Celebrating 50 years since the publication of *Folding and Fracturing of Rocks* by J. G. Ramsay

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Abstract: John G. Ramsay's book *Folding and Fracturing of Rocks* was first published in 1967. It set the research agenda for, and the approaches to, modern structural geology. It is recognized as one of the most influential texts in the subject area and was underpinned by significant research publications by the author; its weight added to by later texts and articles. John was also an enthusiastic teacher of structural geology, and many of his tutees have gone on to forge their own careers in structural geology, inspired to do so by John, his teaching and approaches. This Special Publication serves as a golden 50 year celebration of the book, and also of John's lifelong work and career as an innovative scientist, inspiring mentor, excellent teacher, and great field structural geologist.

Folding and Fracturing of Rocks was first published in 1967 (Ramsay 1967) as part of the 'International Series in the Earth and Planetary Sciences' by McGraw-Hill Inc. The book was published during the period when Earth Science went through its most fundamental reorientation. Plate tectonics emerged as the unifying theory among Earth scientists, convincingly describing the tectonic processes that shape our planet. In this context, John Ramsay's comprehensive book on how rocks deform was welcomed. John used mathematical terms to develop the basic theories of stress and strain in rocks, so that they could be used practically on field examples to illuminate and quantify processes in structural and tectonic geology. It is underpinned by the author's long-standing research into the application of mathematical principals to structural geology documented in numerous research papers. After being out of print for some time, despite being one of the most references texts in structural geology publications (see **Lisle *et al.* 2019**), *Folding and Fracturing of Rocks* was republished in 2003 by The Blackburn Press. In the preface to the 2003 printing of the volume, John Ramsay himself describes why he believes the book and its principles have stood the test of time:

> The reasons for the relevance of this book to current research are; first, the book is based on sound mathematical principles which have not become dated; and, second, the discussions of deformation theory are backed up with many illustrations of the structures seen in naturally deformed rocks.
>
> John G. Ramsay
> September 2003

In the 50th year since the book's publication, international researchers in structural geology and tectonics came together, with John Ramsay, in 2017 at the European Geosciences Union (EGU) meeting in Vienna to celebrate (Fig. 1). The occasion was honoured with a special session '*Folding and Fracturing of Rocks* – 50 Years of Research since the Seminal Text Book of J. G. Ramsay'. This volume, with its collection of research papers, follows the celebration documenting the impact of the book on modern research in structural geology and tectonics, and, in particular, how the concepts and challenges introduced by John Ramsay 50 years ago have been employed, and have evolved into modern-day structural geology. John's work was particularly focused on the use of field analysis and analogues as the basis for theoretical and numerical models, and many of the contributions here follow a numerical or quantitative approach.

Biography

John was born in 1931 in London. He was educated at Imperial College, London gaining a first class bachelor's degree in 1952 and a PhD in 1954,

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Fig. 1. John G. Ramsay addressing his audience at the European Union of Geosciences (EGU) meeting in Vienna, on the morning of 25 April 2017, opening the session celebrating 50 years since the publication of *Folding and Fracturing of Rocks*, and followed by a reception to meet friends, old students and fans (photo credits: Susanne Buiter and Clare Bond).

working on superposed fold systems at Loch Monar, Scotland. After military service, as a musician, he returned to Imperial College in 1957 as a lecturer in geology. In 1964 he was appointed to Readership and then Professor in Geology in 1966, before taking up professorial positions at the University of Leeds (1973) and at ETH in Zurich (1977).

Besides being the founding member of the editorial board for several scientific publications, such as *Tectonophysics* and *Journal of Structural Geology*, John was instrumental in setting up the Tectonic Studies Group (TSG) of the Geological Society of London in 1970.

He has been recognized for his work in advancing structural geology with many awards including: the Bigsby (1973) and Wollaston (1986) medals of the Geological Society of London; the Société Géologique de France Prestwich Medal in 1989; the Sir Arthur Holmes Medal of the European Union of Geosciences (EGU) in 1984; the C. T. Clough Medal (1962) of the Geological Society of Edinburgh, Scotland; and the University of Liège Medal in 1988. In 1992 he was named a Commander of the Most Excellent Order of the British Empire in the Queen's Honours list. He is a Fellow of the Royal Society (elected 1973), and holds honorary fellowships of the Geological Society of America, the Société Géologique de France, the Indian National Science Academy, the American Geophysical Union, the United States National Academy of Sciences and the Geological Society of London.

The impact of *Folding and Fracturing of Rocks*

This Special Publication starts with a personal perspective of the impact of '*Folding and Fracturing of Rocks*' (**Treagus & Hudleston 2018**). In 1967 they were two young students who, inspired by the book and the work of John Ramsay, forged life-long careers in structural geology. Hudleston, like many undergraduate students at Imperial College at the time, took John Ramsay's Advanced Structural Geology course, and later became a PhD student under his tutorage. Treagus (née Beech), an undergraduate at Manchester University, went on to Imperial College to take the MSc course in Structural Geology and Rock Mechanics led by John Ramsay and Neville Price that incorporated much of the book. Their contribution attests to the impact that John's work had on their careers and lives.

