**Project title (acronym):** Centre for Planetary Habitability (PHAB)

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**Principal Investigators (PIs) with submitted CV's**

| | |
|---|---|
| Clinton Phillips Conrad | (PI: Water) |
| Carmen Gaina | (PI: Tectonics) |
| Anne Hope Jahren | (PI: Atmosphere) |
| Lee Hsiang Liow | (PI: Life) |
| Trond Helge Torsvik | (PI: Climate) |
| Stephanie Christine Werner | (PI: Interior) |

**Choose primary (1) sub-committee. If relevant, choose also secondary (2) sub-committee:**

Humanities and Social Sciences ☐ Life Sciences ☐ Natural Sciences and Technology ☒

## Project summary:

The idea that worlds around other stars could develop and maintain environments hospitable to life — in a way similar to our planet — has captivated scientists for centuries. Yet, to investigate this question, we must *recognize and characterize the key conditions that make a planet habitable*. This endeavour is the prime objective for the proposed Centre for Planetary Habitability (PHAB).

The only planet on which life is known to have originated (Earth) appears unique in many ways, including the presence of abundant surface water, a large moon, a long-lived magnetic field and plate tectonics. Yet, which of these and other characteristics are essential for its long-term habitability? Equally, how have Earth's physical and chemical attributes, and thus our planet's proclivity for life, evolved? How can we recognize distant worlds around other stars that have been or could be habitable? These questions, and a new understanding of planetary habitability unfolding from them, are especially important as we now embark on an unprecedented era of exploration and discovery of extra-solar planetary systems.

PHAB will holistically explore the formation and evolution of star-planet systems with the Solar System and the Earth-Moon couple as reference and focus. Our research activities will comprise three interrelated research themes: (1) Planets and Early Earth, (2) Modern Earth and (3) Exo-Earths. Knowledge collected from Earth and other rocky planets in the Solar System will enable us to recognize the key conditions for planetary habitability and to develop predictive models to identify habitable planets around other stars.

A Centre dedicated to research on the habitability of star-planet systems will be *the first of its kind in Norway*. We are a uniquely cross-disciplinary and complementary team. Because the foundation of our work will be built on the world we know the best (Earth), our endeavour will be unique worldwide.

## Primary objective

Recognize and characterize the key conditions that make a planet habitable

## Secondary objectives

[1] Establish absolute timelines for key events in the Solar System
[2] Characterize the initial physical and chemical conditions of habitability for life as we know it
[3] Explore how a planet's composition and interior influence its ability to nurture a biosphere
[4] Unravel correlative versus causal relationships among biotic and abiotic time-series
[5] Identify the drivers for greenhouse versus icehouse conditions
[6] Understand life-threatening tipping points and the fragility of habitability
[7] Recognize planets around other host stars that are or were potentially habitable

# 1.1 Excellence: Novelty

## The Challenge

**Planetary habitability is a measure of a planet's potential to provide environments hospitable to the life that we know, and commonly defined by the presence of liquid surface water. However, a planet's orbital parameters, surface and interior temperature, interior composition and dynamics, surface tectonic style, magnetic field, rotation rate and tilt, atmospheric composition and density, water mass fraction, as well as the type, age and elemental composition of its host star (location in the galaxy), are all key to its habitability. Importantly, habitability is *time-dependent*. Our presently habitable planet was not originally in the "Habitable Zone" — and will fall outside it again in the far future.**

The transience and fragility of habitability is engraved in our own planetary history. After the Sun formed, followed by the first solids 4.567 billion years ago[1], a proto-planetary disc coalesced and evolved from gas and dust to planetesimals and planetary embryos. Through violent collisions, these objects grew to form Earth and the other planets within a relatively short time interval (30-60 million years). Shortly thereafter, our young planet seems to have collided with another massive proto-planet, leading to a circum-terrestrial disc of ejecta that gave rise to our Moon[2]. Following those dramatic formative events, a fast-spinning Earth retained enough heat to keep most of the mantle molten for tens of millions of years; this regime and further impact bombardment (albeit with declining intensity) probably made Earth uninhabitable for some unknown time.

The Earth-Sun distance and the present inventory of atmospheric greenhouse gases make the current surface temperatures optimal for complex life, but with a much fainter Sun in the deep past (by ~30%), early Earth was not at an ideal distance from the Sun (Fig. 1). Instead, *a dense greenhouse atmosphere*[3] *probably saved us from runaway cooling and permanent icehouse conditions.* Mars was once wetter and (arguably) warmer, but is now a permanent icehouse, whilst Venus has been a hothouse for an unknown time. These planetary siblings lack surface water, a long-lived magnetic field and plate tectonics, factors we consider to be key elements for long-term habitability. Additionally, the complex multicellular life we know requires an oxygenated atmosphere not identified elsewhere in the Solar System. It follows that the question, *what makes a planet habitable* (Fig. 1), can be recast as *what makes Earth unique?*

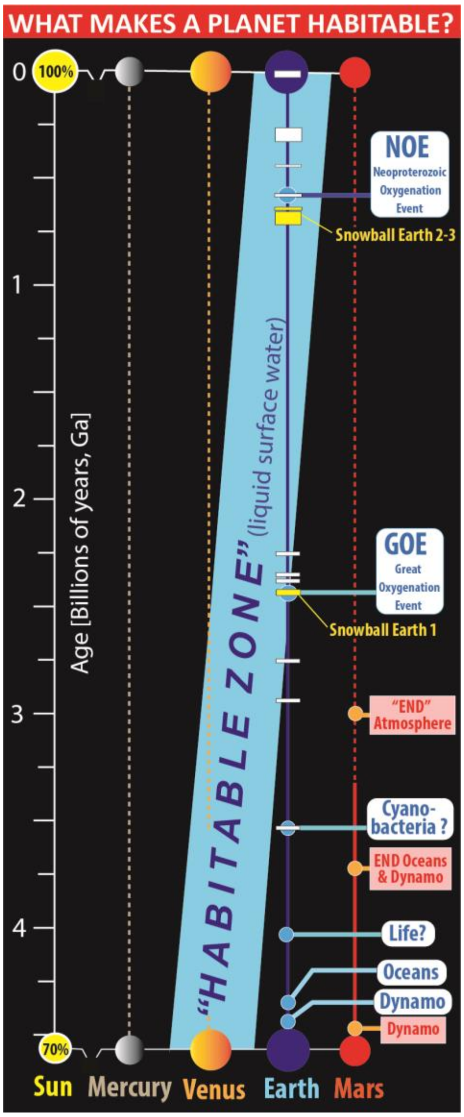

**FIGURE 1.** The *"Habitable Zone"*, known icehouses (horizontal white bars) and three Snowball Earth conditions (horizontal yellow bars) when the Earth was almost fully glaciated.

Earth's habitability may have resulted from a chain of singular events. Yet, the most fundamental characteristics of its habitability are debated, and a *major challenge* is that habitability factors vary because they are *time-dependent* due to changes in the Sun's energy and our planet's chemical, thermal and (thereby) physical and tectonic evolution. An in-depth knowledge of *Earth-like habitability*, and how our planet sustained conditions for life's evolution over geological time-scales, is critical for identifying habitable planets around other stars. A new understanding of planetary habitability is especially important and *timely* as we now embark on an unprecedented era of exploration of extra-solar planetary systems.

## A Habitable Planet: Knowns and Unknowns

When the Earth is viewed from space on a cloudless day, the most visible features are continents, icecaps and especially the oceans. This water was likely delivered by chondritic meteorites during the earliest phases of planetary accretion**,** but some water may also have been delivered and/or removed during the Moon-forming event[4] and by later impacts. Water is life's medium, but the constellation of environmental conditions that allowed life to arise from inanimate matter via abiogenesis is still among the greatest unknowns in science. Unless life was delivered from elsewhere, it should have developed in the first half billion years between Earth's formation and the age of the oldest hints of its existence (~4.1 Ga)[5]. The breathable air we enjoy today was produced much later by cyanobacteria — the inventors of oxygenic photosynthesis — whose evolutionary ancestry is hidden within this early period. Although exactly when oxygenic photosynthesis began is debated, the evolutionary emergence of cyanobacteria and their production of atmospheric oxygen[6] appears to be due to biological innovation, as well as geological evolution.

Earth is singular amongst the rocky planets in the Solar System, including having a *long-lived* magnetic field, a *large* satellite (our Moon), and not the least *plate tectonics* (Fig. 2A).

Plate tectonics regulates interior temperatures, but also atmospheric greenhouse gas concentrations and surface temperatures via sources (mainly volcanic $CO_2$ degassing) and sinks (silicate weathering and carbonate deposition). Subduction enables recycling of volatile elements between the surface and the mantle and is probably essential for sustaining planetary habitability. Plate tectonics has not been identified on other terrestrial planets where cooling largely occurs by conduction through a stagnant lid (Fig. 2B). Because the questions of *when*, *why* and *how* plate tectonics started are debated[7], an improved understanding of Earth's evolution is critically needed.

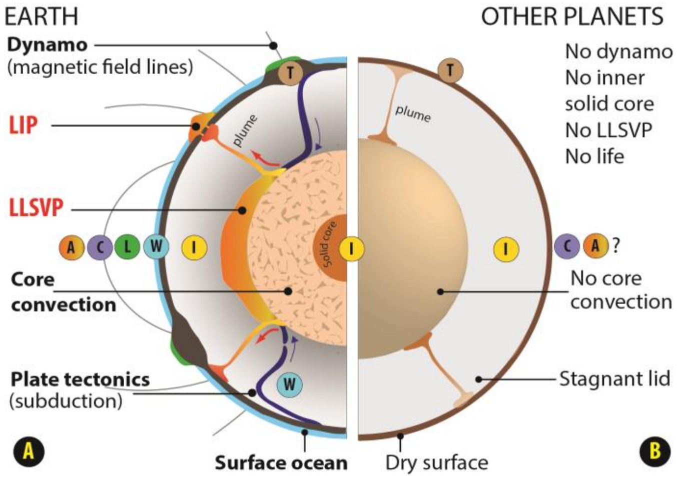

**FIGURE 2 (A)** On Earth, the only known habitable planet, plate tectonics stabilizes the long-term climate and a magnetic field protects us from cosmic radiation. Volcanism and volatile degassing are linked to plate tectonics or Large Igneous Provinces (LIPs) sourced by plumes from the margins of two antipodal thermochemical piles in the deep mantle[8,11] (LLSVPs). **(B)** On other planets, a stagnant lid insulates the interior, plumes form randomly, there is no magnetic field, water/hydrogen has been lost to space, the surface is dry/uninhabitable, an inner solid core may not have evolved, and water and life-components can be missing. An atmosphere can also be lost (Mercury) or very thin (e.g. Mars). PI's oversee specific research topics: I=Interior (mantle/core); W=Water; T=Tectonics, A=Atmosphere; L=Life; C=Climate.

