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A review of the granite concept through time

Eloi González-Esvertit[a,b,c,*], Claudia Prieto-Torrell[a,c], Paul D. Bons[d,e], Àngels Canals[a], Josep Maria Casas[f], Marlina A. Elburg[g], Enrique Gomez-Rivas[a]

[a] Departament de Mineralogia, Petrologia i Geologia Aplicada, Facultat de Ciències de la Terra, Universitat de Barcelona, 08028 Barcelona, Spain
[b] Geosciences Barcelona (GEO3BCN-CSIC), 08028 Barcelona, Spain
[c] Institut de Recerca Geomodels, Facultat de Ciències de la Terra, Universitat de Barcelona, 08028 Barcelona, Spain
[d] Department of Geosciences, Tübingen University, 72076 Tübingen, Germany
[e] School of Earth Science and Resources, China University of Geosciences, 100083 Beijing, China
[f] Departament de Dinàmica de la Terra i l'Oceà, Facultat de Ciències de la Terra, Universitat de Barcelona, 08028 Barcelona, Spain
[g] Department of Geology, University of Johannesburg, Auckland Park, 2006 Johannesburg, South Africa

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ABSTRACT

Granitic rocks are ubiquitous worldwide in ancient and active tectonic settings, representing powerful sources of information about the Earth's past and present geodynamic behaviour. Numerous recent milestones fostering our knowledge of granites would have not been possible without a long-lasting, sometimes controversial, discussion on their origin and significance that has taken place over the last two centuries. Here we present a chronological review of how granites have been defined and interpreted in the context of the major theories that have successively governed the history of Earth Science. The main authors, scientific approaches, interpretations, and type-localities that have influenced knowledge about granitic rocks are summarized from the 18th and 19th centuries, when Earth Science was governed by the Neptunism, Plutonism and Uniformitarianism paradigms, to the acceptance of the Plate Tectonics theory and the very end of the magmatism vs. transformism debate in the late 20th century. Some of the most influential scientific advances in Earth Science, such as the invention of the polarizing microscope and the birth of geochemistry, as well as the role of schools of thought in these successive debates, are further discussed. Moreover, we review the recent and ongoing discussions on the mechanisms of magma generation, segregation, ascent and emplacement leading to the formation of granitic batholiths, as well as the observational, analytical, experimental, and numerical modelling approaches currently used for investigating granitic rocks. The history of granite science is classified into different periods of stasis or "normal" science, which were followed by scientific revolutions triggered by a growing number of inconsistencies. Our current understanding of granitic rocks is inevitably influenced by the preceding paradigms and disputes. Consequently, gathering and valuing the chronology, historical milestones, and overall evolution of ideas and theories on what granites are is crucial for the future directions of granite research.

1. Introduction

"The competition between paradigms is not the sort of battle that can be resolved by proofs"
Thomas S. Khun, 1970. *The Structure of Scientific Revolutions*

Granitic rocks (Fig. 1) constitute a major proportion of the upper continental crust (~86–88 vol%; Wedepohl, 1969, 1995), and the average geochemical composition of the whole continental crust is often interpreted to be granodioritic (Clarke, 1992; Gao et al., 1998; Cobbing, 2000). Investigations of granitoid rocks have historically provided, and are still providing, important constraints on ancient and active geodynamic processes of the Earth. Our current knowledge of the global timing and secular changes of tectonic processes, the temporal variations in the strength of the lithosphere, and the creation and recycling of the continental crust, have greatly benefited from the study of granitic rocks (e.g., Pupin, 1980; Pearce et al., 1984; Pitcher, 1997a, 1997b; Bonin et al., 2002; Brown, 2013; Moyen et al., 2017; Palin et al., 2020; Gómez-Frutos et al., 2023). Moreover, one of the major mechanisms of heat and mass transfer within the Earth's crust is the transport of magma

* Corresponding author at: Departament de Mineralogia, Petrologia i Geologia Aplicada, Facultat de Ciències de la Terra, Universitat de Barcelona, 08028 Barcelona, Spain.
E-mail address: e.gonzalez-esvertit@ub.edu (E. González-Esvertit).

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from zones of melting and melt segregation in the lower to middle crust to zones of emplacement in the upper crust (Sandiford et al., 1991; Petford et al., 2000; Bons et al., 2009; Cruden and Weinberg, 2018 and references therein). The origin and significance of granitic rocks have been debated for more than two centuries, and many milestones have been achieved after controversial discussions that divided different schools of thought and generations of scientists. However, despite their importance for laying the foundations and influencing current knowledge of granites, the historical paradigms and ideas addressing the origin of granitic rocks are often addressed separately (Read, 1957; Rudwick, 1962; Porter, 1976; Pitcher, 1997a, 1997b), and have rarely been reviewed in one place (Clarke, 1996; Young, 2018). Furthermore, the logic through which knowledge of granitic rocks was progressively gained within the Neptunism, Plutonism, and Uniformitarianism paradigms has been often overlooked.

According to the Oxford English Dictionary, a 'concept' is "*an idea or mental image which corresponds to some distinct entity or class of entities, or to its essential features, or determines the application of a term (especially a predicate), and thus plays a part in the use of reason or language*". Here we therefore use the term "granite concept" to refer to how humans have seen and defined granitic rocks as a distinct and meaningful class and how they perceived, interpreted, and understood granitic rocks during different periods of recent history, either by the interpretation of facts, mental impressions, or opinions and beliefs. Considering the historical perspective of this review, as well as the bountiful terminology employed over the ca. 240 yr. time span that it covers, the broad terms "granitic rock", "granitoid rock", or "granite" are used in an interchangeable manner throughout this review to refer to coarse-grained quartz-bearing igneous or igneous-looking rocks (e.g., Marmo, 1967a, 1967b; Pearce et al., 1984; Cobbing, 2000; Chen and Grapes, 2007; Young, 2018). When referring to specific sub-classes of granitic rocks, the non-genetic normative terms and compositions of the subcommission on the Systematics of Igneous Rocks from the International Union of Geological Sciences (IUGS) are used (Streckeisen, 1974; Le Bas and Streckeisen, 1991; Le Maitre et al., 2002). Outdated, obsolete, or archaic terms are solely employed in the context of classical studies or when mentioning rock names in the language they were originally defined.

