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Kate Horan

# Falkland Islands (Islas Malvinas) in the Permo-Carboniferous

## From Icehouse to Greenhouse

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## From Icehouse to Greenhouse

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# Editorial Support to Author

**Simon Crowhurst** read Experimental Psychology at the University of Oxford and worked for more than 20 years with Nick Shackleton learning the principles of astronomical forcing of sediment sequences. He has many publications of which he is a co-author, and illustrated the Willis and McElwain book on the Evolution of Plants. He now works as the Senior Laboratory Technician at the University of Cambridge Earth Sciences department.

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**Phil Stone** is a Research Associate with the British Geological Survey in Edinburgh. Between 1998 and 2009 he acted as Geological Advisor to the Department of Mineral Resources, Falkland Islands Government, and was responsible for recovering from the Falkland Islands the borehole core that forms the basis of this study.

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# Preface

The opportunity to study palæoclimate has been an exciting, challenging and rewarding experience. As a Natural Sciences undergraduate student at the University of Cambridge, I developed a strong interest in Earth Sciences, in particular climate change, sedimentology and geomorphology. During my master's degree, I was lucky enough to take these interests further in a three-month research project. It is the results of this project which provided the impetus for writing this book.

Developing an understanding of Earth's climatic history has become all the more intriguing and necessary in order to appreciate current climate change in the context of longer timescales. Transitions from icehouse to greenhouse worlds and vice versa are the largest of the climatic switches known to occur on Earth and they are accompanied by extreme palæoenvironmental changes. This book documents one such change, the Late Carboniferous to Permian deglaciation of southern Gondwana, by drawing upon evidence from a Gondwana fragment that became the Falkland Islands (Islas Malvinas) microplate following the break-up of the supercontinent.

The sedimentology of the Hells Kitchen Member of the Port Sussex Formation in East Falkland comprises deposits that document the switch from icehouse to greenhouse conditions. These Falkland Islands strata correlate with glacigenic units in South Africa and South America, all of which were deposited during the widespread, Late Carboniferous to Early Permian glaciation of Gondwana. Sedimentary logging, X-ray fluoresence (XRF) scanning and reflectance scanning were carried out on solid rock cores which host these sediments. The data collected was used to support a facies evaluation and an investigation into the nature of the climate change. In addition, it presented a unique opportunity to explore the application of Milankovitch orbital cycles to sedimentary sequences at this time.

This book is published as part of the series of Springer Earth System Sciences. It serves as a case study because the Falkland Islands cores pinpoint evidence from just one locality nested within the Gondwanan supercontinent at the time of the icehouse to greenhouse transition. The research complements other accounts of Falkland Islands geology, the climate and palæotectonic reconstructions of the Gondwanan supercontinent and long-term climate change. It is hoped that it will be a valuable resource to both scientists and students working across a range of disciplines within the Earth Sciences, but primarily its focus is geared towards those with research interests in the above areas.

Kate Horan

# Acknowledgments

I am extremely grateful to my teachers, in particular Richard Tighe and Merrick Weems, who were responsible for sparking my initial interest in this subject area and inspiring me to go on to university to pursue my interests. Special thanks go to Simon Crowhurst for his strong support and enthusiasm throughout the project which, combined with his insightful contributions particularly into time series work, have been invaluable. The borehole cores on which this study was largely based were acquired between 2005 and 2007 by Falklands Gold and Mineral Ltd. Thanks go to Dr. Phil Stone for recovering these cores from the Falkland Islands and to the British Geological Survey for making them available for this study. Logistical support for shipping the borehole cores to the UK was provided by the British Antarctic Survey. Phil Stone also provided excellent scientific editorial guidance.

Additionally, I would like to thank Dr. Morag Hunter and Prof. David Hodell for their helpful discussions during the production of the project at Cambridge. Further thanks go out to James Rolfe who assisted with Total Organic Carbon measurements and to Dr. Claus-Dieter Hillenbrand, Vikki Peck and Claire Allen, from the British Antarctic Survey, who provided guidance on how to approach interpretations of glacial sediments. It has been a great pleasure to work with many different people all of whom have in some way provided me with some inspiration and made the project a lot of fun. Girton College, Cambridge, also kindly covered some of the project expenses.

Finally, I would like to thank my parents for their support during my studies.