Terrestrial planets contain central metallic cores surrounded by rocky mantles, but Earth has additional features, e.g. two large antipodal thermochemical piles (LLSVPs: Large Low Shear-wave Velocity Provinces) in its lowermost mantle (Fig. 2A). PHAB scientists have established that these piles are hundreds of million years old, ~~that they control global mantle flow~~, and that their margins are preferred initiation sites of deep mantle plumes[8,9]. Their surface expressions include episodic climate-altering eruptions of large igneous provinces (LIPs, Fig. 2A), and a causal link between plume-related volcanism and mass extinctions has long been postulated[10]. Plume activity can also alter the tectonic setting by creating and modifying plate boundaries, changing the paleogeography and thus the long-term climate forcing[11].

## Primary Objective

The *primary objective* is to ***recognize and characterize the key conditions for planetary habitability*** that permit the continued survival and evolution of diverse life forms as we know it. Because habitability is a requirement for life, the issue of habitability (PHAB's objective) supersedes origin-of-life theories by encompassing the necessary conditions for the generation, survival and continued evolution, of life.

The search for Earth-like habitability must be directed towards planets in other star-planet systems. An important PHAB activity is therefore to advance comparative planetology beyond the Solar System to identify habitable planets around other stars. This is indisputably ***ambitious***. PHAB will address existentialistic research questions such as "*What makes a planet hospitable? Why is Earth the only planet with life in our Solar System? How can we recognize habitable exo-planets?"* The prime strength is our Earth-based perspective on interpreting planetary/astrophysical observational data. All PIs have proven abilities to produce ***ground-breaking research*** within and across their respective fields — and expanding our Earth System for identifying Exo-Earths that are (or were) potentially habitable — is conceptually distinctive and ***novel***.

## Research Themes and Work-packages

PHAB activities comprise three interlocked research themes: (1) Planets and Early Earth, (2) Modern Earth and (3) Exo-Earths, structured in work-packages, each headed by two PIs (Table 1). Each PI also fronts a triplet of interconnected research topics: tectonics, interior, atmosphere, climate, water, and life (Figs. 2, 3). PIs expertise cover all of the planetary domains, including the biosphere, and demonstrates the multi-disciplinary nature and complementarity.

We have defined *seven secondary objectives* (***SO 1-7***; front page) and most cut across research-theme (RT) and work-package (WP) boundaries. Each WP include activities defining deliverables, intermediate goals or milestones. Computational modelling is central to almost all PHAB activities, but we will undertake extensive Earth-based fieldwork and are currently engaged in three ESA space missions: ExoMars (launch 2022), PLATO[12] (2026: PI is *Rauer* and Chair of our Scientific Advisory Board, Table 2) and Ariel[13] (2029: PI is collaborator *Tinetti*).

## RESEARCH THEME 1: PLANETS AND EARLY EARTH

Addresses planet formation, evolution and comparative planetology to identify the initial conditions for habitability and how a planet's composition and interior influence its ability to nurture a biosphere (*SO 2-3*). Fundamentally, this requires accurate timelines (*SO 1*) to constrain critical changes in the environment and climate, and for Earth specifically, the conditions for early life and Earth's evolution as a habitable planet.

***WP1.1 Timelines.*** Reliably dated and well-localised rocks are only available from the Earth and Moon. Temporal constraints for other planetary bodies mostly rely on cratering-based age-determination, calibrated at the Moon and extrapolated to the solid surfaces of other Solar System objects. Since the pioneering works of Shoemaker, Hartmann and Neukum in the 1970s, PHAB scientists[14-15] have overhauled this dating technique significantly and created a new *crater clock*. New and revised radiometric ages of the Moon, and modern planet formation models ***(WP1.2)***, requires that existing cratering-based ages must be corrected. Mercury and Mars record the early Solar System impact history, but further exploration of the Moon is fundamental to describe the bombardment history and to use the crater clock to derive the correct timing beyond the Earth-Moon system. This will reveal modified timing of major changes in the orbital architecture of our Solar System ***(WP1.2/3.2)***, volatile delivery by small bodies (asteroids/comets; ***WP1.2***), any derived date and rate on the Solar System solid-surface bodies, and timing of the earliest possible life ***(WP1.8)***.

**Table 1.** Research Themes (1-3), WPs and responsible PI's: C=Conrad; G=Gaina; J=Jahren; L=Liow; T=Torsvik; W=Werner.

**Research Theme 1 PLANETS/EARLY EARTH**
WP1.1 Timelines (T, W)
WP1.2 Planet Formation (W, T)
WP1.3 Atmosphere Evolution (W, J)
WP1.4 Early Oceans (C, W)
WP1.5 Magnetic Fields (T, G)
WP1.6 Tectonic Regimes and Interior (G, C)
WP1.7 Snowball Earths & Tipping Points (T, W)
WP1.8 Conditions for Early Life (L, W)

**Research Theme 2 MODERN EARTH**
WP2.1 Plate Tectonics & Paleogeography (G, T)
WP2.2 Volatile Cycles (C, G)
WP2.3 Paleoclimate Proxies (J, T)
WP2.4 Paleoclimate Models (T, G)
WP2.5 Drivers of Biodiversity (L, J)

**Research Theme 3 EXO-EARTHS**
WP3.1 Observational Constraints (W, C)
WP3.2 Exo-Planet Formation (W, C)
WP3.3 Exo-Planet Structure (C, W)
WP3.4 Exo-Planet Evolution (W, T)
WP3.5 Fate of Habitable Planets (T, C)

***ACTIVITIES:* [1]** *Calibrate and correct the cratering chronology model based on re-interpretation and new (U-Pb) lunar sample ages.* ***[2]*** *Radiometric age determinations of meteorites to derive input parameters for* ***WP1.2/1.7****.* ***[3]*** *Age determination of geological units by crater statistics to constrain the rate of processes in the inner Solar System.* ***[4]*** *Establish routines for analysing tiny samples (e.g. U-Pb, Ar-Ar dating) in preparation for a Mars Sample Return Mission (~2030).* ***[5]*** *Precise radiometric ages for key Earth geological units* ***(WP1.5-7/2.1)****.*

***WP1.2 Planet Formation*** (in the Solar System). How planets form is a long-standing puzzle. Theories range from instantaneous formation of giant planets by collapse due to gravitational instabilities in the protoplanetary disc, to accretionary models that build planets step-wise, beginning with the coalescence of planetesimals to planetary embryos followed by more massive cores resulting from embryo mergers and finally gas envelope accretion[16]. The Earth likely formed by the accretion process. Recent models propose rapid growth of embryos and full-fledged planets from pebble-sized fragments drifting sunwards (i.e. pebble accretion), yet it is unclear whether Earth could have been built by this process. These models variably succeed to explain the intrinsic compositional differences ("dichotomy") observed between the inner and outer Solar System[17]. The key for unravelling our system's history and architecture relies on nucleosynthetic isotope tracers and elemental abundances in extra-terrestrial samples, tracking the amount of mixing and migration during planet formation. The heliocentric compositional dichotomy was likely imposed by a radial barrier caused by the early gas giants (Jupiter, Saturn). *PHAB will use state-of-the-art planetesimal and pebble accretion models to numerically investigate giant and terrestrial planet formation to better constrain reservoir mixing.* Our simulations will be benchmarked by the documented cosmochemistry of Solar System samples. We will explore the parameter space of forming the Earth wet, dry or very dry, by investigating the role of giant impacts and their effects on Earth's evolution and habitability. This also provide clues for Exo-Earth formation in systems with (and without) giant planets ***(WP3.2)***, and outcomes that best match the inner Solar System will serve as input for long-term terrestrial bombardment flux estimates (***WP1.1***), as well as revealing pathways for volatile delivery ***(WP1.3/1.4)***.

***ACTIVITIES:* [1]** *Reconstruct the Solar System by modelling of (i) planetesimal and (ii) pebble accretion with both in-house CPU and GPU N-body integrators with constraints from extra-terrestrial samples* ***(WP1.1)****.* ***[2]*** *Extract bombardment flux from these simulations for extending cratering chronology beyond the Earth-Moon* *couple **(WP1.1)**. **[3]** Fuse cosmochemical abundances and flux models **(WP1.3/1.4)**. **[4]** Quantify effects of giant impacts on Earth's habitability **(WP1.1)**. **[5]** Investigate plausible dynamic explanations for the origin of heliocentric compositional gradients by additional analysis of stable isotope nucleosynthetic tracers as well as element ratios and volatile content **(WP1.3/1.4)**.*

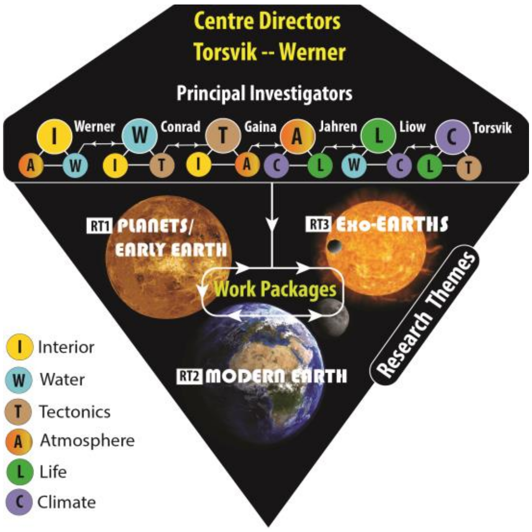

**FIGURE 3.** Project and management structure.

***WP1.3 Atmosphere Evolution.*** *Primary* atmospheres are composed of captured gas of solar composition (H, He), but magma oceans and early volcanic degassing on the terrestrial planets led to *secondary* atmospheres dominated by greenhouse gases, partly preserved on Venus (dense $CO_2$) and Mars (extensive atmospheric loss). Atmospheres are modified by a multitude of processes, including biological innovation on Earth. Photosynthetic $O_2$-production oxygenated the Earth's reduced atmosphere, and a critical milestone, the Great Oxygenation Event (Fig. 1), was reached at ~2.4 Ga. This was the ancestor of our present air, but it took almost two billion years of biotic modulation and abiotic interactions to increase $O_2$ levels to modern values (Fig. 5C).

PHAB will explore Earth's atmospheric evolution by carbon-cycle modelling, combined with sample analysis of the geological record and geochemical proxies for the past four billion years. The composition of Earth's earliest atmosphere is obscured by the fact that the oldest preserved (dated) rocks of sedimentary origin are only ~3.8 Ga. PHAB must therefore rely on modelling based on a combination of ab initio calculations, machine-learning and atomistic simulations at different length and time-scales, combined with thermodynamic calculations and chemical considerations to explain the chemical trajectory of the Hadean atmosphere (≤4 Ga).

