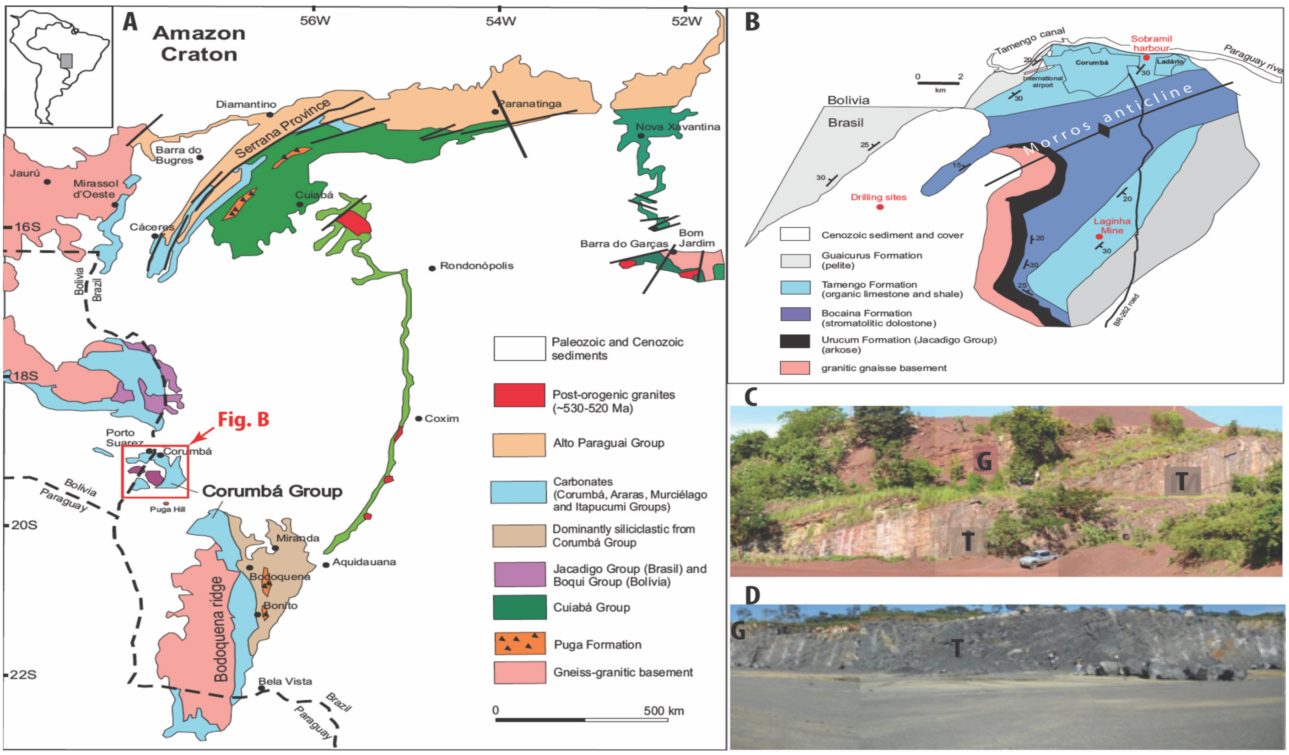


Figure A5. A. Simplified geological map of the Paraguay Belt. **B.** Geological map of the drill site area around Corumbá; structure is a simple, open-fold symmetric anticline and drilling will be inclined ~60º along each dipping limb in order to intersect bedding at 90º. **C.** Sobramill Harbour. **D.** Laginha Mine. G – Guaicurus Formation; T – Tomengo Formation.

A2.2 South China. Six drill cores will target the Ediacaran and early Cambrian strata in both shelf (Dahai, Huangniuya, Beidoushan) and deeper slope settings (Longhizui, Piyuancum, Tongle) of the Yangtze Craton in south China and net a total core recovery of *c.* 2.6 km (Table A3). What is particularly exciting about the South China sections is the abundance of ash beds ideally suited for high-precision U-Pb ID-TIMS zircon geochronology. Cores will also provide pristine organic-rich samples for Re-Os geochronology. The drilling targets are the limestone, dolostone and shale units of the Doushantuo and Dengying formations with their extraordinary archive of mutlicellular life and associated hallmark Ediacaran C-isotope excursions (see references cited in proposal). The drill cores will capture the most representative Ediacaran and early Cambrian successions in South China for addressing the scientific objectives and Research Foci identified in the proposal. The targeted areas selected for drilling are typified by uncomplicated open folding and little to no fault disruptions (Fig. A6). Further, previous drilling experience and conventional cores by local Geological Surveys, mining companies and University-sponsored research projects confirm that high-quality cores of the target intervals can be obtained. Consequently, knowledge about subsurface geology is considerable and, given that cores will be <600 m in length, provides the highest level of confidence that the stratigraphic intervals targeted for coring will be recovered.

Table A3. Summary of core details for the South China drilling sites.

drill site	location; elevation	target interval	core length	geology	access	water
Dahai, Huize, Yunnan Province	26.336365N 103.225214E 2870 m	upper Dengying to middle Yu'anshan Fms	c. 550 m	shallow dipping, mixed siliciclastic-carbonate sedimentary rocks with phosphorites	6 km west of S207, 30 km along S207 to SE of Huize	c. 20 km to the well
Huangniuya, Yichang, Hubei Province	30.817397N 111.095402E 880 m	Doushantuo Fm to top of Shibantan Mbr of Dengying Fm	c. 550 m	shallow dipping, mixed siliciclastic-carbonate sedimentary rocks	25 km along paved road from Sandouping	3 km to well
Beidoushan Weng'an, Guizhou Province	27.010338N 107.390279E 1350 m	Doushantuo Fm to base Dengying Fm	c. 200 m	moderate dipping, mixed siliciclastic-carbonate sedimentary rocks with phosphorites	18 km along X930 to SW from Weng'an	2 km to well
Longbizui, Guzhang, Hunan Province	28.496149N 109.849146E 450 m	Dousuantuo Fm to middle Niutitang Fm	c. 500 m	moderately dipping, mixed siliciclastic-carbonate-chert sedimentary rocks	25 km along S229 to NE of Jishou	1 km to well
Piyuancun, Xiuning, Anhui Province	29.929782N 118.095816E 350 m	Lantian Fm to basal Piyuancun Fm	c. 400 m	moderately dipping, mixed siliciclastic-carbonate-chert sedimentary rocks	500 m W of S103, 20 km along S103 to N of Xiuning	600 m to well
Tongle, Sanjiang, Guangxi Province	25.781540N 109.418971E 250 m	top Silikou diamictite to middle Qingxi Fm	c. 400 m	moderately dipping, mixed siliciclastic-carbonate-chert sedimentary rocks	3 km W of X632, 38 km along G321-X632 to SW of Sanjiang	5 km to well