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# Abbreviations

| | |
|---|---|
| LPIA | Late Palæozoic Ice Age |
| TOC | Total Organic Carbon |
| IRD | Ice Rafted Debris |
| ETP | Synthetic Carboniferous orbital solution including eccentricity, tilt and precession |
| L* | Reflectance parameter: lightness |
| a* | Reflectance parameter: red/green ratio |
| b* | Reflectance parameter: blue/yellow ratio |
| XRF | X-ray fluorescence |
| Fe10 | For elements measured at more than one energy band by the Avaatech XRF core scanner, the number represents the voltage in kV; here iron measured on the 10 kV run |
| $pCO_2$ | Partial pressure of carbon dioxide |
| $\delta^{13}C_{org}$ | Isotope ratio of $^{13}C/^{12}C$ in organic matter |
| $\delta^{13}C_a$ | Isotope ratio of $^{13}C/^{12}C$ in atmospheric $CO_2$ |
| PCA | Principal Component Analysis |
| SPSS | Statistical Package for the Social Sciences |
| BGS | British Geological Survey |

# Abstract

The Late Carboniferous to Early Permian 'icehouse to greenhouse' transition in the Falkland Islands was accompanied by cyclical waxing and waning of the Gondwanan, south polar ice sheet. The cyclical changes are manifested in the sedimentary deposits of the Fitzroy Tillite and Port Sussex formations. This study looks in detail at two sediment cores spanning these formations that were recovered from the Falkland Islands in 2008 following a mineral exploration programme. The lithologies and sedimentary fabrics appear to record a switch from deposition under a grounded ice sheet to glaciolacustrine or glaciomarine deposition punctuated by minor episodes of ice advance and retreat during a period of net ice sheet retreat. X-ray fluorescence and reflectance data have been used to quantify the change in terms of geochemical and geophysical properties respectively. Elements including zirconium, manganese, chromium, iron and titanium helped to constrain the cyclicity. Wavelet and spectral analyses, run to look for prominent periodicities in the data, were suggestive of orbitally forced oscillations within the transition. This permitted the development of a hypothetical time framework for the series spanning approximately 1.2 million years through age modelling. The integrated approach of this research, which combines sedimentological data with geochemistry, makes it a robust insight into this past climatic transition and may help to evaluate and inform predictions of future climate change.

**Keywords** Falkland Islands · Fitzroy Tillite Formation · Hells Kitchen Member · Permo-Carboniferous · Icehouse to greenhouse · Gondwana · Deglaciation

# Chapter 1
# Introduction

**Abstract** Investigating the dynamic behaviour of Earth's climate system remains a significant challenge. It is partly motivated by our limited knowledge of how the system will evolve in the future and the resilience of ice sheets to perturbations. Throughout geological history, the Earth has been subjected to extreme climatic transitions. These have taken place over various spatial and temporal scales ranging from localised decadal oscillations through to millennial- and multi-millennial-scale processes affecting the whole planet. The focus of this study lies within the latter kind, wherein the Earth flips between icehouse and greenhouse states. During the Permo-Carboniferous, when the Gondwanan supercontinent lay close to the South Pole, sedimentary deposits developed that documented one such transition. This chapter outlines the potential for study in material extracted from East Falkland during a mineral exploration programme in 2008. The geographical location of the Falkland Islands in the Permo-Carboniferous based upon Palæozoic reconstructions of Gondwana is discussed and the stratigraphic links between the Falklands deposits and other similar deposits from across the continent explored. Our understanding of how major climatic changes proceed, and the possible triggers behind them, could be significantly improved by studies of such deposits.

**Keywords** Permo-Carboniferous climate change · Icehouse to greenhouse · Gondwana · Falkland Islands · Ice sheets

## 1.1 Overview

The climatic conditions of the Late Palæozoic Earth oscillated between cold 'icehouse' states with persistent polar ice and warm 'greenhouse' states without polar ice (Fig. 1.1). With many questions about the long-term future of our climate,