The atmospheric evolution of other Solar System planets can partially be reconstructed from preserved landforms and surface minerals studied by remote sensing, or data from samples collected by Mars rovers. During PHAB's life-time, several missions to Venus and Mars will provide publicly available data to constrain original atmosphere mass and composition and allow us to derive planetary evolution models. PHAB will also date climate changes on Mars (landforms and mineral surface exposures by crater statistics) and evaluate the driving forces for volatile cycles on the terrestrial planets.

***ACTIVITIES:*** ***[1]*** *Estimate volatile delivery from small-body dynamical evolution modelling **(WP1.2)** **[2]** Model magma ocean degassing and formation of early Earth's secondary atmosphere by ab initio calculations and machine-learning. **[3]** Reconstruct Earth's atmosphere (carbon-cycle modelling) under different tectonic/weathering regimes, benchmarked by available proxies. **[4]** Develop volatile cycles for the early Earth, using Mars or Venus as endmember analogues with respect to temperature/water partial pressure. **[5]** Reconstruct atmosphere evolution for Venus-Earth-Mars through analyses of chemical networks.*

***WP1.4 Early Oceans.*** Water could have arrived early in the terrestrial planet formation process, during the accretion of meteoritic building blocks, and formed reservoirs of dissolved hydrogen in the magma ocean(s). Subsequent volcanic degassing led to the generation of a secondary atmosphere (***WP1.3***) and condensed water (freshwater, ice, oceans) on Earth, Mars, and Venus before 4.4 Ga. Earth's hydrosphere could have provided an essential environmental setting for the self-assembly of vital organic components, which led to life's origin. But the Hadean (>4 Ga) oceans on Earth were likely more voluminous than today, keeping the earliest continents[18] largely submerged. Yet, polymerization as a step towards the formation of living matter would never have occurred on a planet fully covered by oceans, partly because organic ingredients would be too dilute. A "terrestrial" origin-of-life sourced from meteorite-hosted organic compounds released into shallow waters by physical and chemical erosion requires exposed landmass. *Direct constraints on the emergence of subaerial landmasses are therefore critically required*, as they provide diverse aqueous environments (e.g. lakes, beaches and tidal pools) that concentrate organic components via evaporation or eutectic freeze-out.

Liquid surface water was undoubtedly present on Mars. We are currently involved in the ExoMars mission (launch 2022), targeting a landing site possibly representative of ancient deep-water settings and hydrothermal activity, and which may have developed into a shallow coastal sea or a warm salty pond. *Both conditions have been suggested to be the cradle of life on Earth*, and ExoMars's dedicated instruments are designed to search for *biosignatures and habitability potential* from records of the early martian history.

While Venus' prospective primordial ocean would have dried out during runaway greenhouse conditions, Earth's geological processes (particularly subduction) brought water into deep reservoirs of hydrated minerals.

On Mars, however, any seas, rivers or lakes disappeared, perhaps by ~3.7 Ga (Fig. 1), leaving a short window of opportunity for life. The precise timing and cause of a permanent change (i.e. *tipping point*, ***SO 6***) from a wet and likely warm Mars into a permanent icehouse is unknown ***(WP1.7)***. Understanding its timing requires improved crater chronology that PHAB will provide ***(WP1.1)***. Any "water-world" planets will ultimately lose their habitability through runaway evaporation of the oceans/surface waters ***(WP3.5)***, but *how important is the ocean's starting volume for a planet's ability to sustain the "right" amount of water in its mantle, surface and atmosphere?*

***ACTIVITIES:*** ***[1]*** *Geological field studies of Eoarchean (>3.75 Ga) zircon–containing sedimentary rocks to find evidence for the first subaerially formed rocks.* ***[2]*** *Model the emergence of land, ocean volume change, and long-term water storage within Earth's interior, and the early deep water cycle.* ***[3]*** *Remote sensing studies of terrestrial planets to look for the (past) presence of water, e.g. Mars: Mapping morphology and mineralogy related to water activity, and assigning ages and rates using crater statistics.* ***[4]*** *Numerical and physical experiments to characterize the environmental conditions that could support water-bearing minerals and their alteration products (Venus: granites, Mars: clays).*

***WP1.5 Magnetic Fields.*** A magnetic field protects a planet from high-energy solar particles, cosmic rays and biomolecule damage, and is commonly thought to modulate atmospheric escape and maintenance of an atmosphere with adequate pressure for water to exist as a liquid (requirement for *Earth-like life*). Today, Earth is the only terrestrial planet with a strong and *long-lived* dynamo-driven magnetic field, probably operated over most of its lifespan. The ancient magnetic field is recorded in surface rocks (paleomagnetism) and used to create a geomagnetic time-scale (polarity changes), to reconstruct continents and supercontinents (Fig. 4), and to document the strength of the geodynamo (paleointensity) back to at least 3.5 Ga and perhaps 4.2 Ga[19]. Planetary core dynamos initially draw their power from slow core-cooling due to heat loss to the mantle and a gradual crystallisation of a solid inner core provides additional power for the dynamo and increases the atmospheric protective power. The magnetic field intensity has varied considerably over time and after a period of very low paleointensities (600-550 Ma), a sudden (modelled) rise, perhaps at the dawn of the Phanerozoic (~541 Ma), suggests that inner core nucleation may have occurred only very late in Earth's history (Fig. 4C). This low intensity period is contemporary with the appearance of Ediacaran macroscopic animals (Fig. 5A) and raises some fundamental questions: *Did the Ediacaran biota evolve (by frequent mutations) when the Earth's surface was bathed in unusually intense UV and cosmic radiation? And had the field-strength recovered during the Early Cambrian (541-520 Ma) biotic proliferation?*

Early Mars had a strong magnetic field as witnessed by highly magnetized crust in its old southern hemisphere (~4.5-3.7 Ga). Recent seismic imaging of Mars[20] and core-mantle boundary temperatures inferred from interior structure models (assuming a Fe-S system) suggest a large and purely liquid core. This suggests an early dynamo driven by convective cooling, but as the smaller planet cooled, core convection slowed and Mars lost its field, its atmosphere ***(WP1.3)***, and transitioned into a permanent icehouse (Fig. 1). Venus similarly has no modern magnetic field, and yet is nearly Earth-sized. This may be due to a combination of extremely slow rotation and a stagnant lithospheric lid, limiting interior heat loss[21]. A field on Venus and especially on Mars might re-emerge at the onset of core solidification. Using dynamo and mantle flow simulations that incorporate different tectonic styles, PHAB will develop interior planetary evolution models to explain the temporal evolution of magnetic fields on Venus, Earth, and Mars. Such beyond the state-of-the-art models will be constrained by new paleointensity observations on Earth, cratering-based ages on Mars ***(WP1.1)***, and compositional constraints to be discovered from upcoming Venus missions.

***ACTIVITIES:*** ***[1]*** *Earth: World-wide field campaigns for paleointensity studies to determine the strength of the geodynamo through time and potentially the timing of solid inner core nucleation.* ***[2]*** *Mars: Corrected ages from cratering-statistics, supported by ages of meteorites (and possibly returned samples), will improve evolutionary models and determine when the magnetic field was lost.* ***[3]*** *Venus, Earth and Mars: Numerical modelling (also* ***WP1.6****) of convective heat loss to link magnetic field changes to the thermal evolution of planetary interiors.*

***WP1.6 Tectonic Regimes and Interior.*** Environmental conditions for habitability (global water layer *vs.* land-ocean distribution) are linked to the tectonic regime (e.g. stagnant lid *vs.* plate tectonics; Fig. 2). Thus, the interlinked rock and volatile cycles of the life-forming elements (CHNOPS) were significantly modified when Earth transitioned to plate tectonics. Volatile recycling enhanced habitability by storing volatiles within Earth's interior, thus preventing continuous build-up of $H_2O$ and $CO_2$ in the hydrosphere and atmosphere. The tectonic regime and how it evolved during the first billion years can be explored by a combination of proxy measurements (geochemistry, petrology) that constrain mantle temperature and melting behaviour, paleomagnetism (***WP1.5***) and zircon geochronology (***WP1.1)***. The tectonic regime itself results from mantle properties and the capacity of the lithosphere to deform. Some critical properties depend on volatile storage and may change during a planet's evolution (e.g. temperature, water content, lithosphere thickness), and thus the dominant tectonic mode may switch with time. *PHAB will explore changes in tectonic modes using thermal evolution models of mantle cooling vs. time* (such as those developed for ***WP1.5***). By employing specific criteria for when plate tectonics starts (or stops: ***WP3.5***), based for example on our knowledge of subduction, these models will unravel abrupt and gradual changes in *mantle dynamics* during early Earth history.

Estimates for *when* plate tectonics started range from the Hadean (>4 Ga) to 700 Ma and depend on *how* plate tectonics is defined. The tectonic regime when the mantle was at its warmest may have been one of plume- (or impact-) induced subduction type or squishy-lid type[22]. The first continents probably formed by partial melting of hydrated metabasalts, and the assembly of crust into supercratons and supercontinents (Fig. 4) suggest a change to a plate tectonic regime with lateral motion and subduction before 2.8 Ga. Because zircons form an archive of continental crust formation ages, variations in zircon age-frequency may reflect changes in volcanic arc activity or plate tectonic degassing (Fig. 4B), with the largest peak at ~130 Ma[23]. Major and minor peaks occur back to 3.1 Ga and 3.5 Ga, respectively, and early plate tectonics with warm and shallow subduction might have emerged around that time, stabilizing continents with deep cratonic keels.