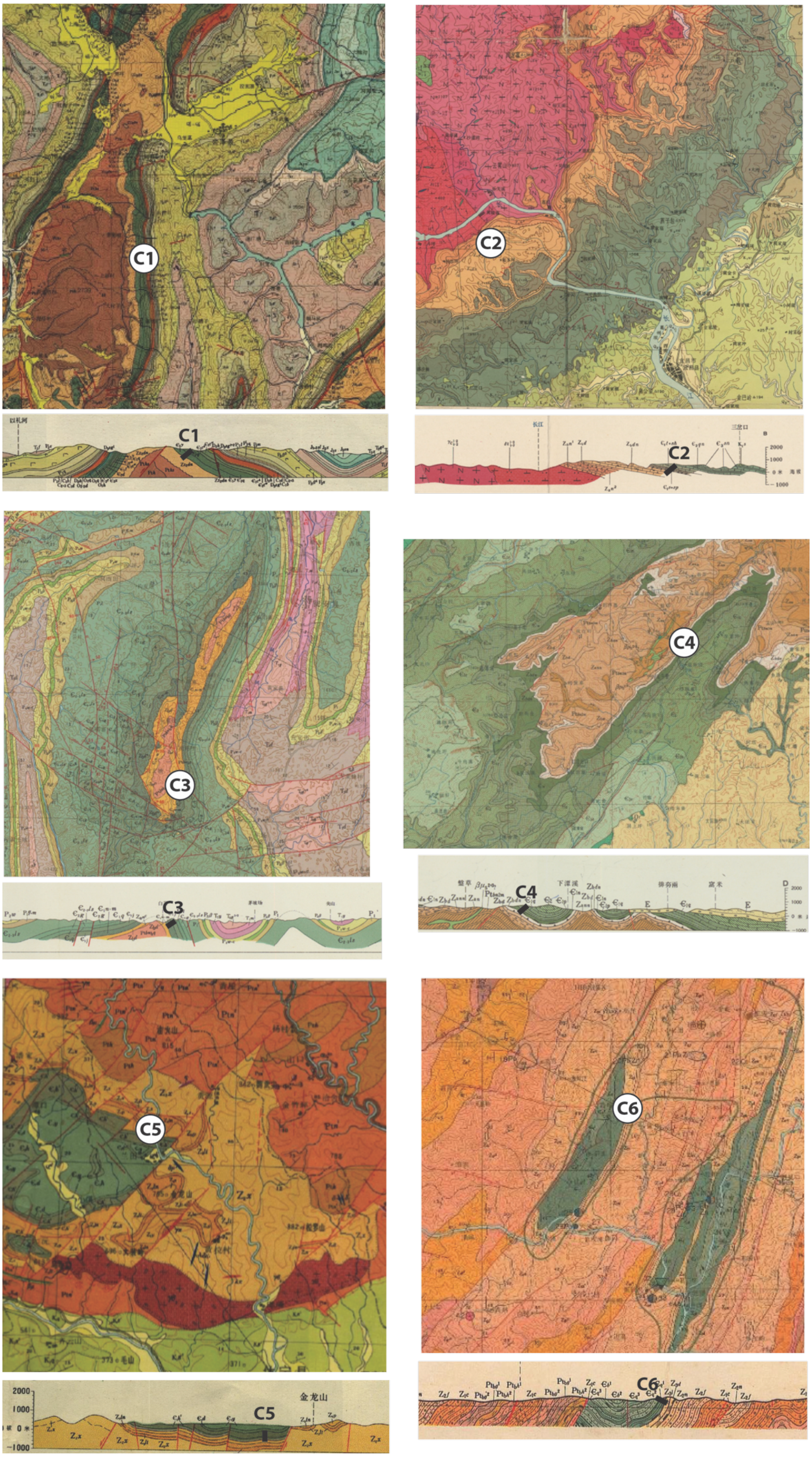


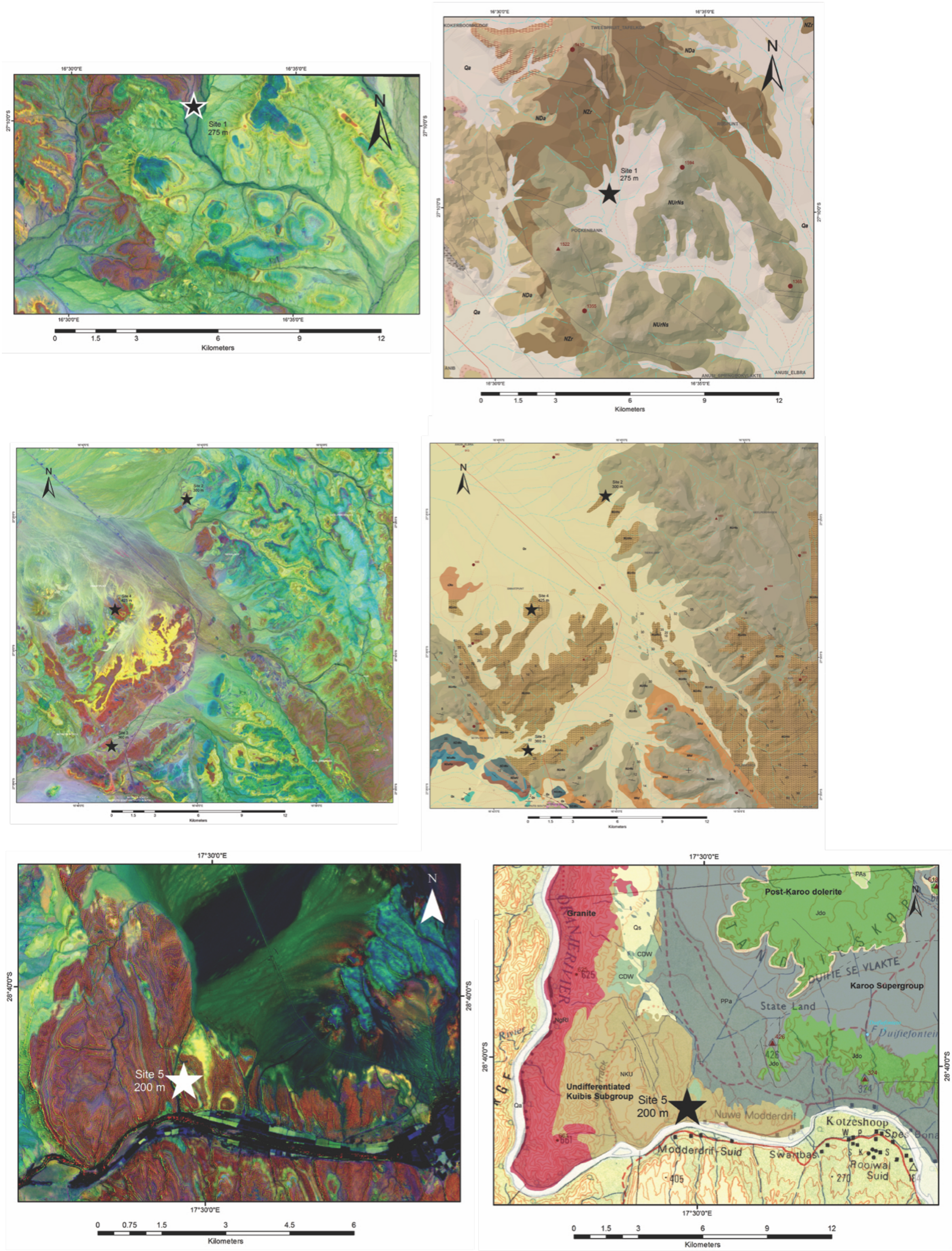
Figure A6. Geological maps and cross-sections of the South China drill site areas. Note that all sites are in regions of simple, open folding with no significant subsurface structural disruptions. C1-Dahai, C2-Huangniuya, C3-Beidoushan, C4-Longbizui, C5-Piyuancum, C6-Tongle.

A2.3 Southern Namibia. Five drill cores are proposed for south Namibia that target the Kuibis and Schwarzrand Subgroups and will net a total core recovery of c.1.5 km (Table A4). These consist of 4 sites (N1 to N4) located in the Witputs area, and one site (N5) located along the Orange River about 200 km to the south east. N1 to N4 capture the Kuibis Subgroup (Dabis and Zaris formations), and the lower, middle and upper Schwarzrand Subgroup (Nudaus Formation and Nasep, Huns, Feldschuhhorn and Spitskopf members of the Urusis Formation). The uppermost part of the Spitskop Member, up to the deeply incised unconformity of the overlying Cambrian Nomtsas Formation (Fig, 8) is only preserved in an isolated, steep-sided hill (with the top part eroded) in the Witputs area, and therefore cannot be drilled. Instead, it will be targeted at site the Orange River site (N5) with the additional benefit of a potential conformable transition into the lower Cambrian near the top.

Together, these will obtain the large C-isotope excursions typical of late Ediacaran-early Cambrian time, all the associated Ediacaran soft-bodied biota, skeletal micro-fossil and key trace fossil assemblages and geochemical signatures that have been central in models for postulating patchy ocean oxygenation leading up to the purported Neoproterozoic Oxygenation Event. The target sites are in areas of simple geology (Fig. A7), marked everywhere by flat-lying to uniformly low-angle dipping strata (<20º; e.g. see photo on front page of proposal) in which there are few faults, those that are present are high-angle and restricted to within readily identifiable zones that are well away from the proposed drill sites. The geology of the Nama Basin is known in exceptional detail owing to outstanding 3-D surface exposure afforded by ubiquitous networks of sinuous, deep canyons in an arid climate, as well as several drill cores spread across the Nama Basin. Combined, these datasets confirm that the characteristic simple and largely flat-lying geology is present everywhere (note that the thrust faulting related to the early Cambrian Gariep orogeny occurs farther west of the drill sites). Hence, given that all core lengths are less than 500 m, we have the highest level of confidence of recovering the stratigraphic intervals targeted for coring.