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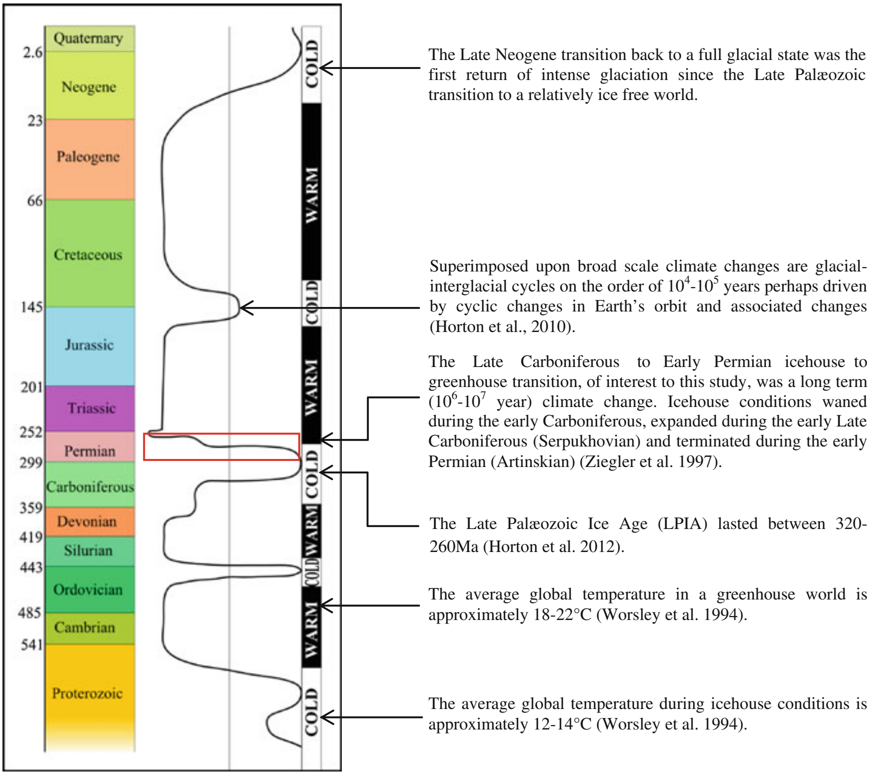


**Fig. 1.1** Earth's long-term climate history modified from Scotese et al. (1999) to reflect the recent international chronostratigraphic chart (International Commission on Stratigraphy, August, 2012). *Numbers on the left hand side* of the figure refer to age in millions of years. Note that this figure does not account for the diachroneity of climate change across continents

it is increasingly important to improve understanding of how these major climatic changes proceed. The Late Carboniferous Ice Age provides the last complete record of a transition from icehouse to greenhouse conditions (Gastaldo et al. 1996) and forms the focus of this study.

Mineral exploration drilling in the Falkland Islands between 2005 and 2007 generated eight core sections located between Old House Rocks and Black Rock, East Falkland, that span the Permo-Carboniferous icehouse to greenhouse transition. Commercial interest in these cores declined in 2008 and permission was obtained from the exploration company, Falklands Gold and Minerals Ltd., for samples to be taken and returned to the UK for assimilation into the national core archive. This is maintained by the British Geological Survey (BGS) at their headquarters in Keyworth, Nottingham. The main objective of this book is to place sedimentological and geochemical data collected from these cores within a framework that explains the interactions between climate and glacier dynamics over the segment of the Gondwanan continent from which the East Falkland Islands formed. The core sequences contain deposits belonging to the Fitzroy Tillite and Port Sussex formations. These are characterised by subglacial, massive diamictite passing upwards into glaciomarine/glaciolacustrine diamictites, mudstones and black shales; a record which provides an excellent opportunity to study ice sheet advance and retreat across the East Falklands margin.

The nature of the icehouse to greenhouse transition may be explored through addressing the following four questions.

1. Does the transition occur through gradual climatic drift to a warmer state or is it marked by oscillations, episodic or periodic, between the extremes before a tipping point is reached?
2. What are the links between the sedimentological and the physicochemical properties of the deposits?
3. Could the climate changes within the course of the transition have been orbitally forced? Improving our understanding of the climate system earlier in Earth's history may have relevance for our ability to gauge future climate change projections operating under similar climate dynamics.
4. How do the deposits in the Falkland Islands correlate with deposits in other localities that also span the transition? Synthesising the stratigraphic record from the Falkland Islands with records across Gondwana could help to constrain the waxing and waning of glacial intervals of the Late Palæozoic Ice Age (LPIA) and provide insights into the drivers of ice growth and deglaciation.

## 1.2 Geographical Context

Today, the Falkland Islands are an archipelago in the South Atlantic Ocean situated between 51° and 52° 30′S and 57° 30′ and 61° 30′W. They comprise two main islands, East and West Falkland, and several hundred smaller islands (Fig. 1.2).