The term *granite*, as well as the rock type of that name (Fig. 1), has played a significant role in the history of modern society. The origin of the term *granite*, from the Latin word *granum*, is attributed to Andrea Celsapino in 1596 CE, an Italian physician, philosopher, and botanist at the Sapienza-Università di Roma (Italy). The influence of the granite concept on the modern history of human society becomes clear, for example, in the toponomy of different regions worldwide (e.g., New Hampshire, the *Granite State* in the United States of America (USA), or Aberdeen, the *Granite City* in Scotland), as well as in its historical and current usage as a building, paving, and sculpting stone (e.g., Langer, 2001). Among other famous monuments, the Amenhotep III statue, now on display at the British Museum (London, United Kingdom) but originally located at the Mut at Karnak temple (Egypt), as well as the Brihadeeswarar Temple building (India) or the Mount Rushmore National Memorial (USA), are made up of granite. The classical literature of the 19th and 20th centuries further provides evidence of the linkage between human cultures and the granite concept, as evidenced for example in Jules Verne's 1864 novel *Journey to the Center of the Earth*. Even well-known historical characters, who were not geoscientists per se, speculated about the origin and significance of granitic rocks. The German poet, playwright, novelist, and scientist Johann Wolfgang von Goethe, for example, wrote extensively about the Brocken granite in the Harz Mountains (Germany) and its significance for understanding the formation of the Earth (Baldridge, 1984; Wolf et al., 1989). Other examples are Leonardo da Vinci, who made detailed drawings and observations of granitic formations in the mountains of northern Italy, and Benjamin Franklin, who wrote about the geology of the Appalachian Mountains in the USA and about the granitic rocks therein (e.g., Gortani, 1962; Dean, 2009).

Granitic rocks have drawn the attention of scientists, particularly geologists, for centuries because of their ubiquity in the Earth's crust (Fig. 1), the historical and ongoing debates on their origin and significance, and their association with orogenesis and ore deposit formation, among other processes. Granites are, however, difficult rocks to work with. In the field, geologists have typically encountered problems related to the common lack of discernible lower and upper contacts of granitic plutons, their internal structural and compositional complexity, and the wide variety of textures and accessory minerals that they contain. Granite research is equally challenging in the laboratory due to the wide range of geochemical and isotopic compositions that these rocks have, and the difficulties in experimentally replicating the physicochemical conditions of their formation. The history of the research on granitic rocks is marked by the fact that different investigations into their origin and significance have yielded numerous contradictory results and interpretations (e.g., Backlund, 1938; Miller et al., 1988; Klötzli et al., 2001, 2002; Finger and Clemens, 2002). Nevertheless, such challenges have not discouraged the scientific community from keeping momentum, as demonstrated by the constant development of new analytical techniques and instruments, and by the paradigm shifts that have represented consecutive *scientific revolutions* (Kuhn, 1970; Bak, 1996) during the long-lasting and controversial history of the granite concept.

The non-genetic German term *Massige Gesteine (massive rocks)* (Rosenbusch, 1877a, 1896) began to be used in the late 19th century to define crystalline or glassy rocks that, when observed in outcrop, show uniform textures and a massive character that allowed them to be distinguished from metamorphic or sedimentary rocks. Long before that time, however, investigations into and discussions about granitic rocks were already frequent. A primitive origin of granites supported by *neptunists* (i.e., being the oldest and hardest rocks of the Earth, formed under deep water conditions; Werner, 1787) contrasted the magmatic origin suggested by *plutonists* (e.g., Hutton, 1794), marking the debate on the origin and significance of granites during the 18th century. Subsequently, other influential works within the uniformitarianism paradigm (e.g., Hutton, 1795a, 1795b; Lyell, 1838; Keilhau, 1843; Darwin, 1845), as well as the invention of the petrographic microscope and the birth of geochemistry (Clarke, 1868; Rosenbusch, 1877a; Iddings, 1890), resulted in the diversification and specialization of research on granites during the 19th century. Ideas about transformism, granitization, and the metasomatic origin of granites later gained popularity due to a growing number of textures, compositions, and field features that could not be explained by the current knowledge of the epoch. With these new ideas, research on granitic rocks abruptly entered a long-lasting debate between the concepts of magmatism vs. transformism (e.g., von Bunsen, 1861; Read, 1957; Marmo, 1967a, 1967b; Pitcher, 1987; Pitcher, 1997a, 1997b; Young, 2018). At the end of the 20th century, after more than two centuries of the emergence, integration, and eventual obsolescence of terminology used to refer to different types of *Massige Gesteine*, the IUGS Commission on Systematics in Petrology (CSP, founded in 1970) officially proposed the term *igneous rock* (e.g., Streckeisen, 1974). This term, although semantically genetic (i.e., from the Latin *ignis*, meaning fire), had non-genetic implications and could be used for both *igneous* and *igneous-looking* rocks, irrespective of their genesis (Streckeisen, 1974; Le Bas and Streckeisen, 1991; Le Maitre et al., 2002). Since the proposal of this term, several genetic and non-genetic classifications for granitic rocks have been proposed, and many of them have already been abandoned. Presently, granites *sensu stricto* are understood to be coarse-grained, crystalline igneous rocks with a modal abundance of quartz between 20 vol.% and 60 vol.% relative to feldspar, and which may include one or more micas, hornblende and many other accessory minerals (Streckeisen, 1974; Le Maitre et al., 2002). As a sub-class of plutonic rocks, granites are presumed to have crystallized at depth from molten material (Hutton, 1794; Walton, 1960; Le Maitre et al., 2002), and references to a possible metasomatic origin of granitic rocks are