Table A4. Summary of core details for the south Namibia drilling sites.

drill site	location; elevation	target interval	core length	geology	access	water
Pokkenbank	27.160737S 16.545447E 1145 m	Dabis and Mooifontein Fms (Kuibis Subgroup)	c. 275 m	flat lying, mixed siliciclastic-carbonate sedimentary rocks	24.6 km along farm track off and NE of C13	water will be trucked in
Tierkloof	27.403949S 16.739627E 980 m	Nudaus Fm and Nasep Mbr (lwr Schwarzrand Subgp)	c. 300 m	flat lying, mixed siliciclastic-carbonate sedimentary rocks	6.4 km along farm track off and E of C13	access to nearby farm well
Witputs Nord	27.558859S 16.689447E 977 m	upper Nasep and Huns Mbrs (mid Schwarzrand Subgp)	c. 360 m	flat lying, mixed siliciclastic-carbonate sedimentary rocks	1 km along farm track off and N of C13	access to nearby farm well
Swartpunt	27.473417S 16.690464E 1011 m	Feldschuhhorn and Spitskop Mbrs (upr Schwarzrand Subgp)	c. 425 m	flat lying, mixed siliciclastic-carbonate-chert sedimentary rocks	6.8 km along farm track off and NW of C13	water will be trucked in
Orange River	28.685900S 17.494231E 243 m	top Spitskop Mbr (top Schwarzrand Subgp)	c. 200 m	flat lying, mixed siliciclastic-carbonate-chert sedimentary rocks	6.5 km along farm track off and W of C13	access to nearby farm well



Schwarzrand Subgroup: Nudaus Fm (NNd), Urusis Fm (NUrNS, NUrHn), Nomtsas Fm (ENo)
Kuibis Subgroup rocks: Dabis Fm (NDa, NDaKa, NDaMa, NDaKl), Zaris Fm (NZr, NZrMo)
pre-Nama Group rocks: MNQ, Npe, NGA

Figure A7. A. Geology of the drill site areas along with remote sensing images that reveal the layer-cake like geometry of the Nama Group rocks. All geological and drilling data confirm that this simple, flat-lying to low-angle-dipping geology occurs in the subsurface thus there is absolute confidence in recovering the target intervals. Black stars mark drill site locations and core lengths. Upper panel drill site 1 (Pokkenbank); middle panels drill sites 2-3-4 (Tierkloof, Witputs Nord, Swartpunt, respectively); lower panels drill site 5 (Orange River).

Appendix 3. Budget and cost estimates

A3.1 Budget summary. Estimated costs for drilling and coring operations and the cost of post-drilling research activities are based on values at the time of submittal of the proposal and hence any inflation and price increases between proposal submission and review, and the start of drilling, need to be considered in final budgetary amounts. The tables below summaries the estimated GRIND-ECT drilling and coring operations budget and the estimated GRIND-ECT research budget.

GRIND-ECT costs estimates for drilling and coring operations		
1. Pre-drilling planning		
Pre-drilling Workshop for Central Science Team, Science Theme Cordinators and Advisory Group (11 persons total); to be held at BGS, Keyworth, UK, at least 2 months prior to start of drilling (cost includes airfare, train travel, accommodation and subsistence for 4 days inclusive of travel time)	**$**	**8,850.00**
1x RT air travel Windhoek-BGS: $950	$	950.00
2x RT air travel Boston-BGS: $500/pers	$	1,000.00
1x RT air travel Bremen-BGS: $150	$	150.00
1x RT air travel Nanjing-BGS: $1350	$	1,350.00
1x RT air travel Trondheim-BGS: $300	$	300.00
2x RT train travel St Andrews-BGS: $200/pers	$	400.00
1x RT train travel Oxford-BGS: $100	$	100.00
2x RT train travel Birmingham International-BGS: $50/pers	$	100.00
3x RT train travel London-BGS: $100/pers	$	300.00
10x acccommodation Nottingham, UK, at $100/pers for 2 nights	$	2,000.00
11x $50 per diem: $50 per diem for 4 days (inclusive of travel time)	$	2,200.00
ICDP DIS training (flights, accommodtion and subsistence [$50/day] to Windisch-Eschenbach for a Brazilian, Chinese and Namibian colleague, and Dr C Rose and M Mesli); estimated for 5 days	**$**	**7,525.00**
1x RT air travel Windhoek-Munich $1100	$	1,100.00
1x RT air travel Nanjing-Munich $1500	$	1,500.00
1x RT air travel Sao Paulo-Munich: $1050	$	1,050.00
1x RT air travel Edinburgh-Munich: $100	$	100.00
1x RT train travel Berlin-Munich: $25	$	25.00
5x accommodation Munich at $100/pers for 5 nights	$	2,500.00
5x $50 per diem: $50 per diem for 5 days	$	1,250.00
2. Drilling costs (costs reflect exchange rates as of 05 January 2018)	**$**	**1,032,250.00**
Brazil (inclusive of all core handling, in-country transport, core-orientation, core boxes, initial core characterisation, etc.)	$	54,570.00
China (inclusive of all core handling, in-country transport, core-orientation, core boxes, initial core characterisation, etc.)	$	734,458.00
Namibia (inclusive of all core handling, in-country transport, core-orientation, core boxes, initial core characterisation, etc.)	$	243,222.00
3. On-site core characterisation costs		
Brazil sites for on-site team (estimated for 4 people: cost includes airfare, in-country travel/vehicle hire, accommodation, subsistence and associated expenses; estimated 2.5 weeks inclusive of travel time)	**$**	**9,470.00**
1x RT air travel from Boston to Sao Paolo: $1100	$	1,100.00
1x RT air travel from Edinburgh to Sao Paolo: $1100	$	1,100.00
1x RT air travel from Windhoek to Sao Paolo: $950	$	950.00
4x RT air travel Sao Paulo to Corumba: $500/flight	$	2,000.00
4x accommodation in Corumba: $30/night for 18 nights	$	2,160.00
4x $30 per diem: $30 per diem for 18 days	$	2,160.00
China sites (estimated for 12 people allowing for 3 team changovers [4 pers/team] cost includes airfare, in-country travel/vehicle hire, accommodation, subsistence and associated expenses; estimated 8 weeks inclusive of travel time and 3 team changovers)	**$**	**72,930.00**
2x RT air travel from Boston to Nanjing: $950	$	1,900.00
2x RT air travel from Edinburgh to Nanjing: $700	$	1,400.00
1x RT air travel from Windhoek to Nanjing: $1350	$	1,350.00
12x RT air travel within south China: $650/flight	$	7,800.00
12x accommodation in south China $50/night for 56 nights	$	33,600.00
12x $40 per diem: $40 per diem for 56 days	$	26,880.00
Namibia sites (estimated for 8 people allowing for 2 team changovers [4 pers/team] cost includes airfare, in-country travel/vehicle hire, accommodation, subsistence and associated expenses; estimated 6 weeks inclusive of travel time and 2 team changeovers)	**$**	**36,550.00**
2x RT air travel from Boston to Windhoek: $1300	$	2,600.00
2x RT air travel from Edinburgh to Windhoek: $1100	$	2,200.00
1x RT air travel from Nanjing to Windhoek: $1350	$	1,350.00
8x RT air travel within south China: $650/flight	$	5,200.00
8x accommodation in south Namibia $50/night for 42 nights	$	16,800.00
8x $25 per diem: $25 per diem for 42 days	$	8,400.00

A3.1 Budget summary continued.

4. Other costs	**$**	**108,845.00**
DIS operations and Core Manager for coordinating BGR Berlin-Spandau repository (Ms Melanie Mesli; $19k/yr as per ICDP guidelines for 3 years)	$	57,000.00
Internships for in-country capacity building and training (2 per nation at $1000 per student)	$	6,000.00
shipping of cores from Brazil to BGR Berlin-Spandau repository	$	2,100.00
shipping of cores from China to BGR Berlin-Spandau repository	$	6,625.00
shipping of cores from Namibia to BGR Berlin-Spandau repository	$	3,620.00
shipping and import of ICDP core-scanning equipment (Namibia; 35% tax)	$	24,000.00
core splitter for Namibian cores	$	3,500.00
Outreach and education materials (initial costs of $3000 per nation; additional costs to be covered by grants to project scientists)	$	6,000.00
Total estimate of costs linked directly to drilling and coring activities	**$**	**1,276,420.00**

GRIND-ECT summary budget		
Total pre-drilling planning meetings and ICDP training	$	16,375.00
Total drilling costs (Brazil, China, Namibia)	$	1,032,250.00
Total on-site core characterisation costs	$	118,950.00
Total other costs (Core manager, internships, core shipping to BGR, hire of ICDP equipment, etc.)	$	108,845.00
Total cost estimate for costs linked directly to drilling and coring activities	**$**	**1,276,420.00**

n.b.: FAPESP has already provided a grant to Prof R Trindade to cover Brazilian research costs that totals $492,461.00