In contrast, current Late Carboniferous reconstructions of the Gondwana supercontinent place the Falkland Islands at high latitudes off the east coast of South Africa and in a rotated position close to Port Elizabeth. These reconstructions (e.g. Adie 1952; Marshall 1994) are based on the continuity of structural trends from the Gondwanan orogeny (Curtis and Hyam 1998), outcrop patterns, palæo-ice flow directions, palæomagnetic reconstructions (Mitchell et al. 1986) and palæocurrent data (Hyam et al. 1997) and are supported by the distribution of Early Devonian marine faunas of the Malvinokaffric Province (Bradshaw 1998). Comparison of Permian facies, ichnology and palæocurrents in the Falkland Islands and the Dwyka, Ecca and Beaufort (part) groups in South Africa also support this (Trewin et al. 2002). Nevertheless, despite the compelling evidence for microplate rotation arising from comparisons of onshore geology, it should be noted that there is a contrary view held mainly by those working with offshore data generated by the hydrocarbon exploration programmes currently active around the Falklands.

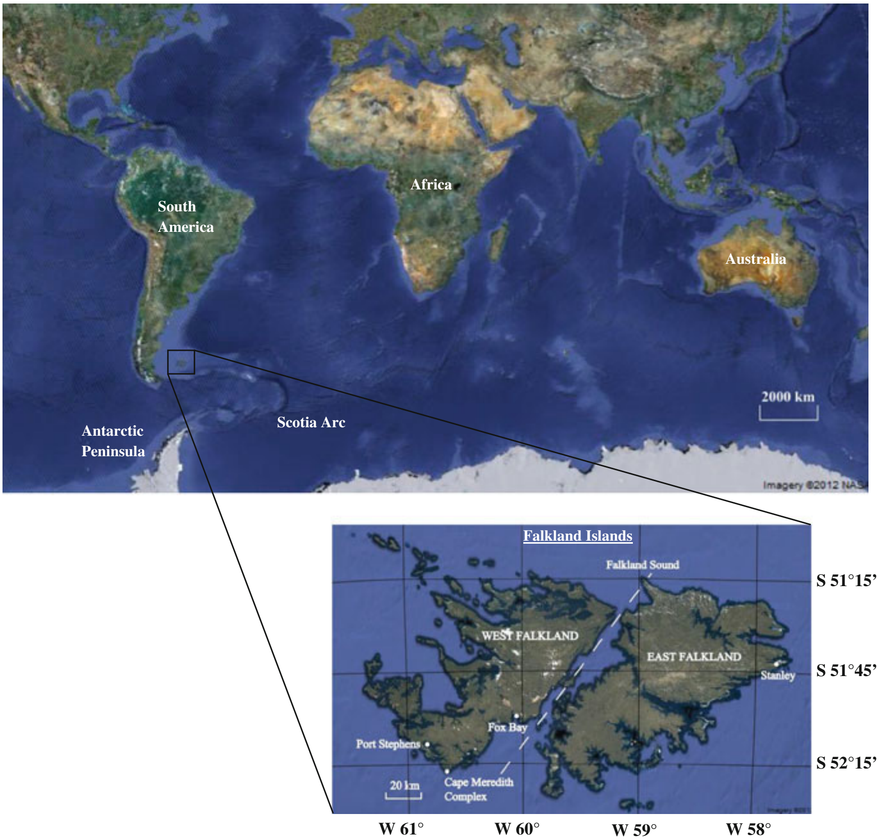


**Fig. 1.2** Geographical location of the Falkland Islands with locations relevant to the LPIA in Gondwana labelled. *Inset* highlights study site. Images were taken and adapted from Google Earth

The offshore data provide no evidence in support of the rotational model. Indeed, they are more readily reconciled with a Gondwana break-up in which the Falklands remain a part of a fixed Falkland Plateau extending from the South American margin (e.g. Lawrence et al. 1999). This debate continues.

Gondwana migrated across the South Pole during the Late Palæozoic (Fig. 1.3), and as a result, glaciation began in western Gondwana (present-day South America) in the Famennian (Late Devonian) (Caputo et al. 2008) and ended in eastern Gondwana (eastern Australia) in the Capitanian (Middle Permian) (Fielding et al. 2008a). As a consequence, secular climate change associated with this latitudinal movement across zonal climatic belts was superimposed on the change from ice-house to greenhouse (Scotese et al. 1999).