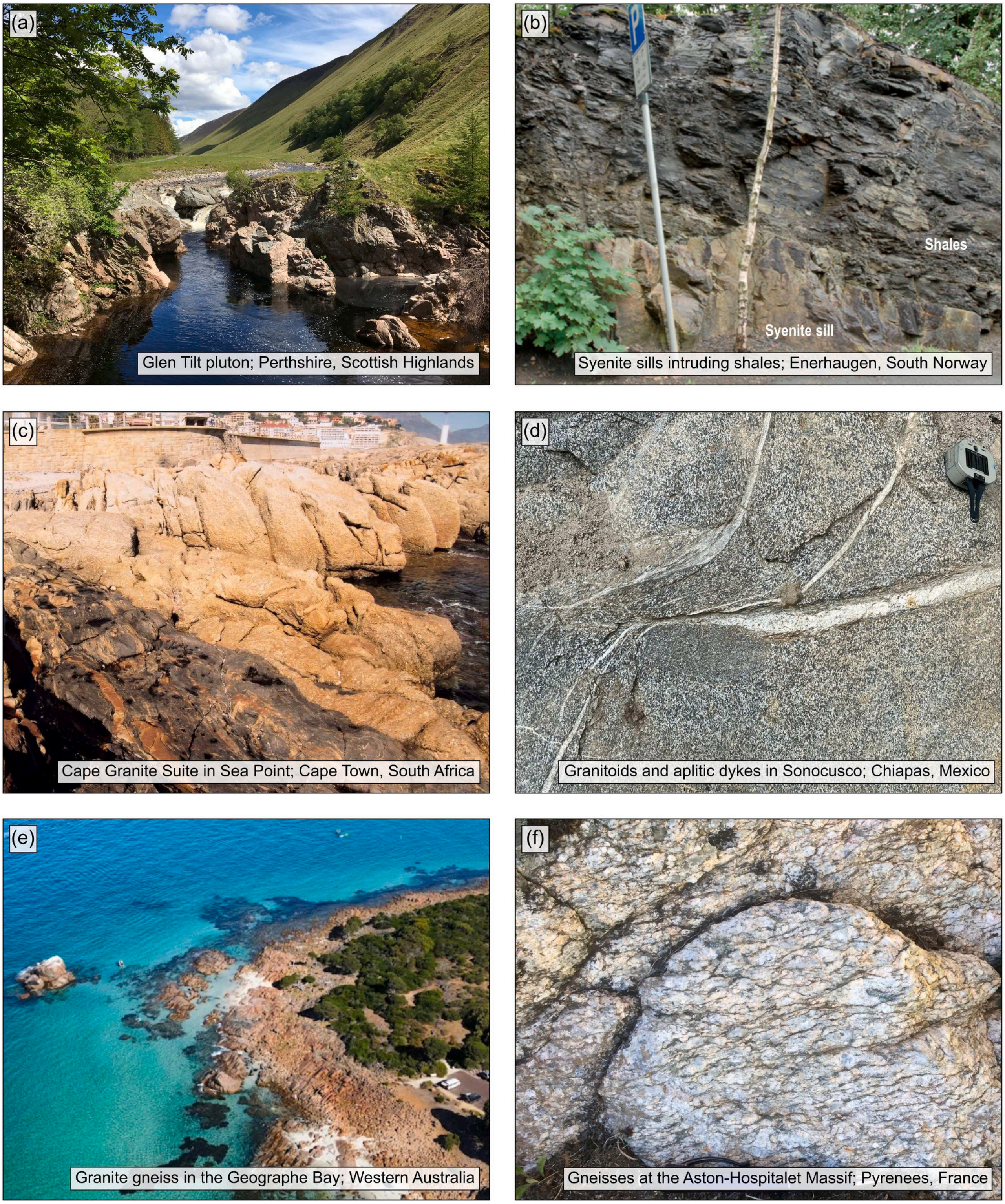

Fig. 1. Examples of type localities where granitic rocks have played a significant role in the history of Earth Sciences: (a) Outcrop of the Glen Tilt complex (granite dykes with pink colour) at its contact area with the metasedimentary rocks of the Dalradian Supergroup (grey-coloured rocks), Tilt river, Perthshire, Scottish Highlands (described in Hutton, 1794); photograph courtesy of Robert Butler (river width is ~3 m; see detailed outcrop sketch in Fig. 2b). (b) Syenite sill intruding parallel to bedding of Cambrian and lower Ordovician shales at Enerhaugen, Oslo, south Norway (described in Lyell, 1841; Keilhau, 1843); photograph reproduced from Hestmark (2011). (c) Contact between the Cape Granite Suite (light coloured) and the metasediments of the Malmesbury group (dark coloured) at the Sea Point locality, Cape Town, South Africa (described in Masson, 1776; Playfair and Hall, 1813; Darwin, 1845); photograph courtesy of University of Cape Town (buildings for scale). (d) Typical field aspect of the granites at Sierra Madre de Chiapas, southwestern Mexico (described in von Humboldt, 1822); photograph courtesy Gabriel Serrano López (compass for scale). (e) Granite gneiss outcrops at the southwestern sector of Geographe Bay, Western Australia (described in Baudin, 1974) (cars in a parking lot on the right side for scale). (f) Granitic gneisses at the Aston-Hospitalet Massif, eastern Pyrenees, SW Europe (described in Lacroix, 1896, 1898; Daly, 1898; Adams, 1901); photograph courtesy of Pilar Clariana (field of view is ~30 cm). See locations in Figs. 6, 7. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

almost non-existent in the modern literature. Present controversies regarding granitic rocks are, mostly, focused on specific issues such as melt generation and segregation, magma ascent and emplacement, and post-crystallization evolution. Here we present a chronological review of the mutual interactions between the granite concept and the history of Earth Sciences. The review is structured following the different currents of geological thought that have existed during the past two centuries, with special emphasis on the arguments, explanations, and controversies on the origin and significance of granitic rocks (Figs. 2–4). The history of the scientific knowledge of granites is divided into different paradigm-governed periods according to the ideas of Kuhn (1970) (Fig. 5), including the 18th, 19th, and late 19th to late 20th centuries. The current state of the art of the granite concept is further summarized by reviewing the different genetic and non-genetic classification schemes for granitoid rocks, as well as the observational, analytical, experimental, and numerical modelling approaches that are currently being employed. We also evaluate the role of FAIR (Findable, Accessible, Interoperable, Reusable) initiatives that have emerged in recent years, which have fostered the quantity, and quality, of granite-related data during the Digital Age (Figs. 6, 7).

