Preface

The turn of the 21st century ushered in an upsurge of questioning of contemporary visions of the nature of mantle convection and, most importantly, its link with surface volcanism. Since the early 1970s the mantle plume hypothesis had been the most popular explanation for volcanism apparently not explained by plate tectonics, including both large-volume magmatism and volcanism in regions not near to plate boundaries. The plume hypothesis, originally proposed by W.J. Morgan in 1971, provided a mechanism for the formation and sustaining of the "hot spot" in the mantle that J.T. Wilson had suggested in 1963 was the cause of the Hawaiian volcano chain.

Morgan's plume hypothesis envisaged a cylindrical column of hot rock rising from the deep mantle to continually feed the surface volcanism. Furthermore, approximately 20 such plumes were proposed to exist in the Earth. In addition to Hawaii, these were postulated to underlie Macdonald seamount, Easter island, the Galapagos. Juan Fernandez, Brazil, Yellowstone, Iceland, the Azores, the Canary Islands, Hoggar, Ascension island, Tristan da Cunha, the Bouvet triple junction, Crozet, Reunion, Kerguelen, Caroline seamount and Lord Howe. Plume theory provided an elegant explanation for time-progressive volcanic chains and relative fixity between melting anomalies. Major later expansions of the hypothesis included the proposals that plume development involves a plume-head/plume-tail sequence, represented by large igneous province formation followed by time-progressive volcanic chains, and that lower-mantle and core-mantle boundary geochemical tracers may be detected in hot spot basalts. More plumes than the original ~ 20 were proposed, popular lists typically containing 50 - 100 candidates. The hypothesis was extended to other terrestrial planets, and applied to explain features interpreted as volcanic on Venus and Mars.

Nevertheless, many scientists have been disappointed at the ability of observational data collected over the last three decades to confirm the predictions of the plume hypothesis. Skeptics noted observational mismatches, pointing out, for example, that the association of large igneous provinces with time-progressive volcanic chains is the exception rather than the rule, that many chains are not time-progressive, that hot spots have not been reliably shown to be relatively fixed and that the interpretation of some geochemical species as indicating deep-lower-mantle origin is not safe. They pointed out the dearth of questioning of the plume explanation for volcanism, and instances of discrepancies being attributed to samples yet to be observed, or local variations in the nature of the presumed plume.

However, what are the alternatives? The development of an alternative was seen by many to offer a new and fresh, win-win avenue of investigation in Earth science. If an alternative could be developed and tested, it could either supplant the plume hypothesis, and bring about arguably the most significant paradigm shift in Earth science since the advent of plate tectonics, or if found unsustainable, would strengthen the plume hypothesis.

In an effort to develop an alternative, a GSA Penrose conference, *Beyond the Plume Hypothesis*, was held in Iceland in 2003. There, over sixty scientists from twelve nations brainstormed the problem, the result of which was the first book on the subject, *Plates, Plumes, and Paradigms* (P^3), published by the Geological Society of America as Special Paper 388, in the Fall of 2005. One of the many positive developments that emerged from the publication of P^3 was an upsurge of enthusiasm amongst plume-advocate scientists to engage in serious debate. As a result, the AGU Chapman conference, *The Great Plume Debate* was held at Ft. William,

Scotland, in 2005. There, the idea for the present book, *Plates, Plumes, and Planetary Processes* (P^4), that includes both plume-advocate and alternative-advocate points of view was conceived.

P^4 is an expression of the current struggle of the Earth science community to deal with the formidable challenge presented by the current debate about the nature and existence of mantle plumes, and its contents represent well the current state of play. During the last four years, the debate has grown from embryonic beginnings in the private exchanges of a few individuals to being global, popular and cross-disciplinary. The present volume marks an important landmark in this development in that it is the first compendium that specifically targets a combination of plume-advocate and plume-skeptical chapters that focus on debate and justification, rather than assumption, of preferred.

Many aspects of the current state of play of the debate are well reflected in facets of P^4. It is clear that a broad spectrum of opinion exists, ranging from the view that the available evidence essentially rules plumes out, to the view that it requires them, with the majority of practitioners occupying the middle ground. To perceive Earth scientists to be divided into two camps is thus to distort reality.

Virtually every subdiscipline of Earth science has contributed relevant data, an aspect that is both a major strength of the subject but also a formidable challenge to the practitioner. How is it possible for the individual scientist to develop an informed opinion when it is first necessary to understand and judge the evidence from several major subdisciplines spanning almost the whole of geology, geophysics and geochemistry? The temptation in the past has been to acknowledge the shortcomings in one's own data whilst trusting that evidence from other (often less familiar) subdisciplines is decisive. When faced with the requirement for a seemingly impossible breadth of knowledge and understanding to understand a subject, the temptation to accept the judgment of perceived magisters becomes strong. The debate concerning the existence or otherwise mercilessly denies those involved the comfort of this approach.

A great deal of progress has been achieved over the last four years. Work has become well focused on the discriminants that have real potential to rule certain models out, such as heat, temperature, mechanisms for producing the observed magmatic volumes and eruption rates, and the nature and location of the magma sources. Hand in hand with this, the uniqueness of common interpretive schemes for many kinds of data, e.g., seismic and geochemical, have been revisited.

