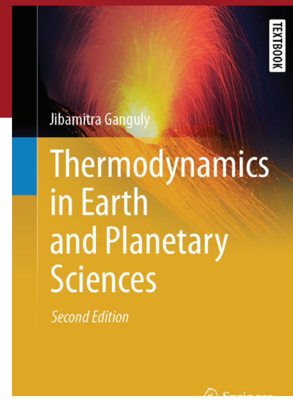
THERMODYNAMICS IN EARTH AND PLANETARY SCIENCES[1]



Thermodynamics is a vast subject with a long and complex history. It is now about two hundred years since the general acceptance of the ideal gas equation of state ($PV = nRT$) (e.g., Biot 1816) and the discovery of limiting behaviour in the high temperature heat capacity of elemental solids (Petit and Dulong 1819). Since then, empirical thermodynamic laws and statistical thermodynamic models have revolutionised our understanding of a myriad of physical and chemical processes and material properties. Thermodynamics underpins much of our modern lifestyle and our understanding of the natural world. It plays, in the words of Russian Nobel laureate in chemistry Ilya Prigogine, "a fundamental role far beyond its original scope" (Prigogine 1977).

Without a doubt, the geological sciences have been one of the greatest beneficiaries of the field of thermodynamics. Thermodynamics provides us with a theoretical framework with which we can understand subjects as disparate as the formation and evolution of the planets, the minerals in the rocks around us, the development of ore deposits, volcanism and the composition and stratification of our atmosphere.

The development of thermodynamic concepts as it pertains to the geosciences is the subject of Jibamitra Ganguly's *Thermodynamics in Earth and Planetary Sciences*. Now in its second edition, this book is a treasure trove of information on thermodynamic concepts and the often surprising and fascinating geoscience applications. Ganguly has gathered together topics that would otherwise not be found in a single text. Thermodynamic aspects of the deep Earth and planetary physics, aqueous geochemistry, and surface effects all have their own chapters, in addition to the more standard fare of the thermodynamic laws, equations of state, and mixing models. The second edition is also graced with a new chapter on statistical thermodynamics and stable isotope geochemistry. Several new examples and updated references have also been added to the text, reflecting the continued advances in the field since the publication of the first edition in 2008.

Ganguly's style is refreshingly down-to-earth. Throughout the book, he introduces important thermodynamic concepts while interweaving them with necessary mathematical derivations. These derivations do require some concentration to work through, but Ganguly takes care to explain each step in the derivation, and students will surely appreciate that he does not omit steps, something all-too-common in other texts. Example problems are scattered through the text to give the reader confidence that they have understood the material. The second edition has a new appendix, which contains worked answers to many of these problems.

For me, where this book really shone was in the geological applications, which are supplied after the elucidation of each major concept. These are both fascinating and varied. One of my favourite examples comes in the middle of the chapter on reactions between solid solutions and gas mixtures, and is taken from Mueller and Saxena (1977). It outlines how observations of the CO_2-rich atmosphere of Venus can be used to constrain the mineralogy of its surface by assuming thermodynamic equilibrium at its hot surface.

In another section, Ganguly discusses the origins of osmotic pressure generated across semi-permeable membranes by gradients in chemical potential. He then highlights several recent studies which have investigated how osmotic pressure generated by natural salinity gradients could be used to provide a source of clean electrical energy. Whether or not this method will ever be economically viable (probably not), the example was such a pleasant surprise that it fully deserves a mention here. Taken together, the collected examples in the book succeed in demonstrating just how powerful having a knowledge of thermodynamics can be. Perhaps even more importantly, Ganguly's choices reveal that thermodynamics in the geosciences remains very much a living subject, driven by the need to explain new observations of the natural world. In this respect, and in its ambitious scope, it distinguishes itself from other works, such as G.M. Anderson's also excellent, and easy-going, *Thermodynamics of Natural Systems* (3rd Edition, 2018).

For the budding practitioner, the appendices are particularly useful. In addition to the worked examples (Appendix D), there are three other appendices. Appendix A is on entropy production and kinetics and serves as a gateway to the field of nonequilibrium/irreversible thermodynamics, a challenging subject which is currently experiencing renewed interest from a number of Earth science fields. Appendix B covers a few important mathematical methods for those who need to consolidate their knowledge of calculus, Taylor Series and Sterling's Approximation. Finally, Appendix C is an extremely useful resource on how to estimate the thermodynamic properties of solids. For those working at the cutting edge of petrology, there is never quite enough experimental data, and so it is common practise to use heuristics to fill in the gaps in our knowledge. This appendix enlists experimental data to provide empirical heuristics, and also briefly introduces modern ab initio techniques which allow us to move beyond such empiricism.

I have only two quibbles with this impressive text. The first is that a couple of important topics, such as short-range order and disequilibrium in solid-dominated systems, could have been extended to give uninitiated readers an understanding of their origins, consequences, and broad relevance to geological systems. However, prospective readers should be assured that even the short sections come with recommended texts for further reading. These are well chosen, as indeed are the vast majority of references in the book.

My second quibble is that the ordering of information within the book feels unnatural at times. For example, electronic orbitals and crystal field theory are introduced very briefly in Chapter 1, but only fleshed out in Appendix C. Additionally, the emphasis on the macroscopic view of thermodynamics has forced the new and much-appreciated chapter on statistical thermodynamics to the end of the book. I strongly recommend buying the print copy rather than the digital version: this will allow you to easily flick between sections.

This revised edition of *Thermodynamics in Earth and Planetary Sciences* succeeds in its goal of providing both the background and the tools required to make useful thermodynamic models of the natural world. It will serve as an excellent resource for senior geoscience students looking to gain a broad understanding of thermodynamics and its applications. It should also become a useful reference text for petrologists, planetary scientists, and other researchers seeking to understand aspects of thermodynamics outside their primary field.

Robert Myhill, University of Bristol

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1 Ganguly J (2020) *Thermodynamics in Earth and Planetary Sciences*. 2nd Edition. Springer. 610 pp, ISBN 978-3-030-20878-3 (print), €89.99 | £79.99 | US$109.99