2. The 18th century: Neptunism and Plutonism paradigms

"I have been particularly anxious about this subject of granite"
James Hutton. *Theory of the Earth: With Proofs and Illustrations, in Four Parts: Volume 3*

The term *granite* has been used without any quantitative mineralogical connotation for centuries. The Swiss naturalist Horace-Bénédict de Saussure recognized and described, in his *Voyages dans les Alpes* travel journals, different granitic rocks cropping out in the European Alps (Figs. 6, 7) (de Saussure, 1779, 1786). From Saussure's works, two main concepts that became central to the debate on granites during the following tens of years stand out: the "stratification" of granites, inferred from the fact that some minerals appear aligned in bands, and their non-primitive origin (i.e., not a primordial part of the Earth), inferred from observations of granitic veins intruding surrounding schists (i.e., *Granit Veiné*). Five years later, Patrin (1791) used the term *Pierre Graphique* to refer to a quartz-feldspar rock that he found forming a mountain in the eastern part of Siberia (Figs. 6, 7), and highlighted its resemblance to rocks from other parts of the world. It was only three years later that the Scotsman James Hutton officially published his interpretations on the *veined granites* hosted in schists and marbles at the type-locality of Glen Tilt in the Central Highlands of Scotland (Fig. 1a, 2b, 6) (Hutton, 1794). Although the basic dynamics of terrestrial processes had already been discussed in his essay *Theory of the Earth: or an investigation of the laws observable in the Composition, Dissolution, and Restoration of Land upon the Globe* (Hutton, 1785), it was in 1794 when Hutton stated that he found "*the most perfect evidence that the granite had been made to break the Alpine strata and invade that country in a fluid state*". In this groundbreaking work, which had benefitted from discussions with John Clerk of Eldin and the Duke of Athol (landowner of the Glen Tilt area), and corroboration by the investigations of Sir James Hall in southwest Scotland (Hall, 1794), Hutton concluded that: *"Granite, which has been hitherto considered by naturalists as being the original or primitive part of the Earth, is now found to be posterior to the Alpine schists"* (Fig. 2b-d). This work, together with the first two parts of Hutton's treatise on the *Theory of the Earth with proofs and illustrations in four parts* (Hutton, 1795a, 1795b), exceptionally illustrated by Playfair (1802), is believed to have established the basic ideas of Plutonism (Fig. 2b-d). The third part of Hutton's *Theory of the Earth* (Hutton, 1899) remained lost for 60 yr. and was published after being released to the Geological Society by the Scottish merchant and geologist Leonard Horner in 1856 (e.g., Bonney, 1899). The fourth part is still missing.

Hutton's observations reinforced the ideas that had originally been proposed by the Italian abbot, geologist, and naturalist Anton Lazzaro Moro during his research on volcanic islands, while trying to explain the occurrence of crustaceans and other marine organisms on mountains (Moro, 1740a, 1740b) (Fig. 6). The breakthrough ideas of Moro and Hutton about the Earth's origin and rock-forming processes were incompatible with the dominant school of geology at the end of the 18th century in Freiberg (Saxony), where Abraham Gottlob Werner was the inspector of mines and professor of mining and mineralogy at the Mining Academy. Unlike Hutton, Werner never published the whole of his theory, and it was only by unpublished materials and the lecture notes of his students that his thoughts could be pieced together (Rudwick, 1962; Seddon, 1973; Hallam, 1983; Stone, 2020). Werner's theory was partially stated in his book *Kurze Klassifikation und Beschreibung der verschiedenen Gesteinsarten* (Werner, 1787), which since its publication constituted the basis of the Neptunism movement. *Neptunists* advocated, based on previous classifications from other authors (e.g., Lehmann, 1756; Füchsel, 1761; Desmarest, 1774) (Fig. 2a), that rocks were formed as a result of chemical precipitation from cosmic material in the early Earth's oceans (i.e., *Allgemeines Gewaesser*) in a sequence of five series: (1) Primeval (*Urgebirge*), (2) Transition (*Übergangsgebirge*), (3) Secondary or Stratified (*Flötz*), (4) Alluvial or Tertiary (*Aufgeschwemmte*) and (5) Volcanic Series. Crystalline rocks, such as granites, gneisses, and metasediments, were attributed by Werner and other Neptunism advocates to the Primitive series and were thus considered the oldest and hardest rocks of the Earth, formed under very deep, calm water conditions. Because no life was thought to have existed during the Primitive series, granite rocks were free of fossils.

The Primitive origin of granites as suggested in Werner's theory clashed with numerous field observations reported during the late 18th and early 19th centuries, as evidenced above with the Saussure's and Hutton's *Granit Veiné*. Another example were the observations of Marzari-Pencati (1806, 1820), who demonstrated that, in the Fassa Valley (Dolomites), igneous dykes crosscut and thus postdate banded limestones (*Predazzite*) that in turn record contact metamorphism. Another example is the work of the Prussian zoologist and botanist Peter Simon Pallas during his expeditions in Russia (e.g., Pallas, 1777, 1812; Parker, 1973). Close to the city of Chelyabinsk, Pallas described porphyritic granites belonging to Hercynian batholiths that intruded as large vein-like bodies into metamorphic schists and marbles of the eastern flank of the Urals (Fig. 6). Early in the 19th century, other intrusive granites than those reported by de Saussure (1786) and Patrin (1791) were described outside of Scotland, in the Western Cape Province (South Africa) (Figs. 1c, 6). As pointed out by Master (2009), the Cape Granites (Fig. 1c) played an important role in the Neptunism vs. Plutonism debate during the late 18th and early 19th centuries. Some descriptions of these rocks pointed out their similarity to the granites cropping out in the Alps (e.g., Hamilton, 1778), and many other naturalists and travellers also reported the textural and mineralogical features of the Cape Granites and discussed their intrusive nature and relationships with the surrounding rocks (e.g., Masson, 1776; Anderson, 1778; Sonnerat, 1782; Sparrman, 1785; Barrow, 1801; Degrandpré, 1801).