Request to ICDP for 50%	$	638,210.00
FAPESP support already obtained for Brazilian drilling	$	62,000.00
FAPESP support already obtained for Namibian drilling	$	120,000.00
Request to NSF for 10% (or greater)	$	127,642.00
Request to NASA for 10% (or greater)	$	127,642.00
Request to DFG for 10% (or greater)	$	127,642.00
Request to NSFChina for 10% (or greater)	$	127,642.00
Request to NERC for 10% (or greater)	$	127,642.00

Science Party and post-drilling research cost estimates (estimates are based on a Science Party of 20-25 project scientists)		
Travel (international airfare, in-country) accomodation, subsistence		
Brazil: travel and 2-weeks accommodation, subsistence and assiciated expenses ($60 *per diem* ; FAPESP already funds Brazilian researchers thus these costs reflect support required for non-Brazilian researchers)	$	46,000.00
China: travel (airfare, in-country travel) and 4 weeks accommodation, subsistence and associated expenses ($70 *per diem*)	$	63,000.00
Namibia: travel (airfare, in-country travel) and 3 weeks accommodation, subsistence and associated expenses ($40 *per diem*)	$	44,000.00
	$	153,000.00
Research analytical costs and personal (PhD, Postdocs)		
Research costs inclusive of all sample shipping and preparation, geochemical-isotopic-biomarker-palaeomag-imaging analyses and related activities on 13 cores totalling c. 4 km; estimate is based on previous experience with ICDP FAR-DEEP (also 13 cores totalling c. 3.5 km), which had research cost estimates of $6.4M and $1.8M for PhD and Postdoctoral researchers, and the FAPESP proposal awarded to Prof R Trindade ($492k)	$	8,700,000.00
	$	8,700,000.00
Total estimate of research costs	**$**	**8,853,000.00**

A3.2 Brazilian drilling costs. In 2016, FAPESP approved 492,460 $USD funding to Co-I Professor R Trindade, this includes the Brazilian drilling and coring operations (see below), 120,000 $USD to help offset the costs of the Namibian drilling and coring programme, and all post-drilling research activities and analyses (see budget next page).

Below is the quote provided by Geomines for drilling and coring operations in Brazil as per the funded FAPESP proposal to Prof R Trindade (see next page). These funds have been secured since 2016 and will be used to commence drilling in Brazil in early 2018. Prices quoted are in Brazilian Real: ***the total amount converts to 54,570 $USD*** as per 05-01-18 exchange rates.

Geominas

Proposta GEOSON 036-2015
FAPESP

Anexo-I - Quadro de Quantidades e Preços

QUADRO DE QUANTIDADES E PREÇOS

OBJETO CONTRATUAL:

Execução de sondagens rotativa tip Wire Line para Projeto de Pesquisa em Corumbá-MS - FAPESP

ITEM	DESCRIÇÃO	UNID.	QUANT.	PREÇO UNITÁRIO (R$)	VALOR TOTAL (R$)	
1	**Mobilização/Desmobilização**					
1.1	Mobilização e desmobilização de equipe e equipamentos de sondagem mista	vb	1,00	25.000,00	25.000,00	
2	**Sondagens**					
2.1	Sondagem Rotativa Wire Line em Solo ΦHQ	m	200,00	425,00	85.000,00	*Quantidade estimada*
2.2	Sondagem Rotativa Wire Line em Rocha ΦNQ	m	100,00	645,00	64.500,00	*Quantidade estimada*
4	**Instalação , Montagem, Desmotagem e Deslocamento de equipamentos**					
4.1	Instalação , Montagem, Desmotagem e Deslocamento de equipamentos de sondagem mista entre furos	vb	1,00	1.250,00	1.250,00	
5	**Relatório Técnico Final (incluso perfis e ART)**	relatório	1,00	1.500,00	1.500,00	
	SOMA				**177.250,00**	

Por extenso (Cento e Setenta e Sete Mil Duzentos e Cinquenta Reais)

Geominas – Geologia e Construtora Ltda
Matriz: End.: Rua B, 462 – Cidade Nova – CEP: 68.515-000 – Parauapebas – Pará
Filial: Av. Alvares Cabral, 593 sl 1804 – Lourdes – Belo Horizonte - MG
www.geominasgeo.com.br - geominas@geominasgeo.com.br
Tel/Fax: 94 3346 2465 ou 31 3293 8254 cel.: 31 9120 6805

A3.2 continued. Summary of budget of FAPESP grant to Professor R Trindade. These funds have been secured since 2016 and will be used to commence drilling in Brazil in early 2018. ***The total amount awarded by FAPESP in 2016 was 492,460 $USD.***

FAPESP SAGe

Processo

Identificação do Processo

Número do Processo	2016/06114-6 - Projeto de Pesquisa - Temático
Situação	Em Execução
Grupo de Financiamento	Auxílio à Pesquisa
Linha de Fomento	Programas Regulares / Auxílios a Pesquisa / Projeto de Pesquisa / Projeto de Pesquisa - Temático - Fluxo Contínuo
Beneficiário	Ricardo Ivan Ferreira da Trindade
Responsável	Ricardo Ivan Ferreira da Trindade
Data Início	01/08/2016
Duração	60 mês(es)

Instituição de Pesquisa/Empresa	Instituto de Astronomia, Geofísica e Ciências Atmosféricas/IAG/USP
Departamento	Geofísica
Data de Abertura	04/04/2016

Benefícios	**Valor (R$)**	**Valor (US$)**
Capital		
Material Permanente	21.115,29	197.356,55
Custeio		
Despesas de Transporte	101.580,00	660,00
Diárias	216.000,00	30.000,00
Infraestrutura	0,00	0,00
Material de Consumo	0,00	475,00
Serviços de Terceiros	977.100,00	203.733,75
Reserva Técnica - Benefícios Complementares	120.000,00	0,00
Reserva Técnica - Custo de Infraestrutura Direta do Projeto	583.005,78	0,00
Provisão para Importação	0,00	60.234,79
Outros	0,00	0,00
TOTAL	2.018.801,07	492.460,09
Bolsas		
Doutorado Direto	0,00	0,00
Ensino Público	0,00	0,00
Iniciação Científica	0,00	0,00
Jornalismo Científico	0,00	0,00
Participação em Curso	0,00	0,00
Pós-Doutorado	0,00	0,00
Treinamento Técnico	0,00	0,00
TOTAL	0,00	0,00
TOTAL GERAL	2.018.801,07	492.460,09

A3.3 Chinese drilling costs. Quotes provided by China Continental Scientific Drilling contractors for mobilisation-demobilisation, green crop compensation and site levelling for six sites in south China. Quote given on 02 January 2018. Note that these are estimates and are subject to change based on inflation and related cost factors that may occur between January 2018 and when drilling commences. Estimates quoted are in both Chinese renminbi and $USD, as per 02 January 2018 exchange rates.

COST ESTIMATE: China Continental Scientific Drilling

Description	*Quantity*	*Rate(RMB)*	*Total(RMB)*	*Rate(US$)*	*Total(US$)*
Two-wayTransport -Drill Site C1	1	¥ 30,000.00	¥ 30,000.00	$ 4,615.38	$ 4,615.38
Two-wayTransport -Drill Site C2	1	¥ 30,000.00	¥ 30,000.00	$ 4,615.38	$ 4,615.38
Two-wayTransport -Drill Site C3	1	¥ 30,000.00	¥ 30,000.00	$ 4,615.38	$ 4,615.38
Two-wayTransport -Drill Site C4	1	¥ 30,000.00	¥ 30,000.00	$ 4,615.38	$ 4,615.38
Two-wayTransport -Drill Site C5	1	¥ 30,000.00	¥ 30,000.00	$ 4,615.38	$ 4,615.38
Two-wayTransportation -Drill Site C6	1	¥ 30,000.00	¥ 30,000.00	$ 4,615.38	$ 4,615.38
Sum			**¥ 180,000.00**		**$ 27,692.31**
Green crop compensation -Drill Site C1	1	¥ 25,000.00	¥ 25,000.00	$ 3,846.15	$ 3,846.15
Green crop compensation -Drill Site C2	1	¥ 25,000.00	¥ 25,000.00	$ 3,846.15	$ 3,846.15
Green crop compensation -Drill Site C3	1	¥ 25,000.00	¥ 25,000.00	$ 3,846.15	$ 3,846.15
Green crop compensation -Drill Site C4	1	¥ 25,000.00	¥ 25,000.00	$ 3,846.15	$ 3,846.15
Green crop compensation -Drill Site C5	1	¥ 25,000.00	¥ 25,000.00	$ 3,846.15	$ 3,846.15
Green crop compensation -Drill Site C6	1	¥ 25,000.00	¥ 25,000.00	$ 3,846.15	$ 3,846.15
Sum			**¥ 150,000.00**		**$ 23,076.92**
leveling out drill site -Drill Site C1	1	¥ 35,000.00	¥ 35,000.00	$ 5,384.62	$ 5,384.62
leveling out drill site -Drill Site C2	1	¥ 35,000.00	¥ 35,000.00	$ 5,384.62	$ 5,384.62
leveling out drill site -Drill Site C3	1	¥ 35,000.00	¥ 35,000.00	$ 5,384.62	$ 5,384.62
leveling out drill site -Drill Site C4	1	¥ 35,000.00	¥ 35,000.00	$ 5,384.62	$ 5,384.62
leveling out drill site -Drill Site C5	1	¥ 35,000.00	¥ 35,000.00	$ 5,384.62	$ 5,384.62
leveling out drill site -Drill Site C6	1	¥ 35,000.00	¥ 35,000.00	$ 5,384.62	$ 5,384.62
Sum			**¥ 210,000.00**		**$ 32,307.69**

A.3.3 continued. Quotes provided by China Continental Scientific Drilling contractors for drilling and coring operations for six sites in south China. Quote given on 02 January 2017. Note that these are estimates and are subject to change based on inflation and related cost factors that may occur between January 2018 and when drilling commences. Estimates are in both Chinese renminbi and $USD, as per 02 January 2018 exchange rates.