***ACTIVITIES:* [1]** *Develop thermal history models of mantle cooling vs. time (including the influence of water, plate tectonic parameterizations, radioactive heat generation and continental formation/insulation).* ***[2]*** *Scrutinize the zircon record and explore a range of statistical approaches to constrain continental crust episodes and Earth's degassing history.*

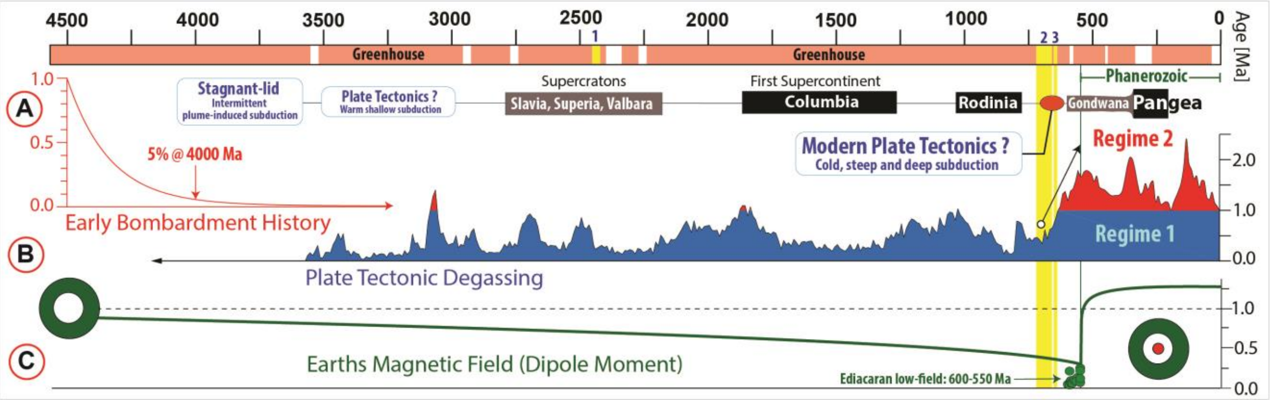

**FIGURE 4.** Earth's temporal variation between greenhouses (orange), icehouses (white) and Snowball Earths marked 1-3 (yellow), and the time-interval for supercratons, supercontinents (Columbia-Rodinia-Pangea) and the Gondwana superterrane. ***(A)*** Preliminary (normalized) early Earth bombardment history. ***(B)*** Normalized plate tectonic degassing (relative to today and inferred from arc-volcanic activity based on subduction fluxes since 350 Myrs[23] and calibrated area-scaled zircon-age frequencies from arc environments for older times). Plate tectonic degassing switched to generally higher values than today (=1) after 635 Ma **(Regime 2)**. Assuming a modern plate tectonic carbon emission of 0.5 Gt/yr, then the maximum peak at 130 Ma will correspond to 1.2 GT/yr. ***(C)*** Synthetic dipole moment for the Earth's magnetic field[19] and recorded dipole field strengths (paleointensity) between 600 and 550 Ma (compiled by collaborator Biggin; normalized to modern values). The model shows a slowly decreasing field and reaching very low values[24] before inner core nucleation and *increased* field strength.

***WP1.7 Snowball Earths and Tipping Points.*** Earth has been in a greenhouse state during most of its history (Figs. 4, 5), interrupted by a dozen icehouse periods (like today) and three Snowball Earth[25] periods. The reasons for such cooling events are disputed but often explained by enhanced rock weathering ($CO_2$ drawdown) of large igneous provinces that erupted on continents near the equatorial regions. Interestingly, the oldest known Snowball Earth (~2.4 Ga)[26] is contemporaneous with the Great Oxygenation Event (GOE) which occurred when Earth was nearing the "Habitable Zone" (Fig. 1). If oxygenation occurred first, then rising atmospheric oxygen levels may have triggered rapid oxidation of atmospheric methane[3], weakening the greenhouse effect and forcing run-away cooling and catastrophic climate change. *Evolutionary innovation by the biosphere (oxygen) may therefore have caused the first Snowball Earth*. But *when* and ultimately *how* the biosphere innovated requires an integration of geological and biological insight that PHAB will provide.

The first Snowball Earth occurred when Mars had lost most of its water and atmosphere (Fig. 1), and had become a permanent icehouse. *But when exactly did this transition occur? And why did Earth not also turn into a permanent icehouse at the same time, since both planets were beyond the habitable zone? Were Earth and Mars initially saved by their secondary $CO_2$-dominated atmospheres? But what kept Earth habitable and not Mars? Was it simply the smaller size of Mars that sealed its fate? Or were the Earth's shorter heliocentric distance, plate tectonics and/or biosphere deciding factors? How close was Earth to losing its habitability?*

The first attempt by PHAB scientists to quantify plate tectonic degassing in deep time (Fig. 4B) shows a remarkable pattern where low (high) degassing generally corresponds to periods of icehouse (greenhouse) conditions for the past 3.5 billion years. PHAB will capitalize on this novel and important finding, and with improved paleogeographical models at critical intervals to constrain silicate weathering efficiency, we will vastly improve carbon-cycle modelling in deep time, allowing us to expose the cause(s) for the onset and termination of Snowball Earth climates *(**SO 5-6**)*.

***ACTIVITIES:*** ***[1]*** *Revisit key sections in South Africa and Russia associated with GOE and Snowball Earth glacials to collect samples for high-precision U-Pb zircon dating.* ***[2]*** *Paleogeographic modelling (in conjunction with **WP1.5/1.6**).* ***[3]*** *Climate modelling (using an extended version of COPSE[24]) to understand how to initiate and terminate Snowball Earth events at times with very different atmospheric compositions and/or tectonic regimes.* ***[4]*** *Determine how close the Earth may have come to losing its habitability in deep time.* ***[5]*** *Model planetary tipping points for Mars and Venus using Earth history as a guide.*

***WP1.8 Early conditions for life.*** Earth was situated outside the "Habitable Zone" during planet formation (Fig. 1) but a dense $CO_2$-dominated atmosphere ***(WP1.3)*** probably pushed it on a biotic path. Otherwise, early Earth would have been frozen for the first two billion years. Mars was once wetter, arguably warmer and potentially habitable but the loss of surface water and the bulk atmosphere prevented any further biological innovations (if life ever started there). Venus may have begun well-positioned in terms of distance to our Sun (Fig. 1) but its closer proximity and increasingly $CO_2$-dominated atmosphere probably set it on an abiotic path. Water may have been abundant but was eventually lost to space, likely leading to arid conditions at an early stage. *Perhaps our closest sister planet may never have sustained hospitable conditions for life to begin?*

An important PHAB objectives is to develop a credible synthesis of the physical-chemical conditions that prevailed on our planet when life first took hold (***SO 2***). The Hadean Eon probably witnessed the emergence of life before ~4.1 Ga[7] but aspects of the primordial environment are debated mostly due to a lack of data. The mantle's redox state and the composition of the prebiotic atmosphere ***(WP1.3)*** are critical to debates about origin-of-life scenarios and the emergence of land ***(WP1.4/1.6)*** may have facilitated prebiotic chemical reactions. Timelines in general and specifically the bombardment flux (***WP1.1***) hold the key to quantify when life could have first emerged. Our preliminary model suggests a Hadean monotonic decline in bombardment rate (Fig. 4A), contradicting models involving a burst in bombardment intensity at ~4 Ga (the so-called Late Heavy Bombardment), which has important consequences for a nascent biosphere[27]. ***WP1.8*** will provide a synthesis of the prebiotic conditions ***(WP1.1-1.6)***, describe why other planets fail to sustain hospitable conditions (***WP1.7***), and will serve as a template for identifying planets around other host stars that are or were potentially habitable (***SO 7***).

***ACTIVITY:*** *Characterize the key conditions for planetary habitability (part of our prime objective).*

## RESEARCH THEME 2: MODERN EARTH

Addresses the most recent 750 million years, starting from the initial dispersal of the oldest well-established supercontinent, Rodinia, and accompanied by dramatic cooling events (Snowball Earths), the onset of modern plate tectonics, unprecedented carbon-cycle fluctuations, rising atmospheric-oxygen levels to modern values, and the rapid evolution of multicellular organisms, including animals, during the early Cambrian (541-520 Ma)[11,25,28-30]. This period of Earth history is much better preserved in the geological record than previous periods, providing an opportunity to examine planetary habitability in detail. PHAB will develop an Earth System Model, including the interior, which will clarify how Earth has remained habitable (***SO 4-6***).

***WP2.1 Plate Tectonics and Paleogeography***. Earth's system of *plate tectonics* is critical for habitability because it recycles climate-regulating volatiles such as water and carbon. *Paleogeography*, which documents tectonic and environmental changes on Earth's surface, is thus essential for understanding the maintenance of habitability on Modern Earth. Because Earth's paleogeography constrains the boundary conditions for deep interior **(WP2.2)** and paleoclimate **(WP2.4)** modeling, and biodiversity dynamics ***(WP2.5)***, it will form the backbone of our Earth System Models.

PHAB scientists have developed full-plate paleogeographic models for most of the Phanerozoic[31,32,11] (541-0 Ma) but these must be extended to 750 Ma to clarify the critical phase in Earth's evolving habitability during the Neoproterozoic and the Early Phanerozoic. Such models do exist back to 750 Ma but a *key challenge* is that the paleomagnetic data used to reconstruct the paleogeography exhibits *chaotic* behaviour between 610 and 520 Ma (Fig. 5A), and published paleogeography is largely unconstrained in this time-interval. An extremely weak, non-dipolar and unstable dynamo during this time-interval (Fig. 4C), may well explain parts of the chaotic paleomagnetic record. A weak magnetic field has also important unexplored implications for habitability due to enhanced flux of high-energy solar particles, galactic cosmic rays, and ultraviolet radiation (due to ozone depletion) reaching the surface. Alternatively, rapid *True Polar Wander* (TPW) has also been suggested as a cause for the "chaotic" paleomagnetic signature for parts of the Neoproterozoic. TPW is a rotation of the entire solid Earth relative to the spin axis, mainly driven by the internal redistribution of mass by subducting slabs, but also by the changing mass of ice sheets and associated viscoelastic response of the mantle. Another important but still unaddressed question is how ice and water mass redistribution on Snowball Earths may have driven *rapid* TPW, interacting with subduction-driven TPW. TPW itself impacts habitability through time by moving paleoenvironments to new latitudes, and changing climate states.

The transition to the current plate tectonics regime[7,30] with cold, deep and steep subduction, probably occurred only after 750 Ma (Fig. 5A). We recognize this change by a major increase in volcanic arc activity and plate tectonic degassing between 700 and 540 Ma (Regime 1→2; Fig. 4B). The mechanism for triggering the onset of modern plate tectonics is unknown, but must relate to changes in the mantle and/or in the tectonic surface layers. Whatever the mechanism(s), it led to dramatic changes in Earth's interior and surface environment[30] that paved the way for sustained habitability. Uncovering and understanding the trigger(s) for modern plate tectonics is a major target for PHAB's thermal evolution modelling **(WP1.6)**. For this, our subduction and mantle convection models will benefit significantly from PHAB research on volatile cycles, which affect subduction, mantle rheology and faulting **(WP2.2)**.