3. The 19th century: "normal" science

"This intrusion the schists all around it does roast,
and when it is absent it alters them most"
The Grizzly Bears Book of the Geological Survey of Scotland (c. 1875)

3.1. Uniformitarianism

During his lifetime (1726–1797), James Hutton did not witness the acceptance of his ideas by the scientific community, in part because his theories denied the influence of supernatural forces on the Earth system. However, at the beginning of the 19th century, currents of thought about the origin of granites, veins, and even mountain building started

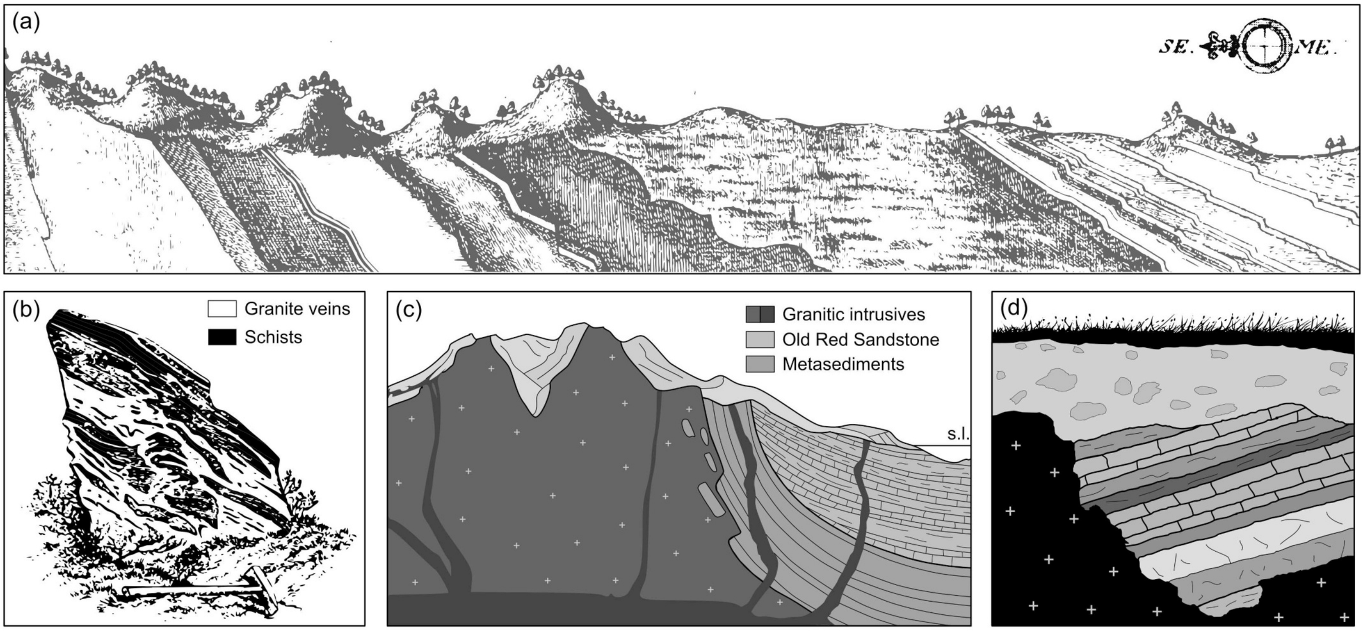

Fig. 2. Representative illustrations from some of the most scientifically influential works on the geological knowledge during the 18th century. (a) Reproduction of an illustration from Lehmann (1756) representing one of the first known geological cross-sections, used by Werner to propose the idea of Neptunism (i.e., rocks belonging to Primitive, Transition, Secondary, Tertiary, and Volcanic series are continuously superimposed) (scale is unknown). (b) Outcrop sketch from Hutton (1794, 1899) of the crosscutting relationships between granite veins and pre-existing schists exposed at Glen Tilt (Scotland) (hammer for scale). (c) Redrawn sketch of a representative cross-section of the Island of Arran (which has a length of ~15 km) from Hutton (1899), showing the relationships of a granite intrusion and the pre-existing sediments and metasediments. (d) Redrawn illustration from James Hutton in the late 18th century and discovered in 1968 by a descendant of John Clerk of Eldin, representing a sequence of sedimentary rocks crosscut by an igneous intrusion in a trench for an artificial canal near Frederick Street in Edinburgh (Craig, 1978) (scale is unknown). See text for further references.

to drift towards the basis of Plutonism (Hallam, 1983; Master, 2009; Leddra, 2010; Rapprich et al., 2019; Stone, 2020).

From 1800 to 1830, granitic rocks were reported around the globe in numerous studies, travel journeys, and correspondence among scientists with no consensus on their origin and significance (among others, Ramond, 1801; Herrgen, 1802; Breislak, 1811; Hall, 1815; Cortesi, 1819; Bakewell, 1823; Gemmellaro, 1823; Palassou, 1823; Crawford, 1824; Enys, 1833; Cormack and Bruton, 1928) (Figs. 3, 6). The progressive shift of thinking on the origin of granite from the 1830s is illustrated by the lectures given between 1809 and 1833 by Robert Jameson, Regius Professor of Natural History at Edinburgh University, who had previously studied with Werner at Freiberg (Bailey and Tait, 1921; Stone, 2020). It is known that, by the 1830s, Jameson had accepted some of the Huttonian ideas about intrusive granites, as revealed by his students' notes (McCormick, lecture 84, 28 March 1831; in Stone, 2020): "*The granite sometimes forms veins in the surrounding mica-slate – and as veins are generally considered newer than the formation in which they occur – the mica slates, it would appear have existed prior to the Granite*".