COST ESTIMATE: China Continental Scientific Drilling

Description	*Quantity*	*Rate(RMB)*	*Total(RMB)*	*Rate(US$)*	*Total(US$)*
Drill Site C1					
Rig Set Up & Alignment	1	¥ 15,000.00	¥ 15,000.00	$ 2,307.69	$ 2,307.69
Wire line Coring	520	¥ 1,200.00	¥ 624,000.00	$ 184.62	$ 96,000.00
Orientation Coring	30	¥ 2,400.00	¥ 72,000.00	$ 369.23	$ 11,076.92
Casing & Cementing	30	¥ 600.00	¥ 18,000.00	$ 92.31	$ 2,769.23
Mud	550	¥ 100.00	¥ 55,000.00	$ 15.38	$ 8,461.54
Down Hole Surveys					
Management Fee			¥ 71,200.00		$ 10,953.85
Tax			¥ 35,600.00		$ 5,476.92
Sum			**¥ 890,800.00**		**$ 137,046.15**
Drill Site C2					
Rig Set Up & Alignment	1	¥ 15,000.00	¥ 15,000.00	$ 2,307.69	$ 2,307.69
Wire line Coring	520	¥ 1,200.00	¥ 624,000.00	$ 184.62	$ 96,000.00
Orientation Coring	30	¥ 2,400.00	¥ 72,000.00	$ 369.23	$ 11,076.92
Casing & Cementing	30	¥ 600.00	¥ 18,000.00	$ 92.31	$ 2,769.23
Mud	550	¥ 100.00	¥ 55,000.00	$ 15.38	$ 8,461.54
Down Hole Surveys					
Management Fee			¥ 71,200.00		$ 10,953.85
Tax			¥ 35,600.00		$ 5,476.92
Sum			**¥ 890,800.00**		**$ 137,046.15**
Drill Site C3					
Rig Set Up & Alignment	1	¥ 15,000.00	¥ 15,000.00	$ 2,307.69	$ 2,307.69
Wire line Coring	194	¥ 1,200.00	¥ 232,800.00	$ 184.62	$ 35,815.38
Orientation Coring	6	¥ 2,400.00	¥ 14,400.00	$ 369.23	$ 2,215.38
Casing & Cementing	20	¥ 600.00	¥ 12,000.00	$ 92.31	$ 1,846.15
Mud	200	¥ 100.00	¥ 20,000.00	$ 15.38	$ 3,076.92
Down Hole Surveys					
Management Fee			¥ 27,980.00		$ 4,304.62
Tax			¥ 13,990.00		$ 2,152.31
Sum			**¥ 336,170.00**		**$ 51,718.46**
Drill Site C4					
Rig Set Up & Alignment	1	¥ 15,000.00	¥ 15,000.00	$ 2,307.69	$ 2,307.69
Wire line Coring	470	¥ 1,200.00	¥ 564,000.00	$ 184.62	$ 86,769.23
Orientation Coring	30	¥ 2,400.00	¥ 72,000.00	$ 369.23	$ 11,076.92
Casing & Cementing	20	¥ 600.00	¥ 12,000.00	$ 92.31	$ 1,846.15
Mud	500	¥ 100.00	¥ 50,000.00	$ 15.38	$ 7,692.31
Down Hole Surveys					
Management Fee			¥ 64,100.00		$ 9,861.54
Tax			¥ 32,050.00		$ 4,930.77
Sum			**¥ 809,150.00**		**$ 124,484.62**
Drill Site C5					
Rig Set Up & Alignment	1	¥ 15,000.00	¥ 15,000.00	$ 2,307.69	$ 2,307.69
Wire line Coring	376	¥ 1,200.00	¥ 451,200.00	$ 184.62	$ 69,415.38
Orientation Coring	24	¥ 2,400.00	¥ 57,600.00	$ 369.23	$ 8,861.54
Casing & Cementing	20	¥ 600.00	¥ 12,000.00	$ 92.31	$ 1,846.15
Mud	400	¥ 100.00	¥ 40,000.00	$ 15.38	$ 6,153.85
Down Hole Surveys					
Management Fee			¥ 51,820.00		$ 7,972.31
Tax			¥ 25,910.00		$ 3,986.15
Sum			**¥ 653,530.00**		**$ 100,543.08**
Drill Site C6					
Rig Set Up & Alignment	1	¥ 15,000.00	¥ 15,000.00	$ 2,307.69	$ 2,307.69
Wire line Coring	376	¥ 1,200.00	¥ 451,200.00	$ 184.62	$ 69,415.38
Orientation Coring	24	¥ 2,400.00	¥ 57,600.00	$ 369.23	$ 8,861.54
Casing & Cementing	20	¥ 600.00	¥ 12,000.00	$ 92.31	$ 1,846.15
Mud	400	¥ 100.00	¥ 40,000.00	$ 15.38	$ 6,153.85
Down Hole Surveys					
Management Fee			¥ 51,820.00		$ 7,972.31
Tax			¥ 25,910.00		$ 3,986.15
Sum			**¥ 653,530.00**		**$ 100,543.08**
Total: two-way transport, green crop compensation, site levelling and 6 drill sites			**¥ 4,773,980.00**		**$ 734,458.46**

A3.4 Namibian drilling costs. Quotes provided by Günzel Drilling for drilling and coring operations for the 5 sites in Namibia. Quote given on 17 December 2017. Note that these are estimates and are subject to change based on inflation and related cost factors that may occur between December 2017 and when drilling commences. Estimates are in $USD, as per 17 December 2017 exchange rates.

QUOTATION - AGQ 1712

To: Tony Prave
St Andrews University
Email: ap13@st-andrews.ac.uk

GÜNZEL DRILLING

Günzel Drilling cc
P.O.Box 4261
Swakopmund
Tel: +264 81 322 89 18
11-Dec-17

Service Provided:

Research Core Drilling		**Rate in USD**
Minus 70 - 90 Degrees		
Start Depth	End Depth	HQ/m
0	200	120.00
200	450	130.00

Auxiliary Services - Core Drilling	**Unit**	**Rate in USD**
Mobilization & Demobilisation		
Mobilisation - Drill Site 01	Unit	8,855.00
Mobilisation - Drill Site 02	Unit	287.50
Mobilisation - Drill Site 03	Unit	287.50
Mobilisation - Drill Site 04	Unit	287.50
Mobilisation - Drill Site 05	Unit	598.00
Demobilisation - Drill Site	Unit	8,855.00
Drill Platform Preparation & Rig Moves		
Rig Alignment & Set up	Per Setup	100.00
Access to drill site	Per platform	to be discussed
Drill platorm preparation	Per platform	to be discussed
Rehabilitation of Drill site	Drill Area	to be discussed
Water		
Pumping of Water (if required)	Per day	86.00
Pump Installation	Per pump	included
Carting of Water up to 1km	Per driving km	included
Carting of Water for more than 1km	Per driving km	4.60
Water Payment	Per 5000l load	50.00
Other		
Down Hole Surveys (Reflex Eezi-Track) through rods only	Shot	85.00
Rental of Reflex Eezi-Track	Month	included
Insertion of NW/ HW Casing	Meter	23.00
Removal of NW/ HW Casing	Meter	23.00
Reaming 4 9/16 for casing	Per meter	85.00
Grouting	Per hour	170.00
Waiting & Standby Time	Hour	115.00
Material		
Cement	Bag	11.50
HW Casing	Per m	115.00
Core Trays Plastic	Per Tray	Client
Equipment Lost - drillers fault	unit	no charge
Equipment Left behind formation related	unit	replacement cost plus transport