Alternative theories have matured and strengthened and are now clearly divided into two categories. One, the "Plate" model, attributes melting anomalies to processes related to plate tectonics. The occurrence of magmatism is attributed to the existence of extensional stress in the lithosphere, which is viewed as resulting directly or indirectly from plate tectonic processes, and in the case of intraplate magmatism, also the non-rigidity of the plates. Variable magmatic volumes are attributed to variable fusibility of the source, inhomogeneity being maintained again by plate tectonic processes. Bolide impact comprises the other category of alternatives. It is applied to Venus and Mars, and its power to explain the formation of LIPs on Earth is being explored.

The debate has sometimes been inaccurately portrayed as being emotionally charged to the extent that objective judgment is impaired. We direct readers interested in the human aspects of the subject to the insightful analysis chapters that comprise the final section of P^4.

A particularly pleasing aspect of the debate is the many younger scientists who are becoming involved and contributing to the field fresh and innovative new ideas, investigative approaches and cross-disciplinary working groups. The debate is now commonly taught in undergraduate and graduate student classrooms, guaranteeing a healthy supply of fresh,

enquiring new minds to the subject in the future. The debate regarding the origin of melting anomalies is a subject that most professional Earth scientists would today agree is to a greater or lesser extent undecided – the time is not yet ripe. In that context the redoubling of effort amongst the experienced, and the influx of more fresh minds to the subject is needed and welcomed. We, the editors, hope that the present book will both equip and encourage some scientists from the cradle and others to their graves in their pursuit of this subject.

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Scope of the Volume, the Review Process, and Acknowledgments

The chapters in this book are grouped into sections comprising plates & plumes, convection & seismology, heat & temperature, geochronology & reference frames, oceanic and continental melting anomalies, planetary volcanism, education, and platonics & plumacy. Many of the chapters are followed by a block of formal discussion.

The chapters in this volume were formally reviewed by two or more external critical reviewers and by both of the volume editors. The review process for chapters authored by one of the editors was handled by the other editor. We sought reviewers expected to advocate contrasting viewpoints, to expose authors to the most challenging criticisms possible and to encourage the confrontation of difficulties.

We extend our grateful thanks to all the reviewers, who include Jon Hernlund, Marge Wilson, David Green, Paul Alexandre, Derek York, Don Anderson, Ellen Stofan, J.C. Aubele, Paul Stoddard, David Naar, Jeff Karson, Keith Bell, Ajoy Baksi, Joann Stock, Bernhard Steinberger, Jeff Gu, Bruce Julian, Kaj Hoernle, *falloon rev2, John Mahoney, Albrecht Hofmann, Peter Vogt, Richard Ernst, Anne Hofmeister, Dion Heinz, Jolante van Wijk, Keith Putirka, Trevor Falloon, Chris Hawkesworth, Tristram Hales, Bob Christiansen, Andy Saunders, Lindy Elkins-Tanton, Stephen Marshak, Bob Tilling, Alexander Basilevsky, Claudio Vita-Finzi, Angelo Peccerillo, Ercan Aldanmaz, Peter Bunge, Walter Kiefer, Rob Harris, Art Lachenbruch, Richard Ketcham, Walter Zuern, Zhijun Du, Romain Meyer, Sebastien Pilet, Leone Melluso, Scott King, Arie van den Berg, Garrett Ito, Erik Lundin, Peter Vogt, 1 anonymous, Alison Shaw, David Graham, Richard Gordon, Hetu Sheth, Piero Comin-Chiaramonti, Godfrey Fitton, Will Sager, Dave Scholl, John Tarduno, Norman Sleep, Jun Korenaga, Tim Minshull, Greg McHone, Sergio Rocchi, Françoise Chalot-Prat, Rajesh Srivastava, Jyotiranjan Ray, Senthil Kumar, Manoj Pandit, S.K. Tandon, Mike Widdowson, Carol Stein, Mark Richards, Ian Norton, Paterno Castillo, Alan Woolley, *Stuart reviewers, Peter Hooper, Erin Beutel, Warren Hamilton, C.J. Talbot, John Cosgrove, Bob Detrick, Cinzia Farnetani, Jerry Winterer, Lars Rupke, Steve Grand, Soichi Omori and an additional *number anonymous reviewers.

Chapters were posted on the world wide web as they were accepted, and formal discussion of them was open to the public from November 2006 until the end of January 2007. Contributions were posted rapidly as they were submitted. To the Editors' knowledge, this is the first time such an exercise has been conducted. Our experience was that it was extremely successful. Response was vigorous and many emails of appreciation were received from both participants and observers.

Our goal in producing this volume has been to assemble a diverse compendium of papers representing a broad variety of subdisciplines, field areas and viewpoints, under a single cover. In this way we hope that this volume documents well the state of the subject and the viewpoints of many scientists, at this point in the present re-evaluation of the origin of melting anomalies. We hope that P^4 will comprise a milestone and a useful resource that will help to further this fascinating subject. We gratefully thank the Geological Society of America for facilitating both P^3 and its present daughter volume, P^4.