***ACTIVITIES:*** ***[1]*** *Targeted paleomagnetic/paleointensity and geochronological field campaigns worldwide, notably between 610 and 520 Ma, to investigate and identify the origin(s) of aberrant (chaotic) data.* ***[2]*** *Build a robust global paleogeography and full-plate model for the entire lithospheric plate system since 750 Ma using an in-house version of the GPlates software.* ***[3]*** *Incorporate the time-evolution of subduction, continents, and sedimentation into thermal evolution models of Earth's convecting mantle, to explore the transition from early plate tectonics to Modern Plate Tectonics.* ***[4]*** *Determine TPW numerically at specific time intervals (e.g. Snowball Earths) using the subduction history from full-plate models with added contributions from ice-sheet driven TPW and potentially stable LLSVPs (Fig. 2A), to understand how these processes may have upset or reinforced habitability during critical intervals of biological innovation.*

***WP2.2 Volatile Cycles*.** Full-plate paleogeographic reconstructions (***WP2.1***) will enable estimation of surface-mantle fluxes of volatiles (e.g. carbon and hydrogen) and thus inform time-dependent models for volatile cycling between Earth's surface and the interior. Water, $CO_2$ and carbonates play important roles in climate modulation on short timescales, but are also central to the silicate-weathering cycle, affecting climate stability on geological timescales (***WP2.4***). Subducted slabs are the main carriers of water and carbonates into the mantle, but most of the water is released at shallow depths and returns to the Earth surface through arc volcanism, which also affects the atmosphere and the long-term climate through the release of greenhouse gases. However, some of the hydrogen and carbon remain in the sinking slab to greater mantle depths, where they can be stored for much of Earth's history. This deep storage, which can be spatially heterogeneous, affects volatile abundances within the surface environment, and ultimately controls long-term changes in sea level and greenhouse gas concentrations. Despite their importance, the regions of the mantle with the greatest water and carbon concentrations have not been mapped, and it is thus difficult to estimate their impact on mantle processes such as melting and outgassing, as well as the deep-Earth residence time of the volatiles. The deep storage of water also influences mantle rheology by hydrolytic weakening, and thus affects rates and patterns of mantle convection. This will in turn affect core-mantle boundary heat flow ***(WP1.5)***, the magnetic field and Earth's thermal evolution. *Volatile cycling between the Earth's surface and interior is critical for planetary evolution* since water, in particular, seems to be essential for plate tectonics ***(WP1.6)***.

***ACTIVITIES:*** ***[1]*** *Deep recycling of hydrogen and carbon: Estimate rates for water and carbon transport into the mantle via slabs using ab initio simulations. Incorporate the subducted water into models of global mantle flow to understand the impact of heterogeneous storage of volatiles in the deep mantle on planetary evolution, volcanism, and sea level change during Earth history.* ***[2]*** *The shallow carbon cycle: Develop weathering models for the continents and sedimentation models for the seafloor, which track carbon cycling and storage within Earth' surface environment, as constrained by geological observations.* ***[3]*** *Couple models of land/seafloor relief, isostasy, sedimentation, and volcanic output into the global climate models* ***(WP2.4)****, parameterized for feedbacks into the mantle convection system.*

***WP2.3 Paleoclimate Proxies*.** Key paleoenvironmental parameters include temperature, $CO_2$ and $O_2$ (Fig. 5C, D), but there are no direct measurements of these variables, and we therefore rely on proxies or modelled values. Temperature reconstructions rely on geochemical proxies of sea surface temperatures (SSTs), e.g. oxygen isotopes[37] ($\delta^{18}O$), which suggest very high and debated temperatures (~50ºC) during the Late Cambrian (Fig. 5C). This was followed by rapid Ordovician cooling, and since 400 Ma, greenhouse and icehouse climates averaged 23ºC and 16ºC, respectively. Other types of temperature curves, e.g. global average temperatures[38] are broadly similar to the SSTs for the past 400 million years, but before that time they are 15-25ºC *lower* than the SSTs, including during the Great Ordovician Biodiversification Event (GOBE) (Fig. 5). PHAB must therefore seek to resolve these temperature discrepancies by expanding the existing clumped isotope database to verify (or reject) high SSTs in the Early Paleozoic. Temperature estimates have deep implications on the maintenance of biodiversity ***(WP 2.5)***. For example, *did cooling from very high temperatures in the Late Cambrian provide ideal conditions for the GOBE? How do we explain the recently identified Carboniferous–Permian Biodiversification Event*[34] *which occurred during stable icehouse conditions?* Increased $O_2$ levels (Fig. 5C) is perhaps a common denominator for these two biodiversification events (and the Cambrian radiation), but published $O_2$ models differ markedly for the early Paleozoic.

Atmospheric $CO_2$ concentrations for the early Earth were probably several orders of magnitude higher than today[3], but there are no reliable $CO_2$ proxies before the Early Devonian[23] (~420 Ma). Thus a detailed picture of the long-term drawdown of $CO_2$ across geologic time is lacking and $CO_2$ levels for most of Earth's history are estimated from carbon-cycle models, suggesting $CO_2$ levels of 5000-6000 ppm (Fig. 5D) at the dawn of the Phanerozoic (541 Ma). Well-known Devonian proxies for atmospheric $CO_2$ include paleosols and stomata, which are commonly combined with liverworts, alkenones and boron for the younger geological record to derive a mean proxy curve[40] (Fig. 5D). Proxy-based $CO_2$ estimates, however, are notably coarse in the 420-340 Ma and 260-240 Ma periods (~2 per 10 Myr interval) leading to critical gaps in our general understanding of the Earth's climate. Peak $CO_2$ concentrations (>2000 ppm) are associated with a greenhouse climate in the Early Devonian, and an apparent decline between 410 and 340 Ma is commonly linked to the idea of $CO_2$ absorption by a massive increase of terrestrial plants and the advent of large trees. This contributed to the Earth's longest icehouse, the Late Paleozoic Ice Age, with $CO_2$ levels averaging 430 ppm between 330 and 260 Ma. But low $CO_2$ proxy levels are recognized well after the termination of the icehouse and are at odds with a warm greenhouse climate and theoretical thresholds for greenhouse/icehouse climates (Fig. 5C, D). Other types of proxies, e.g. the *C3 plant* method[41] pioneered by PHAB members, predict higher $CO_2$ levels that better comply with carbon-cycle models. *PHAB seeks to fill crucial gaps to rectify key discrepancies in Earth's greenhouse gas history by joint analysis of multiple proxies and carbon-cycle models* ***(WP2.4)****, temperature proxies and conjectural $CO_2$ thresholds for glacial inception, but also by expanding the existing $CO_2$ proxy and temperature databases, particularly targeting time periods of sparse and/or coarse estimates.*

Targeted field work to boost the *C3 plant proxy* record will include a unique Svalbard site with terrestrial sediments in continuous sections across the Paleozoic. Using the *C3 plant* method[41], we will construct a high-resolution history of atmospheric $CO_2$ across ~200 million years but also complement carbon isotope data with clumped oxygen isotopes in carbonates from interbedded marine sediments, to explore the variation of SSTs.

***ACTIVITIES:*** ***[1]*** *Review of existing proxies, including those meant to reconstruct $CO_2$, sea surface temperatures and seawater $\delta^{18}O$ (i.e. clumped isotopes).* ***[2]*** *Targeted field work on Svalbard (among other areas) to provide fine-scale resolution to the $CO_2$ and SST proxy database.* ***[3]*** *Clumped isotope measurements of marine sections worldwide (extending ongoing work with international collaborators).*

***WP2.4 Paleoclimate Models***. Full-plate models ***(WP2.1)*** will provide vital inputs for carbon-cycle models[35,39,42], which play a key role, not only in reconstructing past $CO_2$ fluctuations, but also in understanding their causes. By controlling the long-term distribution of continents and oceans, mountain building, arc volcanism, topography, weathering and more, *plate tectonics* has a key role in shaping the long-term climate. *Yet, the formal hypothesis that plate tectonics is a key driver for long-term atmospheric $CO_2$ variation requires testing.* Our planet has been dominated by greenhouse climates and low atmospheric $CO_2$ is considered necessary for icehouse conditions, and commonly explained by reduced volcanic arc degassing or enhanced carbon sinks by silicate weathering. However, quantitative long-term estimates of these parameters are lacking. PHAB has developed novel ways to quantify *volcanic arc degassing*[23,10] in deep time (Fig. 4B), and as a supplement to computationally intensive 3D climate simulations[42], we have parameterized theoretical silicate weathering based on the latitudinal distribution of exposed land from our paleogeographic maps[23]. *PHAB's unified full-plate model will for the first time be used to estimate both plate tectonic $CO_2$ sources and sinks for climate modelling over the past 750 Myr. Along with improved models for biogeochemical cycling, this will allow us to expose the cause(s) for greenhouse versus icehouse conditions (****SO 5****).*

A key feature of multiple climate models is the sequestration of $CO_2$ during rock weathering, a process that has proved very difficult to quantify in the field and laboratory. In order to provide new insight, we will *quantify biologically-mediated weathering rates for Modern Earth* under variable biogeochemically-modulated conditions. Because interactions within and between plants and soils (and microbes) comprise key controls over mineral weathering, both primitive (e.g. bryophyte/sporophyte) and complex (gymnosperm/angiosperm) plants will be grown under varying $CO_2$ (sub-ambient up to 4200 ppm) and soil treatments containing rock thin-sections within environmentally controlled growth chambers.

Large igneous provinces (Fig. 2A) can trigger rapid climate perturbations but a longer-term role includes reduction of atmospheric $CO_2$ through enhanced silicate weathering that PHAB will quantify. We will also explore little studied forcings in climate models such as true polar wander and changes in the length of the day (Fig. 7). Earth is in fact the only terrestrial planet in our Solar System with a large natural satellite, influencing the climate and the spin axis (axial tilt). As the Moon moves away due to tidal interaction, the Earth's rotation rate decreases (~15% since 600 Ma) and the warm and wet tropics are slowly expanding[10], and thus increasing silicate weathering efficiency. PHAB will explore how this affects the climate and climate gradients in deep time through carbon-cycle modelling, benchmarked by the distribution of climate sensitive facies.