COST ESTIMATE - NEOPROTEROZOIC RESEARCH

Description	Quantity	Rate	Total
Mobilisation - Drill Site 01	1	8,855.00	8,855.00
Mobilisation - Drill Site 02	1	287.50	287.50
Mobilisation - Drill Site 03	1	287.50	287.50
Mobilisation - Drill Site 04	1	287.50	287.50
Mobilisation - Drill Site 05	1	598.00	598.00
Demobilisation - Drill Site	1	8,855.00	8,855.00
		TOTAL MOBLISATION:	**19,170.50**

Description	Quantity	Rate	Total
Drill Site 1. Pokkenbank (Kuibis Subgroup); core length ~275 m			
Rig Set Up & Alignment	1	100	100.00
0m - 200m	200	120	24,000.00
200m - 450m	75	130	9,750.00
Reaming 4 9/16 for casing	12	85	1,020.00
Insertion of Casing	12	23	276.00
Removal of Casing	12	23	276.00
Down Hole Surveys (Reflex Eezi-Track)	9	85	765.00
Pumping of Water	7	86	602.00
Purchasing the Water	21	50	1,050.00
		Sum Drill Site 1	**37,839.00**
Drill Site 2. Tierkloof (Lower Schwarzrand Subgroup); core length ~300 m			
Rig Set Up & Alignment	1	100	100.00
0m - 200m	200	120	24,000.00
200m - 450m	100	130	13,000.00
Reaming 4 9/16 for casing	12	85	1,020.00
Insertion of Casing	12	23	276.00
Removal of Casing	12	23	276.00
Down Hole Surveys (Reflex Eezi-Track)	10	85	850.00
Pumping of Water	8	86	688.00
Purchasing the Water	24	50	1,200.00
		Sum Drill Site 2	**41,410.00**
Drill Site 3. Witputs Nord (Middle Schwarzrand Subgroup); core length ~360 m			
Rig Set Up & Alignment	1	100	100.00
0m - 200m	200	120	24,000.00
200m - 450m	160	130	20,800.00
Reaming 4 9/16 for casing	12	85	1,020.00
Insertion of Casing	12	23	276.00
Removal of Casing	12	23	276.00
Down Hole Surveys (Reflex Eezi-Track)	12	85	1,020.00
Pumping of Water	11	86	946.00
Purchasing the Water	33	50	1,650.00
		Sum Drill Site 3	**50,088.00**
Drill Site 4. Swartpunt (Upper Schwarzrand Subgroup); core length ~425 m			
Rig Set Up & Alignment	1	100	100.00
0m - 200m	200	120	24,000.00
200m - 450m	225	130	29,250.00
Reaming 4 9/16 for casing	12	85	1,020.00
Insertion of Casing	12	23	276.00
Removal of Casing	12	23	276.00
Down Hole Surveys (Reflex Eezi-Track)	12	85	1,020.00
Pumping of Water	15	86	1,290.00
Purchasing the Water	45	50	2,250.00
Trucking of Water	1600	4.6	7,360.00
		Sum Drill Site 4	**66,842.00**
Drill Site 5. Orange River (Top Schwarzrand Subgroup); core length 200 m			
Rig Set Up & Alignment	1	100	100.00
0m - 200m	200	120	24,000.00
200m - 450m	0	130	-
Reaming 4 9/16 for casing	12	85	1,020.00
Insertion of Casing	12	23	276.00
Removal of Casing	12	23	276.00
Down Hole Surveys (Reflex Eezi-Track)	12	85	1,020.00
Pumping of Water	5	86	430.00
Purchasing the Water	15	50	750.00
		Sum Drill Site 5	**27,872.00**
		TOTAL DRILLING:	**224,051.00**
		ESTIMATE OF TOTAL COST:	**243,221.50**

GÜNZEL DRILLING

A.3.4 continued. Quotes provided by Günzel Drilling for drilling and coring operations in the 5 sites in Namibia. Quote given on 17 December 2017. Note that these are estimates and are subject to change based on inflation and related cost factors that may occur between December 2017 and when drilling commences. Quotes are in $USD.

Appendix 4. Core archiving and the BGR Berlin-Spandau core repository agreement

As noted in the main proposal (Section 4), cores will be cut and half of the core will be placed in in-country repositories and the other half transported for storage at the BGR in Berlin-Spandau, Germany. The core repository in Brazil will be the Instituto de Geociências and de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, São Paulo, in China it will be the China Geological Samples Center of Land and Resource (CGSC), China Geological Survey, Beijing, and in Namibia it will be at the Ministry of Mines and Energy, Namibian Geological Survey, Windhoek. Sampling protocols will follow those outlined in Section 4 and designation of archive status to at least ¼ portions of each core. The dual-location approach (one repository in-country and one centralised at the BGR) has the advantage that a portion of the core is retained nationally and will be accessible to researchers in country for educational, training and research purposes. However, given ease-of-access to air, road and rail transport networks we expect that the bulk of the sampling will be carried out at the BGR. Sampling will be standardised and coordinated across the entire GRIND-ECT project following protocols detailed in Section 4 to ensure every sample is recorded and traceable.

For advice and aide in archiving and sampling, we can draw on the wealth of experience of Dr Aivo Lepland and Ms Melani Mesli. Dr Lepland co-coordinated, and continues to do so, the research activities associated with the ICDP FAR-DEEP programme. The FAR-DEEP cores are archived at the Norwegian Geological Survey and Dr Lepland has actively encouraged and supported researchers to continue using the cores for scientific studies that are continuing to this day. Ms Mesli was FAR-DEEP's Core and DIS manager, and has more than 10 years' experience supervising the sample numbering and archiving of FAR-DEEP data using the DIS. As back-up, she will be aided by Dr Catherine Rose who will also be trained in the use of DIS and ICDP data management protocols. This example shows that such a centralised core repository can work exceptionally well and we envisage the same smooth operation for GRIND-ECT cores at the BGR. Mr Jochen Erbacher, Head of Unit of Stratigraphy and Collections at the bGR has agreed its use by GRIND-ECT; see letter on the following page.

Having the BGR as a centralised repository for all GRIND-ECT cores will mark the first step towards meeting the goal of creating a global core archive and network for ICDP-sponsored on-shore continental scientific drilling that will match in scope and scale that of the IODP.

BGR

Bundesanstalt für Geowissenschaften und Rohstoffe
Federal Institute for Geosciences and Natural Resources

Bundesanstalt für Geowissenschaften und Rohstoffe
Postfach 51 01 53, 30631 Hannover

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St Andrews, Scotland/UK, KY16 9AL

Prepared by
Dr. Jochen Erbacher

GRIND-ECT: Geological research through Integrated Neoproteorozoic Drilling – the Ediacaran-Cambrian Transition

Direct dial +49 511 643-2795

Hannover, 03.01.2018

e-mail: erbacher@bgr.de

Dear Prof. Prave,

this is to confirm the possibility to store the drillcores retrieved during the drilling campaigns of **GRIND-ECT** in our core repository in Berlin-Spandau, Germany. The core repository is regarded as a central research facility in Germany, accessible for international scientists to do research and education. Our facility has the capacity to store the cores and we are able to offer access to modern, lab-facilities for non-desctructive drill core investigations such as Multi Sensor Core Loggers and an XRF-Scanner.

Best regards

Jochen Erbacher
(Head of Unit, Stratigraphy and Collections)

Office
GEOZENTRUM HANNOVER
Stilleweg 2
30655 Hannover
How to reach BGR
tram no. 7 to Pappelwiese

Telephone
+49 511 643-0
Telefax
+49 511 643-
E-Mail
Poststelle@bgr.de
Internet
http://www.bgr.bund.de

Banking details
Bundeskasse Halle
Deutsche Bundesbank - Filiale Leipzig
IBAN:
DE38 8600 0000 0086 0010 40
SWIFT-BIC:
MARKDEF1860

Tax number
Tax payer number at the local tax office, Hannover North:
25/202/27510
V.A.T.-ID:
DE 811289832

Appendix 5. Additional information on data and sample management and Science Themes
The science management and coordination plan (Section 5) will ensure that scientific collaboration occurs efficiently between the Brazilian, Chinese and Namibian projects. Noteworthy is that research activities are not site or country specific but instead are driven by Research Foci addressed via five Science Themes, which will require concerted integration of information across all Themes using the core records of the three nations. Each Theme will consist of both established and early-career researchers, with Theme coordinators who will ensure both clear and open communication and efficient incorporation of data between Themes. Communication will be further optimised by field trips to drill sites and meetings held at the major geoscientific conferences in South America (organised by Co-I Trindade), United States and Africa (organised by co-I Macdonald), and in Europe (organised by Co-I Rose). We will also maintain a website that posts up-to-date progress of drilling (mirroring the daily updates used by FAR-DEEP).