The main people responsible for promoting and extending Hutton's theory on Plutonism (which formerly was, in fact, a theoretical construct; e.g., Kuhn, 1970; Baker, 1998; Rossetter, 2018) were Charles Lyell (1797–1875) and Mary Elizabeth Horner (Rudwick, 1970, 1998; Dott, 1998; Virgili, 2003) (Fig. 3b, e). In the three volumes of the *Principles of Geology*, Lyell revisits the work of Hutton and settles an even more solid paradigm for the rock-forming processes across space and time: the theory of Uniformitarianism (Lyell, 1830, 1832, 1833) (Fig. 5). This theory postulated that the Earth's landscape had been sculpted over the course of an inconceivably long natural history by gradual processes that are visible at the surface and are governed by natural laws. For a summary of different aspects of the research, lectures, theories, letters, and travels of Lyell and Horner, which are out of the scope of this work, the reader is referred to Lyell (1849, 1853, 1881), Bailey and Hartley (1960), Greene (1973), Porter (1976), Dott (1998), Wool (2001) and Virgili (2007). Concerning granites, their relevance and influence on the novel ideas is clearly recognisable in Lyell's work.

One of the best documented studies on granites carried out by Lyell and Horner is their 1837 trip to Norway and their observations, together with Prof. Baltazar M. Keilhau, in the vicinity of Christiania (present-day Oslo) (e.g., Holtedahl, 1963; Marmo, 1967a, 1967b; Hestmark, 2011) (Figs. 1b, 3b, 6). They documented contact zones between sedimentary rocks and large intrusive bodies of granite and syenite, revisiting the phenomenon of metamorphism that they had already coined in the *Principles of Geology* (Lyell, 1833) and citing examples from the Highlands of Scotland (Fig. 1a), the Alps, Cornwall, and Table Mountain at the Cape of Good Hope (Figs. 1c, 6). The observations and interpretations in Oslo confirmed Lyell's theories and were key for the development of the well-known book *Elements of Geology* (Lyell, 1838), which was presented to the research community three years later (Lyell, 1841) and became an influential work in Lyell's lectures in North America between 1841 and 1853 (Dott Jr., 1996; Dott, 1998). According to Lyell's view, rocks could be classified in four great classes (Lyell, 1838 - Part I, Chapter I): Aqueous (i.e., sedimentary), Volcanic, Plutonic, and Metamorphic (Fig. 3e). Regarding Plutonic rocks, Lyell wrote: "*The granites have been formed at great depths in the earth and have cooled and crystallized slowly under enormous pressure where the contained gases could not expand. [...] large masses of granite are found to send forth dikes and veins into the contiguous strata, very much in the same way as lava and volcanic matter penetrate aqueous deposits*" (Fig. 3e).

On the other hand, during the same trip to Christiania (Fig. 1b, 6), Baltazar M. Keilhau interpreted a gradual and complete passage of granitic rocks into stratified rocks with fossils, and described gradual changes from granite to a "primitive" gneiss (Hestmark, 2011). With his ideas, Keilhau was probably one of the pioneers of the transformism (i.e., granitization) theory that divided many geologists some tens of years later. In fact, widely used terms during the 19th century, such as *transmutation* and *granitification,* were already coined by Keilhau, who probably also was the first geologist noting the *room problem* (see below) in the emplacement of igneous rocks (Keilhau, 1828, 1838, 1843; Marmo, 1967a).

Another important source of information for Lyell during the development of his theories on the origin and significance of granite were the observations of Charles Robert Darwin (1809–1882), who in turn benefited from Lyell's theories during his investigations aboard the HMS Beagle (e.g., Burchfield, 1974; Rosen, 1982; Herbert, 1991, 2005; Secord, 1991; Master, 2012) (Fig. 6). Among Darwin's numerous geological observations, those made at Cape Town in 1836 and in South America in 1831–1836 stand out (Fig. 6). In Cape Town, Darwin revisited previous interpretations of the Green Point Contact (also known as the Sea Point Contact; Fig. 1c), (Masson, 1776; Anderson, 1778; Sonnerat, 1782; Playfair and Hall, 1813) and interpreted the schist enclaves lying within the granitic mass as "*interconnected pendant slivers of infolded suprapositional schists that were intruded parallel to their schistosity by thin fingers of granite, and then eroded to reveal apparently detached schist fragments in the granite*" (Master, 2009, 2012). In South America (Fig. 3c), Darwin also made abundant contributions to the understanding of granitic rocks as demonstrated by the number of times (172) that the word *granite* appears in his *Geological Observations on South America* (Darwin, 1846). During his visits along the eastern coast of Brazil (Fig. 6), Darwin wrote (Darwin, 1845, 1846): "*Along the whole coast of Brazil, for a length of at least 2000 miles, and certainly for a considerable space inland, wherever solid rock occurs, it belongs to a granitic formation. The circumstance of this enormous area being constituted of materials which most geologists believe to have been crystallized when heated under pressure, gives rise to many curious reflections*". With *curious reflections* Darwin was referring in part to the *room* or *space problem*, first noted by Keilhau (1838): "*Was this effect produced beneath the depths of a profound ocean? or did a covering of strata formerly extend over it, which has since been removed?*". Darwin's observations in Chile also raised some controversial points for scientific knowledge and for Darwin himself, e.g., about the structure and crosscutting relationships in the red granites from the Chilean Cordillera (Darwin, 1846): "*There are gigantic mountain-like masses of red granite, which have been injected whilst liquefied, and which, nevertheless, display in parts a decidedly laminar structure*" (Fig. 3c).