***ACTIVITIES:*** ***[1]*** *Calculate volcanic arc degassing using subduction fluxes from our full-plate model and area scaled arc-zircon frequencies in deep time as a proxy.* ***[2]*** *Estimate theoretical silicate weatherability from paleogeographic maps of exposed land* ***(WP.2.1)****.* ***[3]*** *Perform computationally intensive 3D climate simulations*[42] *to estimate silicate weathering at critical greenhouse-icehouse transitions.* ***[4]*** *Determine biologically mediated weathering rates by controlled experimentation across elevated $CO_2$ levels.* ***[5]*** *Model the climate/habitability effect of true polar wander and rotation rate changes.* ***[6]*** *Estimate $CO_2$, $O_2$ and temperatures by carbon-cycle modelling, using a special adaptation of COPSE (Early and Modern Earth simulations) and an in-house version of GEOCARBSULF for Modern Earth simulations.*

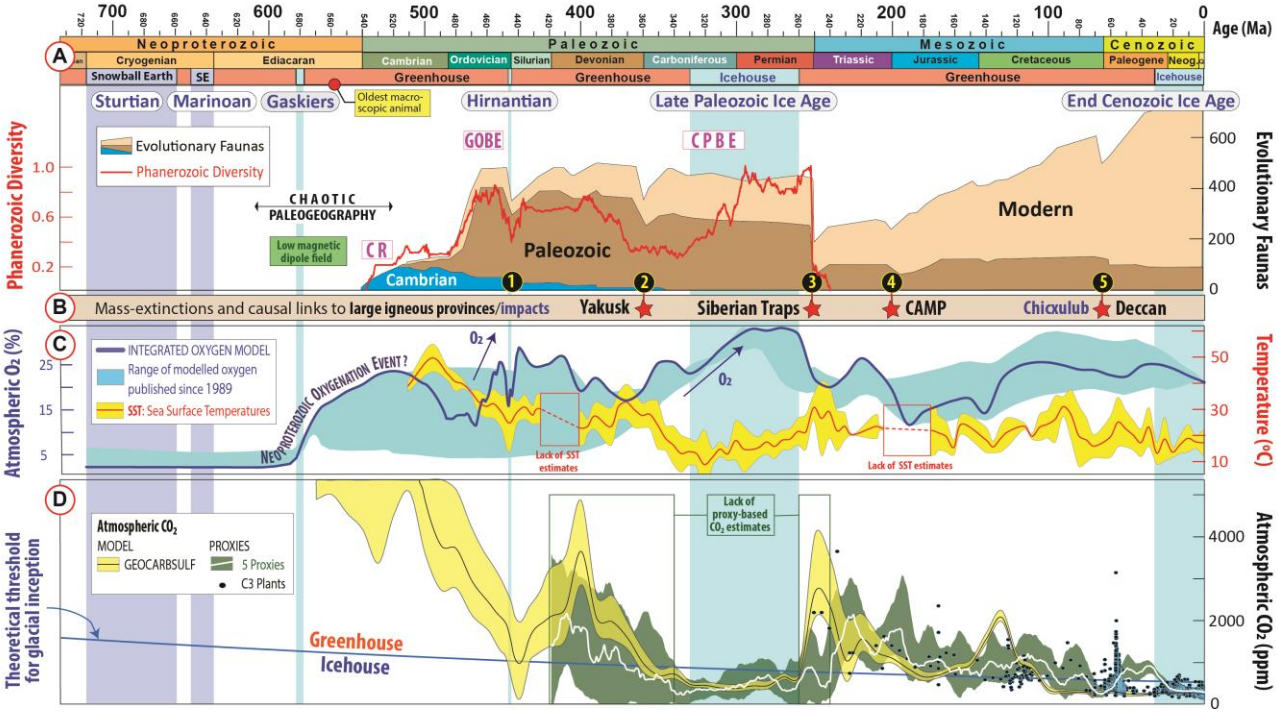

**FIGURE 5. (A)** Modern Earth time-scale and greenhouse (hot) *vs.* icehouse (cold) conditions (including Sturtian/Marinoan Snowball Earths), global Phanerozoic taxonomic diversity for marine animal families[33] (right-hand scale) adapted to modern time-scale, and a normalized Paleozoic diversity[34] (left-hand scale). CR, Cambrian Radiation; GOBE, Great Ordovician Biodiversification Event; CPBE, Carboniferous-Permian Biodiversification Event. **(B)** Mass extinctions 1 to 5 in black numbered circles. 2, 3 and 4 are linked to three large igneous provinces and 5 is linked to the Chicxulub impact/Deccan Traps. **(C)** Integrated model for atmospheric $O_2$ levels[28,35,36] advanced here and the range of published $O_2$ levels. Our tropical sea surface temperature curve (based on stable oxygen isotopes from fossils that once lived within 30° from the equator and assumes seawater composition as today) is averaged over 2 million year bins and shown with 95% confidence envelope (if N>1). **(D)** Modelled atmospheric $CO_2$ with 95% confidence envelope: GEOCARBSULF[23,35] model run with climate sensitivities of 6°C (3°C) per doubling of $CO_2$ during icehouse (greenhouse) conditions. We also show a $CO_2$ proxy curve[40] with 95% confidence envelope (5 proxies), *C3 Plant* proxies (compiled by Jahren/Schubert) and a theoretical threshold for glacial inception (blue line: assumes a modern glacial threshold of 500 ppm, a dimmer Sun (-7.5° at 540 Ma), and climate sensitivity of 6°C per $CO_2$ doubling for icehouse conditions.

***WP2.5 Drivers of Biodiversity***. Biological diversity is one of the most prominent characteristics of Modern Earth. Fossil remains of multicellular organisms appeared perhaps as early as 1000 Ma[43] but the Cambrian radiation (starting ~541 Ma, Fig. 5A) was one of the most significant evolutionary transitions, when all major animal phyla appeared in the fossil record. The evolutionary diversification that followed from 480-470 Ma[11], the *Great Ordovician Biodiversification Event* (GOBE), showed a dramatic increase in the number of different complex animal forms and ways of life. This was followed by a short-lived icehouse (Hirnantian) and a mass extinction at ~445 Ma, the first of the Big Five extinctions (Fig. 5A, B). The reason(s) for this mass extinction is debated; the other four occurred during greenhouse conditions and are thought to be causally linked to large igneous provinces or large impact events[10,11].

While it is commonplace to focus on a few singular "events", such an approach, when viewed in isolation, is deeply unsatisfactory[44]. As a remedy there has been a recent focus on understanding patterns and inferred processes in the deep past using time-series analyses. Yet, both analyses and data remain inadequate[44]. This is exemplified by *(i)* analyses that fail to adequately account for sampling heterogeneity in the fossil record[34], *(ii)* well-known problems in time-series analyses that are seldom tackled in paleontological studies[45,44] and *(iii)* failure to include potentially important explanatory variables (such as biotic drivers) in the analyses of drivers of biological diversity on geological time-scales. After a planet has proven habitable, the diversification of life is possible. This diversification is surely influenced by planetary temperature, $CO_2$, $O_2$ or tectonics, but mechanisms are unclear and prediction difficult. More important for biodiversification on Modern Earth may be the biological interactions between competing groups of organisms[45]. We thus include multiple activities to address the critical issue of how the diversification of life proceeded after conditions of habitability were met.

To obtain a deeper understanding of *how* and *why* biological diversity has varied over geological time-scales (***SO 4***), we need rigorous modern statistical analysis[45], solid geological data with high temporal resolution (***WP 2.1 to 2.4***), and sufficient measures of uncertainty. We will apply and further develop methods that account for biased sampling and age-uncertainty, which plague inferences from the fossil record to estimate biodiversification rates[46]. In addition, we will also filter the literature for reliable time-calibrated phylogenies to compile timings of major radiations with organismal groups as an independent data source of biodiversification rate estimation. With new toolboxes (including *layeranalyzer*[47]and *causality.jl*[48]) developed by PHAB scientists, and cutting edge repositories[49] structured for automated data extraction from the fertile paleontological literature, we will quantify the effects and potential *feedback*[45,47] between multiple abiotic, biotic and hidden/latent drivers of biological diversification, beyond comparisons of singular events.

***ACTIVITIES:*** ***[1]*** *Combine new fossil occurrences compiled with a text-mining/deep-learning approach using XDD (https://geodeepdive.org/) with the Paleobiology Database (https://paleobiodb.org) to have the most comprehensive fossil occurrence database to work with.* ***[2]*** *Improve and expand on existing statistical models to estimate origination and extinction rates while accounting for temporally varying sampling rates and age uncertainties for major fossil taxa spanning the Phanerozoic.* ***[3]*** *Analyse diversification time series (i.e. origination and extinction rates) and vetted paleoenvironmental time-series* ***(WP2.1 to 2.4)*** *that are thought to influence diversification rates.* ***[4]*** *Develop new tools that (i) simultaneously model diversification rates and the influence of external time series on such rates and (ii) examine the adequacy of models and allow the modelling of unobserved/latent variables.* ***[5]*** *Integrate temporal information on diversification from fossil occurrences and time-calibrated molecular phylogenies to fill knowledge gaps.*

## RESEARCH THEME 3: EXO-EARTHS

> *It is inconceivable that in an infinite universe, it should be only here that a world has formed* (Titus Lucretius Carus: 99-55 BC).

Aims to identify planets orbiting other stars (Fig. 6) that potentially are, or have been, habitable (***SO 7***). Currently exoplanets are recognized in a wide range of planetary systems. The physical parameters of the central stars and planets are quite diverse, and of the nearly 5000 known planets, as few as 5% are potentially Earth-like in terms of *mass* and *orbital distance*. A key observable for Earth-like habitability today is a highly oxygenated atmosphere, an ozone layer, and low levels of $CO_2$. But the Earth's atmosphere has changed dramatically over billions of years, and thus the *age of a planetary system is critically important*. The search for life in other planetary systems tends to focus on finding intelligent species, but habitable conditions exist in many shades. Considering Earth's evolutionary path it may prove challenging to recognize microbial stages of inhabitation.

PHAB will extend *comparative planetology* beyond the Solar System. The evolutionary perspective that comparative planetology provides will be indispensable in recognizing planets that may be ripening into habitable worlds, as well as those that once were habitable. With this, we aim to produce a new *Drake-type equation*[50] to estimate probabilities of finding intelligent life.

***WP3.1 Observational Constraints.*** Identification of habitable planets depends on emerging technologies and future missions, and PHAB participates in two ESA telescope missions that will collect data during the Centre period. The ***PLATO mission***[11] (launch 2026) to search for *transiting planets* (Fig. 6, 7-top), will be capable of detecting Earth-sized planets in Earth-like orbits around Sun-like stars, and determine their ages. The ***Ariel space telescope***[12] (2029) will collect information about their atmospheres through spectroscopy. The mass of a transiting planet will be essential to evaluate which evolutionary pathway a planet took and will be obtained either through follows-up measurements by radial velocity and/or transit timing variation techniques. Currently, systems with Earth-sized planets are rare, but mostly a result of observational biases. *PHAB will develop techniques and contribute in collecting planets' mass, radius and atmospheric composition, and increase the number of known Earth-like planets in the habitable zones of their respective host stars.* To do this, PHAB will observe and interpret physical and spectral properties of the surveyed planets from open mission and telescope data, a prerequisite for recognizing key conditions that could classify planets as habitable. From de-biased observational data and models of Solar System formation, PHAB will identify planet formation locations in the protoplanetary disc, potential planetary migration patterns, planet interior structure, and construct atmosphere evolution models.