To further ensure effective and efficient running of GRIND-ECT, during the drilling, coring, and sampling and characterisation activities, there will be weekly to bi-weekly conference calls between all Central Science Team members. Management efficiency is attained in that CST members are also Heads of Operations, overall Coordinator of the Science Themes and the DIS Data Management and Outreach Coordinators; these individuals have been identified and are:

- Chair, Central Science Team: Tony Prave
- Head of Operations Brazil: Ricardo Trindade
- Head of Operations China: Maoyan Zhu
- Head of Operations Namibia: Karl Heinz Hoffmann
- Science Themes Coordinator: Francis Macdonald
- DIS and Data Management Coordinators: Dan Condon, Melanie Mesli, Catherine Rose
- Outreach and Education Coordinators: Dan Condon, Catherine Rose

Overseeing and coordinating the core sampling and DIS data management are key jobs. GRIND-ECT is fortunate in that Ms Melanie Mesli, the previous DIS operator and Core Manager for ICDP's FAR-DEEP programme, has agreed to take on the same role for GRIND-ECT. DIS Data Management and archiving is central to GRIND-ECT and consist of two main components. The first is ensuring data management and archiving of all sample and core information in DIS. The second will be to integrate that information with federated and international databases (*e.g.* EARTHTIME, NIGPAS's GBDB, USA's PBDB) for open-access to the worldwide scientific community.

Science Themes. The five Science Themes will be managed by a respective Coordinator (Appendix 6; Section 5, Fig. A). Brief descriptions of each Theme are given below and Figure A7 shows a schema of how each Theme is linked to the three Research Foci of Section 1.

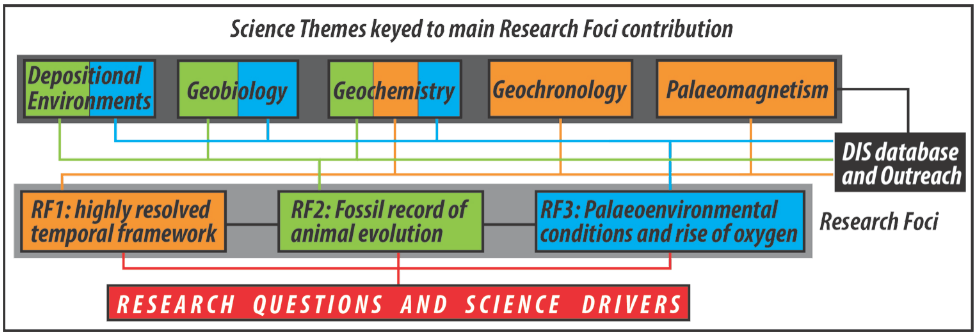

Figure A7. Science Themes and their links to the three main Research Foci. All data will be integrated and coordinated through DIS and incorporated into outreach and educational training activities.

Depositional Frameworks – Coordinator: Macdonald. The Depositional Frameworks Theme will be tasked with inferring palaeoenvironmental settings and developing stratigraphic frameworks for each of the cores and establishing how those correlate with stratigraphies developed from outcrop studies. This goal will be accomplished through standard sedimentological techniques and enable construction of a 3-D model of palaeoenvironmental information. This information will provide fundamental geological context (*e.g.* depositional settings, lateral and vertical facies changes) within which all geochemical, isotopic and palaeontological data will be considered. In addition, Theme members will work iteratively on constructing regional and global correlations by integrating sedimentological and stratigraphic information with the data generated by all other Science Themes.

Geobiology – Coordinator: Bosak. The Geobiology Theme has expertise in identifying and developing macro-, micro- trace-fossil and biomarker records for Precambrian time. All fossil and biomarker work will be integrated tightly within chronostratigraphic frameworks constrained with the new geochronological data obtained in *RF1*. It is unlikely that complete macrofossils will be encountered in core but partial macrofossils no doubt will. Promising strata will be macerated or dissolved for study of microfossils. Bioturbation will also be assessed in cores via CT scanning (see Appendix A1.1) and compared to surface outcrops to establish patterns of bioturbation (and their changes) through time. First and last appearance datum for all fossils will be established in coordination with the Depositional Frameworks and Geochronology Themes. Fossil and biomarker data will be integrated with the Geochemical Theme to address ecological changes, particularly, across large C-isotope excursions, facies changes and changes in redox proxy data, to assess linkages with respect to processes driving local and global environmental changes. Biomarker work will focus initially on the Brazilian cores because many of the Namibian and Chinese localities are thought to be over-mature. Biomarker data are complementary to body fossils and inorganic geochemical proxies and can yield information about, for example, dominant primary producers in marine ecosystems and used to track changes in the importance of cyanobacteria, rhodophytes and chlorophytes, or the abundance of sponges and predatory protists (Brocks et al. 2015). Temporal changes in the modes of marine primary productivity and predation will be investigated via lipid profiles to track microbial community structure variance and combined with biomarker redox parameters to provide independent redox proxy data to compare/contrast to those generated by the Geochemistry Theme.

Geochemistry – Coordinator: Kasemann. The Geochemistry Theme will generate time-series records of major and minor element abundances as well as a suite of traditional and non-traditional isotope and redox proxies profiles for each of the cores. These will be used to provide constraints on the major biochemical cycles (*e.g.* C, S, N, P) and oxidation state (*e.g.* δ^{98}Mo, Fe-speciation) of surface environments. Diagenesis will also be assessed robustly, and in-concert with the Depositional Frameworks and Palaeomagnetism Themes, as per screening techniques outlined in Section 1 and Appendix 1.2. All geochemistry data will be integrated with the Geobiology Theme to interpret the nature of isotope excursions and the effect on oxidant budgets. Isotope data (*e.g.* δ^{13}C, δ^{11}B, ^{87}Sr/^{86}Sr) have been a rich source of ideas for the Neoproterozoic Earth system and new isotopic and geochemical data will be used to construct high-resolution profiles (cm- to m-scale sample spacing) through key stratigraphic intervals archiving the conditions leading into, through and in the immediate aftermath of the ECT. Integration of the core-derived geochemical data, in combination with appropriate published data, with the Geochronology Theme's age models will enable determining rates and durations of isotopic and geochemical excursions and gain insights into weathering and nutrient delivery (*e.g.* changes in δ^{7}Li, δ^{44}Ca, ^{87}Sr/^{86}Sr), organic productivity and burial (*e.g.* changes in δ^{13}C, δ^{34}S, δ^{11}B) and redox and oceanic alkalinity (*e.g.* changes in δ^{13}C, δ^{34}S, δ^{44}Ca, δ^{98}Mo, Fe-speciation) through the ECT.

Geochronology – Coordinator: Condon. The Geochronology Theme will focus on the development of age models for the cores and their correlative outcrop sections, inclusive of all associated palaeontological and geochemical archives that will be integrated temporally with one another and to coeval sections worldwide (*e.g.* Oman, Newfoundland, Eastern European Platform). The Theme will use established radio-isotopic dating methods, primarily U-Pb (zircon) dating of volcanic ash beds and Re-Os dating of organic-rich sedimentary rocks. Each of the intervals targeted are known to contain ash beds datable by U-Pb (zircon) methods and, as noted previously, many additional un-dated tuff horizons can be identified in cores relative to outcrop exposures (*n.b.* previous experience by project PIs confirm that the amount of material in a core contains enough zircon for U-Pb dating). Organic-rich intervals will also be dated via Re-Os methods. The Theme will interface with all other Themes to provide robust temporal frameworks for sequence stratigraphy, chemostratigraphy (*e.g.* δ^{13}C, ^{87}Sr/^{86}Sr), and cyclo- and magneto-stratigraphy (*e.g.* geomagnetic polarity reversals) to inform on rates, durations and timings of all processes and events.