Darwin was not, however, a pioneer in the study of granites in Latin America, which always had been seen as a valuable building stone. During the Incan Empire, granitic rocks were exploited and worked from the Cañar mountains, in the present-day province of Cuenca (Ecuador) (Velasco, 1844), and granite was also used to build most of the city of Machu Picchu in the Vilcabamba range (south Peru) (Delgadillo, 2013). The first known geological reports on the granites of Latin America are those from the German explorer Alexander von Humboldt in Mexico (von Humboldt, 1822, 1825), where he described *pics granitiques* (i.e., granitic summits) in the Sierra Madre of western Mexico (Figs. 1d, 6). Humboldt also showed large granitic bodies and their crosscutting relationships with sedimentary and volcanic rocks in many representative cross-sections of the Earth's crust. The von Humboldt, 1841 cross-section (Fig. 3f) provides an excellent synthesis of the geological knowledge of that epoch, where granites are depicted as large intrusive masses with different ages relative to the surrounding strata. The French naturalist Alcide Dessalines d'Orbigny also provided very detailed descriptions of the geology of South America during his trip from 1826 to 1834 (Orbigny, 1834).

Other detailed maps and descriptions carried out before Darwin's publications were those from the Salesian Juan de Velasco and his expedition colleagues (e.g., Velasco, 1844; Garrido, 2020) (Fig. 6). Another important contribution to the knowledge of granitic rocks in South America during the 19th century (postdating the work of Darwin) is considered to be the travel chronicle of Jean Baptiste Boussingault, Joaquin Acosta, and Francois Desiree Roulin in Nueva Granada (a Spanish Viceroyalty that extended over present-day Colombia, Venezuela, Ecuador, Panama, and Guyana) (Boussingault, 1849). In this work, granite bodies from different areas are described in detail, including their structure, mineralogy, and relationship with the surrounding rocks. In Ecuador, the Professor of Geology and Mineralogy at the National Polytechnic School of Quito, Franz Theodor Wolf, also made important contributions to the knowledge of the geology of the country, including investigations on granitic rocks (Wolf, 1892). Besides numerous descriptions of the field occurrence, mineralogy, and structure of granitic rocks across the country, it becomes clear that Wolf was familiar with the ongoing debate on the origin of granites: "*geologists do not agree (...) it is one of the most difficult questions in geology (...) we do not claim that all plutonic rocks have the same origin of an igneous-fluid magma, or that they are in their primitive state, because I admit for many a very deep metamorphosis*" (Wolf, 1892).

The Australian continent also played an important role on the origin and development of the knowledge of granites during the 19th century (Figs. 6, 7). Darwin visited Australia in 1836 and, although his investigations on granites there were limited, he reported the existence of granites in the Vale of Clwydd (New South Wales) and on the Vancouver Peninsula (Western Australia) (Darwin, 1845; Armstrong, 1985; Nicholas and Nicholas, 2008) (Fig. 6). The geology of Australia had been previously described by the Frenchman Nicolas Baudin and his team during expeditions in 1800–1803 (Mayer, 2009), and later on by other several exploration projects that focused on the biodiversity, geography and geology of the region (e.g., Péron et al., 1807; King, 1827; Lesson and Duperrey, 1830). The mineralogist of the Baudin expedition, Louis Depuch, was responsible for most of the geological observations that can be found within the travel chronicles (Baudin, 1974). Among the observations, similarities between the granites in the *Baie du Géographe* (now Geographe Bay; Western Australia; Fig. 1e) and those described by de Saussure (1779) in the European Alps are remarkable (Baudin, 1974; Mayer, 2009): "*it is impossible not to be convinced here of the fact, which Mr. de Saussure was the first to recognize and which several naturalists still contest, that granites are apt to stratify*". The Baudin expedition also reported and described granite outcrops in north Tasmania, the Blue Mountains in New South Wales, and the southern Australian Coast. According to their observations and the dominant, *Wernerian*, rock classification scheme of the epoch, they suggested a mostly primitive origin for this whole part of the continent (Werner, 1787; Baudin, 1974; Mayer, 2009).

The second half of the 19th century saw both a diversification and specialization in the study of granites. The Plutonism paradigm proposed by Moro (1740a, 1740b) and Hutton (1795a, 1795b), popularized and embedded within Uniformitarianism by Lyell (1833, 1838), and supported by the observations and descriptions of Darwin (1845, 1846), among others, gave rise to a period of paradigm-governed, "normal" science (Kuhn, 1970) (Fig. 5). This period, comparable to the states of *stasis* according to Bak's (1996) model of self-organised criticality, was characterized by the accumulation of inconsistencies and the emergence of new ideas leading to a collapse and to the occurrence of a scientific revolution (Kuhn, 1970), or an "avalanche" in the sandpile analogy (Bak, 1996) (Fig. 5). The study of granites moved from being purely observational and based on reports of their existence and mode of occurrence in different parts of the world, to become somehow reductionist. Thus, many scientists started to carry out more detailed investigations of granites focused on, for instance: the development of foliations and other structural features (Sharpe, 1852; Mackintosh, 1868; Ormerod, 1869; McMahon, 1887), their mineralogy and petrology (Haughton, 1858, 1859, 1864; Cooke, 1866; Hull, 1874) (Fig. 4); their formation mechanisms and effects on their host rocks (Ramsay, 1841; Von Buch, 1845; Duke, 1853; Bonney, 1888; Reade, 1889), their mafic and felsic enclaves (Phillips, 1880, 1882; McCormick, 1886), and their relationship with ore deposits and mining districts (Ansted, 1849; Hunt, 1849; Phillips, 1849; Pissis, 1850; Domeyko, 1855).

The knowledge of granites was probably further fostered by the emergence of several large-scale geological maps. Although the first known maps representing geology were drawn by the Count Luigi Ferdinando Marsili (Marsili, 1717; Romano et al., 2016), William Smith (Smith, 1815), and Carlos de Gimbernat (de Gimbernat, 1806, 1808; see a review in Vila, 2016), those produced during the mid-19th century allowed larger-scale comparisons between different regions of the world and provided a global overview of the occurrence of granitic rocks and their distribution. For example, the geological maps of Europe (Dumont, 1857) and the United States (Marcou, 1853) provided very detailed information about the classes of granitic rocks in these territories, in all cases accompanied by detailed mineralogical information. The geological maps of the globe from Boué (1844) and Marcou (1861), described in detail by Oldroyd (2014), also represented the worldwide distribution of granites, which were in some cases lumped together with different metamorphic schist series, and in other cases distinguished as *granite* in the legend.