***ACTIVITIES:*** ***[1]*** *Collect and de-bias the radial velocity measurements and transit data for planet density estimates.* ***[2]*** *Prepare for data processing of PLATO and Ariel mission data.* ***[3]*** *Train on and utilise collected and future observational constraints for deciphering evolutionary pathways of Exo-Earths (e.g. TESS and JWST).* ***[4]*** *Constrain the number of potentially habitable planets in exoplanetary systems.*

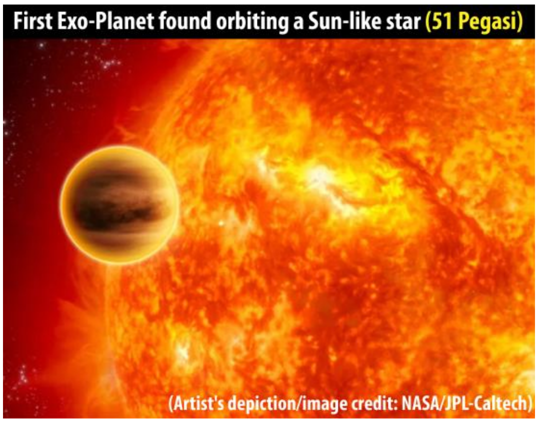

**FIGURE 6.** Michel Mayor and Didier Queloz observed the first Exo-Planet orbiting a Sun-like star in 1995. They shared the 2019 Nobel Prize in Physics with Jim Peebles for 'unraveling the structure and history of the universe and for changing our perspective of Earth's place in it'.

***WP3.2 Exo-Planet Formation.*** Exoplanetary systems show an incredible diversity, and most are seemingly unlike our Solar System. Not all systems are dominated by a Jupiter-sized planet, because somewhat different disc properties could delay or prevent gas giant formation, or reduce their sizes. Different disc properties change planetary migration dynamics and the final architecture of the system, and planets larger and/or wetter than Earth can form. Stellar luminosity, metallicity and element abundances do not directly predict the likelihood of hosting Exo-Earths, but allow inferences on the compositional gradient within the planet-forming discs around diverse stars. As such, a *key challenge* in understanding the diversity of exoplanet systems, and thus which systems could host habitable planets, is to undertake sensitivity tests to narrow down the vast parameter space that exists. Such exploratory simulations of planet formation require extensive computational hardware and runtime, because of the great diversity of different stellar masses and compositions (including observational constraints on metallicities, with implications for the protoplanetary discs, as well as migration and accretion models). To facilitate this exploration, PHAB will build on results from the Solar System (***WP1.2***) and with initial conditions dictated by the star to constrain the parameter space permitting Earth-like planets and habitability.

***ACTIVITIES:*** ***[1]*** *Construct planetary systems with Earth-twins in star's habitable zone by modelling (i) classical planetesimal and (ii) pebble accretion with in-house versions of CPU/GPU N-body integrators, using constraints from* **Research Theme 1** *and observational data from* **WP3.1**. ***[2]*** *Use stellar compositional databases and observed structures of proto-planetary discs as well as discovered multi-planet systems to guide the initial conditions for the simulations.* ***[3]*** *Perform ab-initio calculations to constrain the partitioning of the stellar elementary inventory.* ***[4]*** *Use condensation sequence obtained from Solar System meteorites and experimental data to guide the composition of planetary interiors.*

***WP3.3. Exo-Planet Structure.*** Mini-Neptunes, Super-Earths, Super-Lunas or Super-Mercuries, planets of similar size but very different *compositions* and *interior structures* can be distinguished by their *total mass* or *averaged density*, respectively. Exoplanet observables such as *mass*, *radius* and *atmospheric composition* are restricted by current observational precision, and require theoretical approaches to bolster our understanding. A limited collection of the planets stemming from ***WP3.1/3.2*** will probably satisfy habitability conditions as defined in ***WP1.8***. Even if a planet's volatile content is relatively straightforward to define and select (e.g. presence of water), the type and relative amount of the major elements building a planet can vary hugely, for example because of compositional variations amongst stars. The bulk planetary chemistry can turn a planet with a perfect position relative to its star and perfect volatile content to an uninhabitable planet. *PHAB will therefore perform thermodynamical phase-equilibria analyses based on available petrological databases, extended by ab initio simulations (when needed) to model planetary interiors.* We will estimate internal structure, crystallization pathways of magma oceans, cooling of iron-based cores, as well as the planet's convective vigor and its likelihood of hosting plate tectonic behavior and/or a strong magnetic field. The atmospheres contribute little to the average density of rocky planets but reflect the chemical evolution of the planet (differentiation and degassing history, potential presence of life forms). PHAB will explore the likelihood that Earth-mass planets actually have the structure and composition that permits them to become habitable, based on their computed mantle compositions and observed outer atmospheres.

***ACTIVITIES:*** ***[1]*** *Predict (i) interior structure and composition, (ii) uncompressed density and observable average density, and (iii) atmosphere compositions of Exo-Earths, using bulk planetary chemical composition from* **WP3.1/3.2**. ***[2]*** *Predict rock-gas transition and properties of primary atmospheres of rocky planets.* ***[3]*** *Evaluate Earth-like habitability of Exo-Earths, using probability maps of starting mantle compositions and atmospheres.*

***WP3.4 Exo-Planet Evolution.*** The knowledge of planetary habitability is mainly based on the evolution of the Earth, the Sun, and our Solar System. PHAB will focus on temperate Earth-like exoplanets. Although

PLATO may discover Earth-like planets with appropriate star-planet distances, major differences may stem from the star's luminosity and age-related composition. Different disc structures may also influence the late accretion of volatiles and bombardment flux and place Exo-Earths on evolutionary pathways differing from our Earth. An example might be the contrasting accretion history and resulting compositions for Venus (inwards from Earth) and Mars (further out). Although Sun-like stars of different ages will acquire different element ratios, e.g. with increasing Fe/H, Fe/O and Fe/C, in that order, as the universe ages, the variable radii of planetary accretion zones might partly offset the inherited stellar element abundances[51]. Bulk planetary compositions determine core fractions and influence core-mantle separation processes and chemical core-mantle evolution. The compositional starting point (e.g. the Mg/Si ratio) will also set the stage for further planetary evolution and dynamics, from magma-ocean crystallisation and surface degassing, forming possible atmospheres and hydrospheres, to later solid-state mantle structuring and convective flow. Hot and massive Exo-Earths with large volatile fractions dissolved in long-lasting magma oceans, might degas greenhouse atmospheres like Venus. An intense and long-lasting impact bombardment will repeatedly melt the crust and stall prebiotic chemistry. Because initial habitability is expected to vary by star type and age, our goal is to study planetary evolution and impact bombardment with modified parameters that compensate for variable initial conditions. PHAB will provide probability maps of habitable planets over the range of initial conditions, fingerprinted by their observable atmospheres, thereby making predictions to be tested via recommendations for observations performed by existing and to be launched telescopes.

***ACTIVITIES:*** ***[1]*** *Planetary interior modelling of thermal/compositional evolution to predict likely dynamic/tectonic regimes considering the Exo-Earth's orbital and compositional peculiarities inherited from the star-planet formation.* ***[2]*** *Explore effects of late accretion on long-term habitability and crustal resetting.* ***[3]*** *Predict observable atmospheres relevant for early planet formation (magma ocean phase) and hot, close-in planets observed by Ariel, using* ***WP1.3/1.4*** *ab initio calculations.* ***[4]*** *Predict likely atmosphere composition and evolution, using chemical cycles from the Solar System planets* ***(WP 1.3/1.6/2.2)***. ***[5]*** *Evaluate thermal evolution models of Exo-Earths* ***(WP3.3.)*** *and their potential long-term habitability.*

***WP3.5 Fate of Habitable Planets***. It is not necessarily obvious that key habitability factors such as plate tectonics will persist once started. Even a dynamo-driven magnetic field can stop and perhaps re-emerge later through inner-core nucleation, and a planet will also eventually become tidally locked into synchronous rotation to its star. The Earth's axial tilt may also become unstable as the Moon is moving away, and if instability results in a climate varying too rapidly for complex life, then there is also a habitability life-time associated with the Earth-Moon coupling. All planets ultimately lose their habitability, and in about one to two billion years, when the Sun's energy has increased by 10-20%, Earth will enter a moist greenhouse, followed by runaway evaporation of the oceans (Fig. 7, top). Plate tectonics and the entire carbon-water cycle may then end. Following that, the dynamo will cease, potentially leading to accelerated loss of volatiles from the outer atmosphere. On even longer time-scales, the increase in surface temperature will cause a runaway greenhouse effect and heat the surface to the melting point and all life on Earth will be extinguished. If Earth is viewed remotely in the distant future, one may observe a Venus-like planet and wonder if Earth was ever habitable — *although are we certain that Venus predicts our future? What about planets that were habitable (or even, inhabited) in the past? Which signatures of their previous state could they possess?*

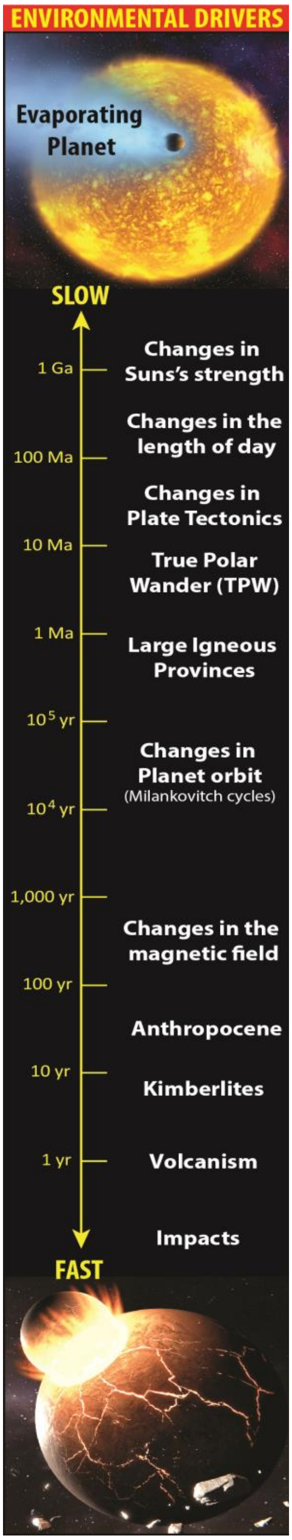

**FIGURE 7.** Key environmental drivers, operating at different time-scales, from slow changes in the Sun's strength to abrupt impacts.