Palaeomagnetism – Coordinator: Trindade. The Palaeomagnetism Theme will focus on developing magnetostratigraphic data to determine ferromagnetic mineralogy through rock magnetic experiments. There has recently been increased interest in the nature and behaviour of the geomagnetic field during the Ediacaran to Cambrian time slab. A recent magnetostratigraphic study conducted on late Ediacaran sediments in the southern Urals was interpreted to indicate more than 20 reversals per million years (Bazhenov et al. 2016). Newly constrained values for the thermal conductivity of Earth's core predict a late onset of inner core growth and such magnetic field hyperactivity may be a consequence (Smirnov et al. 2016). Further, this interval of hyperactive reversals could have significant chronostratigraphic value if found in drill core and correlated globally. The Palaeomagnetism and Geochronology Themes will work closely together to establish age models for magneto-stratigraphic data and an associated reversal timescale through the cores. The advantage of drill core for magnetostratigraphic studies is that they provide a relatively continuous record of the geomagnetic field through time, enabling direct correlation with chronostratigraphic and biostratigraphic markers and geochemical proxies, while avoiding surface alteration of magnetic carriers (see Appendix 1.1). Palaeomagnetic study will be particularly focused on the core from Brazil where robust Neoproterozoic palaeomagnetic poles have been previously acquired. Oriented core will also be acquired in Namibia and China, although these rocks may have a magnetic overprint acquired during subsequent tectonothermal events (*e.g.* Meert et al. 1997). To chances of obtaining primary magnetic carriers are maximised with the targeted core intervals because they have varying rock types, each of which would have been variably effected by fluid flow hence differing levels of authigenic clays that may (or may not) have led to magnetite authigenesis. Further, post-depositional remagnetisation from fluids results in alteration that can influence redox proxies such as Fe-speciation. Consequently, the Palaeomagnetism Theme will work with the Geochemistry Theme to contribute understanding to diagenetic overprints and processes.

Data Management – Coordinators: Condon, Mesli, Rose. Grind-ECT will use the ICDP's Data Information System (DIS) for all data obtained in describing, cataloguing and analysing the core and core samples. Dr Aivo Lepland, member of the Advisory Group, coordinated the data management for the highly successful ICDP FAR-DEEP programme and he will help oversee this activity with Ms Melanie Mesli, who was the DIS and Core Manager for FAR-DEEP. We will also utilise the GEOCHRON database (www.geochron.org) for all geochronological data and EARTHTCHEM (www.earthchem.org) for other geochemical data. All data management schemes will use IGSN so that data and metadata can be linked back to specific samples within the cores. Noteworthy is that our partner organisation, the BGS, has an established track record in developing data management systems and that expertise is available through Science Team member Dr Dan Condon, including liaising to use NIGPAS's GeoBiology Diversity Database and the USA's PaleoBiology Data Base.

Outreach and Education – Coordinators: Condon, Rose. Outreach and Education provides capacity building in each country through a programme that is focused on a suite of key deliverables noted above and in Section 6: training early-career geoscientists, public educational outreach, in-country capacity building, museum exhibits, research Workshops, scientific community, and press releases and social media. All these activities will be coordinated by Central Science Team member's Drs Dan Condon and Catherine Rose.

Appendix 6. GRIND-ECT research network

Below is a non-exhaustive list of collaborating scientists who were present at the ICDP Workshop, actively support this GRIND-ECT proposal and, with their own research groups, will be involved conducting the science to achieve Research Foci 1-3. These collaborators are organised according to Science Theme. * denotes Theme Coordinators.

Name	**Institution**	**Country**
	Depositional Frameworks	
Paulo Boggiani	Universidade de São Paulo	Brazil
Galen Halverson	McGill University	Canada
Karl Heinz Hoffmann	Geol. Survey Namibia (ret.)	Namibia
Ganqing Jiang	Univ. Nevada Las Vegas	USA
Francis Macdonald*	Harvard University	USA
Tony Prave	University of St Andrews	UK
Catherine Rose	University St Andrews	UK
Ute Schreiber	Geol. Survey Namibia	Namibia
Garneth Shamaila	Geol. Survey Namibia	Namibia
Emily Smith	Johns Hopkins	USA
Justin Strauss	Dartmouth	USA
Maoyan Zhu	Nanjing Inst. Geology, Paleontology and Strat.	China
	Geobiology	
Tanja Bosak*	Mass. Institute of Technology	
Jochen Brocks	Australian National University	Australia
Louis Buatois	University of Saskatchewan	Canada
Nick Butterfield	University of Cambridge	UK
Phoebe Cohen	Williams College	USA
Mary Droser	UC Riverside	USA
Douglas Galante	Brazilian Synchrotron Lab	Brazil
Mark LaFlamme	University of Toronto	Canada
Juliana Leme	Universidade de São Paulo	Brazil
Alex Liu	University of Bristol	UK
Gordon Love	Univ. California-Riverside	USA
Jack Matthews	Oxford University	UK
Susannah Porter	UC Santa Barbara	USA
Sara Pruss	Smith College	USA
Erik Sperling	Stanford	USA
Roger Summons	MIT	USA
Detlef Walde	University of Brasilia	Brazil
Rachel Wood	University of Edinburgh	UK
Shuhai Xiao	Virginia Tech	USA
Maoyan Zhu	Nanjing Inst. Geology, Paleontology and Strat.	China
	Geochemistry	
Magali Ader	Institut de Physique du Globe de Paris	France
Christian Bjerrum	University of Copenhagen	Denmark
Jacinta Enzweiler	Univer. Estadual de Campinas	Brazil
David Fike	Washington University	USA
Romain Guilbaud	University of Cambridge	UK
David Johnston	Harvard University	USA
Simone Kasemann*	University of Bremen	Germany
Jay Kaufman	University of Maryland	USA
Cao Li	Chinese University of Geosciences	China
Hongfei Ling	Nanjing University	China

Melina Macouin	Geosciences Env. Toulouse	France
Simon Poulton	University of Leeds	UK
Graham Shields	University College London	UK
Noah Planavsky	Yale University	USA
Pierre Sansjofre	Univ. Bretagne Occidentale	France
Yusuke Sawaki	Tokyo Inst. of Technology	Japan
Jan Środoń	Inst. Geol. Sci. Polish A. Sci.	Poland
Nick Tosca	University of Oxford	UK
Xiangkun Zhu	Institute of Geology, CAGS	China
	Geochronology	
Marly Babinski	Universidade de São Paulo	Brazil
Dan Condon*	British Geological Survey	UK
Xianhua Li	Institute of Geology and Geophysics, CAS	China
Jahan Ramezani	Mass. Institute of Technology	USA
Alan Rooney	Yale University	USA
Mark Schmitz	Boise State University	USA
	Palaeomagnetism	
Dave Evans	Yale University	USA
Joe Kirschvink	Caltech	USA
Joe Meert	University of Florida	USA
Tim Raub	University of St Andrews	UK
Nick Swanson-Hysell	UC Berkeley	USA
Ricardo Trindade*	Universidade de São Paulo	Brazil
Shihong Zhang	Chinese University of Geosciences	China
	Advisory Group	
Aivo Lepland	Geological Survey of Norway	Norway
Bruce Levell	Oxford University	UK

Appendix 7. Risk Assessment Matrix

Risk #	Description	Likelihood	Impact	Risk	Mitigation	Likelihood	Impact	Risk
1	Permit delays or changes in operator	High	Low	Moderate	The drilling programme comprises 13 holes in three countries with contingency sites identified. This provides flexibility.	Moderate	Low	Low
2	Budget over-run	Moderate	Moderate	Moderate	Low cost of drilling and experienced contractors; good control of drilling depths from outcrops; 20% budget contingency.	Moderate	Moderate	Low
3	Missing 3rd party co-funding	Moderate	High	Moderate	Different national agencies involved reducing risk of default. Funds required from each agency is low (<$200k), providing flexibility.	Moderate	Moderate	Moderate
4	Unexpected geology	Moderate	Moderate	Moderate	Multiple short holes; excellent outcrop control.	Moderate	Low	Low
5	Missing or short supplies of services, equipment, water	Moderate	High	Moderate	Drilling sites chosen considering best infrastructure in each country, including proximity to services and water. Operators in each country have experience in drilling areas.	Moderate	Moderate	Low
6	Mis-coordination	Low	Moderate	Low	Clear scientific targets; communication between PIs; workshops with involved teams.	Low	Low	Low
7	Miscommunication in Science Team	Moderate	Moderate	Moderate	Continuous communication between PIs and science teams; meetings before each drilling operation; detailed planning of priorities	Low	Low	Low
8	Mis-coordination between activities in each country	Moderate	High	Low	Independent teams will operate in each country; project schedule is flexible to enable coordination of activities between countries	Moderate	Moderate	Low
9	Poor planning of operations and on-site data acquisition	Moderate	High	Moderate	Operations run by experienced contractors; pre-drilling workshop for training and definition of standards for scientific teams that will follow operations and optimise on-site science.	Moderate	Moderate	Low
10	Problems during drilling	Low	Moderate	Low	Daily detailed drilling plans and communication between contractor and on-site science team.	Low	Low	Low