The impact of *Folding and Fracturing of Rock*s was, of course, much broader and long-lived across the structural geology community. In their paper, **Lisle *et al.* (2019)** use 'modern-day' metrics to investigate the research impact of the volume not just through citation history, but also through the rise in research of the key topics that form some of the main chapters in the book, namely: superimposed folding; fold classification based on layer thickness variation; simple shear deformation; the R_f/φ method; and flexural-slip folding. The metrics show that these topics have spurred and shaped subsequent research. These research themes also form the basis of other papers in this volume, such as analysis of progressive deformation (e.g. **Lloyd 2018**; **Cawood & Bond 2019**; **Forster *et al.* 2019**), strain analysis (**McCarthy *et al.* 2019*a***); the role and analysis of shear zones (**Czeck *et al.* 2019**; **McCarthy *et al.* 2019*b***) and folding (**Griera *et al.* 2018**; **Moulas & Schmalholz 2018**; **Alsop *et al.* 2019**; **Burberry *et al.* 2019**; **Butler *et al.* 2019**; **Watkins *et al.* 2019**). **Lisle *et al.* (2019)** conclude that *Folding and Fracturing of Rocks* is, to date, the most influential text in structural geology research.

Multilayer controls on folding and thrusting

Following the metric theme, and Ramsay's quantitative approach, **Butler *et al.* (2019)** consider 'Where have all the buckle gone?', recognizing that methods adopted to better understand regional-scale folding and thrusting have led to a false distinction between fault-related folding and buckle folding. **Butler *et al.* (2019)** call for a better integration of faulting and folding concepts based on an understanding of the interplay between these processes. Ramsay (1967) provided an overview of the pioneering work on buckles at the time, which led to further work mainly using analogue modelling to better understand the processes at play. Today, numerical modelling is used alongside analogue models, affording new insights into the understanding of folding processes. Here, the role of interfaces between multilayers in determining folding and fold geometries is investigated through numerical modelling by **Griera *et al.* (2018)** and **Moulas & Schmalholz (2018)** in which their work takes a mathematical approach, much lauded by John Ramsay, to better understand folding processes in multilayers. Continuing with the folding theme, **Alsop *et al.* (2019)** apply the quantitative approaches developed by John Ramsay for mechanically 'hard' rocks to folds and thrusts developed in soft unlithified sediments. Their contribution is illustrated with eye-catching photographic images of deformed Pleistocene sediments exposed around the Dead Sea. The photographs and analysis of the fold geometries, following the analytical methods of Ramsay (1967), attest to a complex evolution including superimposed folds, commonly assumed to be associated with higher pressure and temperature deformation processes. The authors conclude by warning that careful interpretation of fold structures is needed in metamorphic rocks of sedimentary origin, as they may have precursor soft-sediment fold structures.

The contributions on folding all highlight the role of multilayers in determining fold geometry and evolution; and the role of multilayer stratigraphy in controlling deformation processes is the topic of many papers in the volume. The final paper in this section investigates the impact of multilayer behaviour on a single fold–thrust structure: **Cawood & Bond (2019)** revisit the classic fold–thrust structure at Den's Door, Broadhaven, Pembrokeshire, SW Wales. The structure famously described by Williams & Chapman (1983) as a fault-propagation fold is reconsidered using a photogrammetric model to ensure geometrical precision in the analysis of the fault-displacement characteristics. The resulting model of fault and fold evolution suggests a more complex evolution, with strain partitioned in different layers during faulting and fold growth.

Progressive deformation and strain

Partitioning of strain during progressive deformation is a second common theme in the Special Publication, with examples ranging from cleavage and vein formation to fracturing in folded multilayers. Ramsay (1967) established a series of, subsequently well used, techniques to determine finite strain in rocks, and associated methods to consider strain partitioning within a rock volume and also strain accumulation through time during progressive deformation. **Lloyd (2018)** applies theories for simple and pure shear applicable to linear objects, as described in Ramsay (1967), to consider different models for vein development and associated formation of the Rhoscolyn anticline, North Wales. The contribution is illustrated with detailed field observations of the veins and host rock, combined with quantitative analysis of their relationships. Such combined field and quantitative approaches were much advocated and pioneered by Ramsay. **Czeck *et al.* (2019)** take a similar approach but utilize cleavage refraction in deformed interlayered quartzites and phyllites to increase the understanding of the rheology of the rock volume. They use detailed observations of cleavage refraction and mineral assemblages in the multilayers to show that the mineral content controls rheology and the associated mineral-specific deformation mechanisms.