***ACTIVITIES:*** ***[1]*** *Model the effects and consequences of ending plate tectonics and magnetic fields for Earth and planets.* ***[2]*** *Model the effects on climate of stability/instability of the axial tilt (obliquity) as the Moon is moving away, and tidal-locking of a planet.* ***[3]*** *Propose methodologies for searching for previously inhabited planets (e.g. excess complex hydrocarbons in the atmosphere, metals and industrial pollutions).*

## 1.2 Excellence: Solidity

PHAB consolidates its ***feasibility*** by combining *(i)* integration and transfer of knowledge and methods/tools across disciplines, *(ii)* our data from field, laboratory and space missions, *(iii)* strong international collaboration (Table 2) and *(iv)* proven ability by all PIs to produce ground-breaking research results (see CVs), directed toward an overarching goal of understanding planetary habitability. The successful implementation and completion of a research task of the outlined size and scope requires a Centre of Excellence (CoE) structure, including *(v)* substantial, long-lasting and directed resources that allow *(vi)* targeted (complementary) recruitments and sustained collaborations across fields.

PHAB also builds strength upon the experience collected from three previous CoEs at the University of Oslo: *Physics of Geological Processes* (Physics), *Centre for Ecological and Evolutionary Synthesis* (Biology) and *Centre for Earth Evolution and Dynamics* (Geoscience). We take advantage of the synergies of these CoEs, all rated "Exceptional" by international committees, to advance a new centre by gathering a group of researchers crossing disciplinary boundaries within and between geoscience, evolutionary biology, physics, planetary science, cosmochemistry, astronomy and astrophysics.

PHAB research raises no ethical issues, it is not gender-related, and we follow UiO safety regulations.

## 2. Impact

A Centre dedicated to research on the habitability of star-planet systems will be *the first of its kind* in Norway, and our cross-disciplinary expertise, building on our own planet, makes it unique worldwide. A key Centre component is to *(i)* expand planetary science in Norway, *(ii)* advance comparative planetary sciences beyond the Solar System, *(iii)* establish new interdisciplinary research, and open up *(iv)* new opportunities for the training and advancement of young scientists, including establishment of *(v)* a new National Research School. This, along with *(vi)* a generous visiting program and *(vii)* a mobility program to allow scientists and students to be abroad for longer periods, will create an internationally visible Centre and *grant PHAB a lasting impact beyond the proposed duration of the Centre*, by training young scientists, giving them transferable skills, and seeding their scientific networks.

The Centre research will have wide *societal interest* as prospects of hospitable environments and life beyond Earth have captivated humankind for centuries. Our study of past climate variations will prove important for debates on human-made Climate Change, rejected by some due to claims that such change is a natural feature of our planet's history. Studies that only measure today's variations cannot overcome such scepticism. The only way to do so, is to reconstruct records of the ancient and recent past and compare them to today's changes. As an example, our estimate of maximum carbon emissions from *natural* plate tectonic arc volcanism is about 1.2 Gt/yr (Fig. 4B), an order of magnitude lower than *Anthropocene* carbon emissions (20-40 Gt/yr), and therefore raise concerns for the future of our planet.

PHABs scientific results will be published in internationally peer-reviewed journals where impacts can be judged using bibliometric measures. PHAB scientists have an outstanding record of studies published in high-profile journals, but impact comes in various forms, and social media and new digital research infrastructures are changing scientific knowledge creation and dissemination. PHAB research will be presented at *(i)* national and international workshops and conferences, we will *(ii)* actively propose and run dedicated sessions and symposia to promote international studies of planetary habitability, and *(iii)* we will organize a bi-weekly publically accessible seminar series with invited international speakers. This will set the scene for potential collaborations, but allows reaching a broader audience. We will also *(iv)* annually organize a workshop with invited guest lectures and the presence of the scientific advisory board (Table 2) to evaluate PHAB progress.

PHAB will disseminate research results and experiences by blogs to the general public/policy makers, and use available social media to maximize distribution. In addition to an official University of Oslo (UiO) website domain, we have reserved an external domain (*planetaryhabitability.org*), which will also be used to promote all Centre activities and results, *in-house* laboratory facilities, software and data repositories. PHAB will have a dedicated Media Coordinator, who will assure that dissemination is streamlined, targeted and realistic, but also organize training for young scientists and assist senior members with their already extensive record of engagement activities. PHAB PI Anne Hope Jahren has recently published two international bestsellers and we will publish at least two popular science books during the lifetime of the Centre. PHAB scientists are currently finalizing a film on *Wilson Cycle Tectonics*. We aim at producing at least two documentaries highlighting our visions and findings, but we also plan to release a series of sonification-based podcasts, documenting the evolving PHAB project to a broad audience through the interaction of science and sound.

## 3. Implementation

**Centre Directors.** The Centre will be headed by *Professor Trond Torsvik* in the first three years, and thereafter by *Professor Stephanie Werner*. Werner is the first and only professor in Planetology in Norway and will act as Deputy Director in the opening years. She has extensive project management experience, most recently as consortium coordinator for a large EU-funded project (PTAL — Planetary Terrestrial Analogues Library: 2016-2021). Werner is also Director of a Norwegian Research School (DEEP — Dynamics and Evolution of Earth and Planets: 2016-2024), funded by the Research Council of Norway (RCN), and she currently participates in three ESA space missions (ExoMars, PLATO and Ariel). Werner is honored by a named asteroid 11449StephWerner for her groundbreaking work on Mars' evolutionary history.

*Professor Torsvik* is an ERC Advanced Grant winner (2011) and founder of the Centre for Earth Evolution and Dynamics (CEED), which he directed between 2013 and 2016 and since 2021. Torsvik has published ~260 peer-reviewed papers and an award-winning book on *'Earth History and Palaeogeography'* (2017). For more than a decade, Torsvik has fronted the development of a unified theory explaining how plate tectonics and mantle processes interact. These efforts were portrayed in the TV documentary *The Mind of the Universe* (2017) and he has been awarded the *Arthur Holmes Medal* (2016), the *University of Oslo Research Prize* (2016) and the *Fridtjof Nansen Medal* (2017), among many other awards and prizes.

**Group Leaders.** All PIs (67% female) have excellent records of accomplishment and documented abilities to conduct groundbreaking research. Four PIs (Gaina/Jahren/Torsvik/Werner) are elected members of the Norwegian Academy of Science and Letters. *Lee Hsiang Liow* holds an ERC Consolidator Grant in biology, *Carmen Gaina* is a former CEED director (2016-2021) and *Anne Hope Jahren* is an author of award-winning popular-science books. Her first book — 'Lab Girl' (2016) — was eight consecutive weeks on *The New York Times Bestseller List*. The PIs have received numerous awards and prizes, and most recently, *Clinton Conrad* was awarded the *Evgueni Burov Medal 2020.*

## Centre Organisation.

PHAB is organized into three *research themes*, overseen by the Directors, which are subdivided into *work-packages* (WPs) headed by two PIs (Table 1) that also oversee responsibility for specific *research topics* and *topical triplets* (Fig. 3). All PIs, led by the Directors, form the Leadership Team that directs research, training, hiring and allocation of resources towards WPs, identifying new projects and promoting synergies. Experienced management is secured through our designated administrator (*Gørbitz).* An Advisory Board, headed by *Professor Heike Rauer* (Director German Aerospace Center Berlin and PI PLATO[12]), includes prominent scientists (Table 2) with expertise covering important PHAB research directions.

PHAB will be hosted by UiO and physically located in one building (ZEB) at the main campus (near the Geoscience Department), optimizing scientific collaboration and a prolific student environment. In addition to the six PIs, PHAB will include nine key scientists at start-up (55% female, Table 2), including three early career scientists (Callegaro/Kiraly/Shephard) with ongoing *OUTSTANDING YOUNG TALENT* grants. *Domeier* is a former recipient of this prestigious RCN grant and currently an ERC Consolidator finalist. Two new full-time professors will be recruited and the total number of scientists in the opening year will be about twenty-five, funded through PHAB or existing projects lasting to 2023-2025. We will also engage six adjunct Professors (20% position) at any given time.

Our early and mid-career scientists have received many awards and prizes, including the *EGU Arne Richter Outstanding Young Scientist Award* (Shephard/Domeier) and the *Else-Ragnhild Neumann Award for Women in Geosciences* (Shephard/Kiraly). PHAB will sustain its excellent gender balance in leadership and recruitment (60% overall female), and increase diversity by soliciting applications from candidates with different cultural backgrounds. We will actively maintain an open and inclusive research culture, promoting and facilitating junior scientists to build careers that go beyond those of senior scientists at PHAB.

In-house laboratories include CLIPT (stable isotopes: Led by *Jahren*), and two National Research Infrastructures, the Ivar Giæver Geomagnetic Laboratory (IGGL: Led by *Torsvik*) and the Goldschmidt Laboratory (U-Pb geochronology and radiogenic isotopes: Led by *Augland*). Laboratory (~1.3 MNOK/yr) and computational/data-storage costs (~0.6 MNOK/yr) are extensive and PHAB will have access to high-performance computing resources hosted by the Norwegian Research Infrastructure Services (computing effort led by *Werner* and *Conrad*) and the European Partnership for Advanced Computing in Europe (awarded to collaborator *Caracas*).

**Table 2. Organization**

***DIRECTORS***
T.H. Torsvik, S.C. Werner
***ADMINISTRATOR***
T.-L. Gørbitz
***ADVISORY BOARD***
H. Rauer *(Germany)*
D. Canfield *(Denmark)*
J. McElwain *(Ireland)*
P. Tackley *(Switzerland)*
***PRINCIPAL INVESTIGATORS***
C.P. Conrad, C. Gaina
A.H. Jahren, L.H. Liow,
T.H. Torsvik, S.C. Werner
***KEY SCIENTISTS***
L. Augland, S. Callegaro
M. Domeier, A. Kiraly
K. Mair, V. Maupin
T. Reitan, G. Shephard
R. Trønnes
**SUPPORT STAFF**
N.N. *(Media Coordinator)*
W. Hagopian, P. Silkoset
*(Laboratory Managers)*
***KEY COLLABORATORS***
A. Biggin *(UK)*
A. Bouvier *(Germany)*
R. Brasser *(Hungary)*
J. Brodholt *(UK)*
R. Caracas *(France)*
C. Davies *(UK)*
T. Gerya *(Switzerland)*
B. Hannisdal *(Norway)*
T. Lenton *(UK)*
J. Luu *(USA)*
I. Mann *(Norway)*
S. Mojzsis *(Hungary)*
S. Peters *(USA)*
D. Royer *(USA)*
B. Schubert *(USA)*
I. ten Kate *(Netherlands)*
G. Tinetti *(UK)*

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