Crowell and Frakes (1972), Crowell (1983) and Caputo and Crowell (1985) concluded that a centre of glaciation migrated across South America, South Africa and Antarctica from 350 to 240 Ma. Ice centres waxed and waned across the


**Fig. 1.3** Palæomagnetic studies demonstrate that movements of the continents resulted in a relative drift in the position of the South Pole; figure adapted from Henry et al. (2012), and Crowell and Frakes (1972)

different sites during this time interval. Glaciation likely ensued when broad continental areas reached near-polar positions, and expanses of open water were sufficiently near to provide evaporative moisture. A reconstruction of ice cover in the Late Carboniferous is provided in Fig. 1.4 and illustrates the likely ice flow patterns.

In most localities from the Gondwanan landmasses, glacigenic deposits are relatively thin and consist of a variety of rock types and/or striated surfaces interpreted to indicate terrestrial or grounded marine ice sheets (Matsch and Ojakangas 1992). When Gondwana began to break up ~200 Ma (Stone et al. 2012), the glacial deposits became dispersed across the continents. Table 1.1 collates information from various sources on the thickness and age of the corresponding glacial deposits across the present-day continents, and Fig. 1.5 synthesises this information in time. Difficulties in correlating thicknesses arise because glacial strata are often eroded; only those dumped during glacial retreat are typically preserved. The correlation carried out in the time domain involved hypotheses about the relative timing of events documented in the sedimentary record. Some inconsistencies between sources (shown in Table 1.1) mean some boundaries are approximate, highlighting the need for improved chronology. Oman, Pakistan and Yemen were in the Northern Hemisphere at this time, which explains their deviation from the trend of glacial strata becoming progressively younger in successive stratigraphical columns from left to right across Fig. 1.5. Australia underwent early

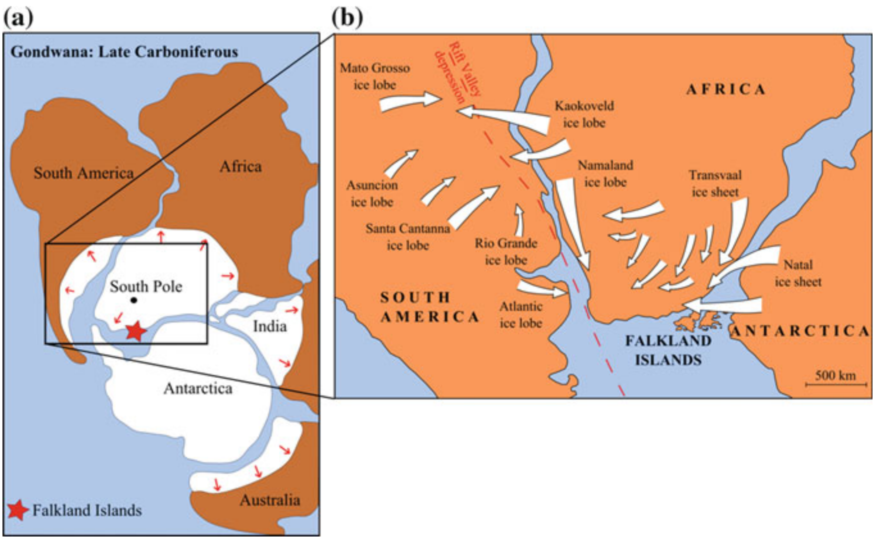


**Fig. 1.4** **a** Reconstruction of ice extent across Gondwana with supporting evidence from various authors utilised (e.g. Scotese et al. 1999). The Falkland Islands lay off the southeast coast of South Africa at this time. **b** Ice flow patterns in the Late Palæozoic; adapted from Stollhofen et al. (2008). Work by Visser (1987, 1997) and Grill (1997) showed that not all of these ice centres were active at the same time

glaciations and later Permian glaciations as a result of its position relative to the South Pole (Fielding et al. 2008b, c). Therefore, it is also difficult to correlate Australia with glaciations in Antarctica, Africa, the Falklands and South America.

## 1.3 Geological Context

The geology of the Falkland Islands has three main divisions: the Proterozoic Cape Meredith Complex, the Silurian to Devonian West Falkland Group and the Carboniferous to Permian Lafonia Group (Aldiss and Edwards 1999). These are illustrated in Fig. 1.6. The Lower Lafonia Group, of interest to this study, is composed of three stratigraphic units, the Bluff Cove, Fitzroy Tillite and Port Sussex Formations (Fig. 1.7).

## 1.4 Structural and Tectonic History

The Falkland Islands are just one segment of the Permo-Triassic Gondwanan Fold Belt which was displaced during the fragmentation of Gondwana and opening of the South Atlantic Ocean ~300 Ma. As the ocean opened, the Falkland Islands