McCarthy *et al.* (2019*a*) provide an overview of the determination of finite strain; they consider the strengths and limitations of the strain analysis methods described in Ramsay (1967), and look towards future developments and techniques, asking 'how far have we progressed?'. They conclude, as Ramsay himself remarked in 2003 on the republication of

Folding and Fracturing of Rocks, that the underlying mathematical principals and techniques have not dated and that they remain the underpinning quantitative approach. What has changed is the improvements in image capture, including 3D (and developing 4D) digital images of rock volumes and associated semi-automated analysis. The result is greater 3D information and statistically more robust datasets.

Strain and fractures in regional-scale thrust sheets

Three contributions (**Burberry *et al.* 2019**; **McCarthy *et al.* 2019*b***; **Watkins *et al.* 2019**) to this volume use the Sawtooth fold–thrust belt of Montana as a well-exposed field example to address questions on how strain partitions in regional-scale fold-thrust structures. This carbonate fold–thrust belt is used by **McCarthy *et al.* (2019*b*)** for the application of anisotropic magnetic susceptibility (AMS) analysis to determine strain. **McCarthy *et al.* (2019*b*)** conclude that, despite calculations of up to 60% regional shortening in the Sawtooth Range, there is little evidence of a penetrative deformation fabric, with brittle deformation dominating the evolution of the fold–thrust belt. This brittle deformation is the subject of the contributions by **Watkins *et al.* (2019)**, who consider the fracture patterns in exposed carbonate beds in the frontal fold structure at the Swift Reservoir Anticline, and by **Burberry *et al.* (2019)**, who take a similar approach for the Teton anticline – a classic locality for the study of fracture sets (Stearns 1964) – and the equivalent fold structure along strike to the north. **Watkins *et al.* (2019)**, reaching similar conclusions to those of **Czeck *et al.* (2019)** based on cleavage refraction, suggest that lithology is the main control on fracture intensity at outcrop, due to the combined factors of porosity and bulk composition, with the structural position on the fold having a limited influence on fracture intensity. In contrast, **Burberry *et al.* (2019)** use fracture orientations exposed on bedding surfaces that form the Teton anticline to determine its evolutionary history, and suggest that the observed fractures result from a combination of early stretching, followed by fracture generation and reactivation during folding and thrusting on both the backlimb and forelimb of the fold structure.

Stress and strain to unravel crustal deformation and beyond

In the final set of contributions, the authors **Deng *et al.* (2019)**, **Forster *et al.* (2019)** and **Patton & Watkinson (2019)** apply the concepts of stress and strain to investigate crustal-scale processes. **Deng *et al.* (2019)** consider the influence of existing structures and crustal heterogeneities on later deformation using analogue models. Testing differences in compressive stress obliquity angle to pre-existing graben structures, **Deng *et al.* (2019)** document the discontinuity of fold–thrust structures traced along strike, with the obliquity angle controlling the extent of the rotation of fold–thrust structures away from the original compressive stress direction. In contrast, **Forster *et al.* (2019)** use field observations and Ar/Ar thermochronology of the Ios basement terrane to interpret the South Cyclades Shear Zone as accommodating extensional offset during two episodes of shearing. They use this interpretation to support exhumation of the basement schists and gneisses of Ios from below an eclogite–blueschist facies upper sheet. In the final contribution to the volume, **Patton & Watkinson (2019)** interpret global gravity, topography and seismicity data to explore what the integration of these datasets can tell us about the viscoelastic properties of the Earth and its associated rheological properties. Their contribution applies the mathematical concepts outlined by Ramsay (1967) and employed by him and others to explain geological structures observed in the field, and also to explain large-scale crustal, lithospheric and mantle processes, based on the concept of irreversibility of rock deformation in the solid state. They conclude that the structural processes of folding, shear localization, brittle fracture and strain, as outlined in John Ramsay's *Folding and Fracturing of Rocks*, influence whole Earth dynamic processes.

This Special Publication celebration marking 50 years since the first publication of the *Folding and Fracturing of Rocks* by John G. Ramsay affords a journey through time to discover the personal influence of the book on individuals taught by John, and how over the intervening 50 years the book has influenced the global structural geology community. The Special Publication also considers the practical use of the concepts contained in *Folding and Fracturing of Rocks* to address a range of current issues and questions in structural geology, and documents how the theories and applications described in 1967 have developed as technology and other factors have influenced our science and as new techniques have been employed. Finally, application of the techniques and concepts outlined in the book are applied at increasingly larger scales, to the extent that the concepts originally published in *Folding and Fracturing of Rocks* can be shown to link to whole Earth dynamics. As editors, we hope that this journey is a fitting tribute to John's influence on global structural geology, and particularly through the publication of *Folding and Fracturing of Rocks*.

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