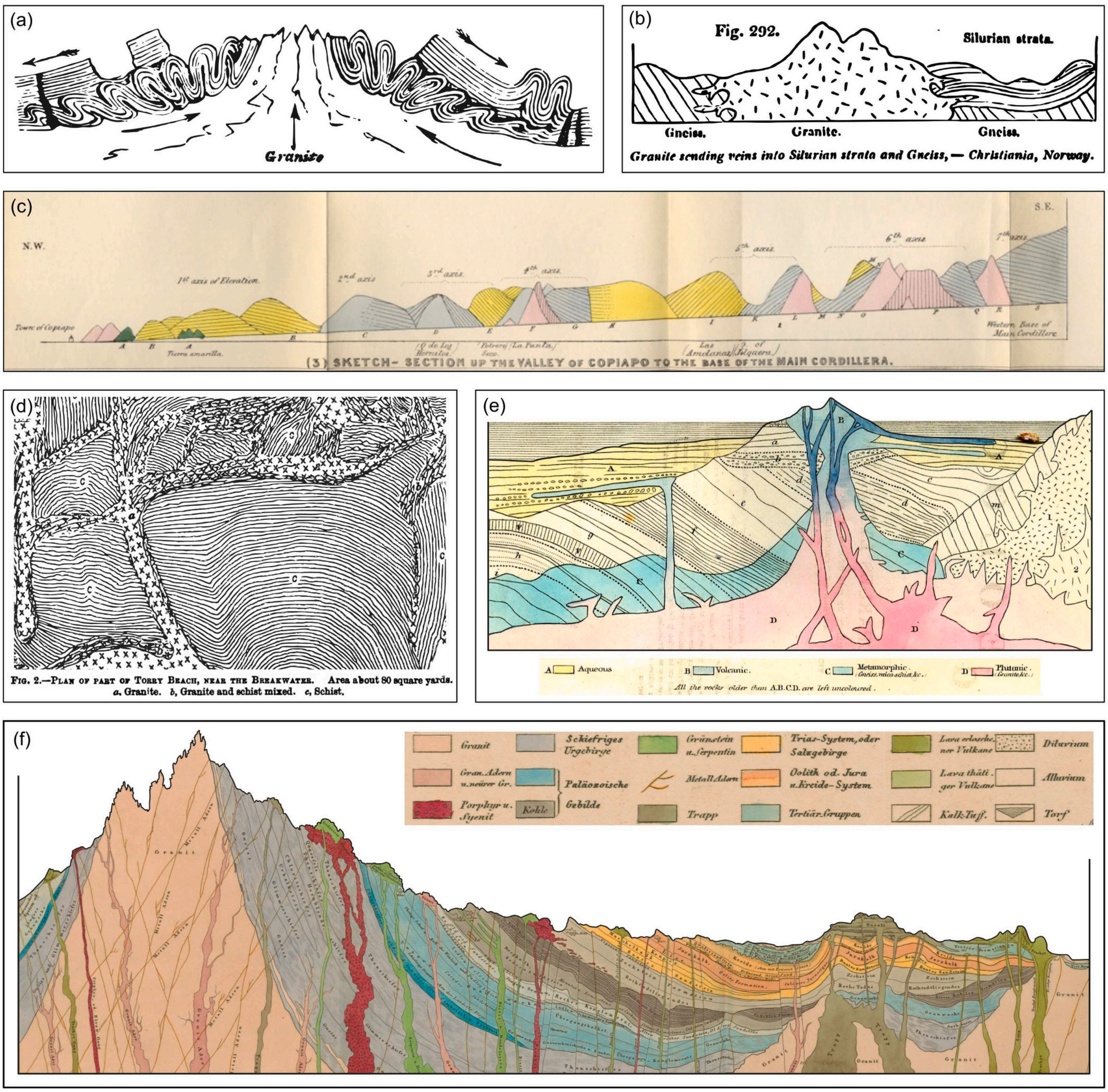

Fig. 3. Representative illustrations from some of the most scientifically influential works on scientific understanding of granitic rocks during the 19th century. (a) Emplacement dynamics of a granite according to Scrope (1825) (scale is unknown). (b) Granite veins intruding Silurian strata and gneiss in the vicinity of Christiania, Norway (Lyell, 1838) (scale is unknown). (c) Representative cross-section from the town of Copiapo to the western base of the Andean Main Cordillera (Darwin, 1846) (cross section length is ~225 km); pink and red colours represent granites and andesites; blues correspond to porphyries and conglomerates; yellows represent gypsum or gypsiferous formations; dark-green refers to feldspathic clays and slates. (d) Observations on the structural relationships between granite, schist, and mixture zones in the Torry Beach area (Aberdeen, Scotland) from Harris (1888) (mapped area is ~67 m^2). (e) Idealized illustration of the origin and mode of occurrence of different rock types published as the frontispiece from Charles Lyell's *Principles of Geology* (second American edition; Lyell, 1857) (scale is unknown). (f) Representative cross-section summarizing the mid-19th century understanding of the structure Earth's crust and its major constituents, including granites (von Humboldt, 1841) (scale is unknown). See text for further references. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. The birth of geochemistry

The last decades of the 19th century saw an increasing interest in granites through the emerging discipline of *Geochemistry*. This term was coined by the chemist Christian Friedrich Schönbein in 1838 in Basel (Switzerland) (e.g., Fairbridge, 1998) based on the work of Lunn et al. (1835). Noteworthy is the work on granite geochemistry, and more specifically on fluid and melt inclusions, by the British geologist Henry Clifton Sorby, to whom the manufacture of the first rock thin sections is attributed. Through the comparison of the properties of experimentally-grown and natural crystals (the latter belonging to metamorphic rocks, quartz veins, and igneous rocks), Sorby (1858) demonstrated that the study of *cavities containing fluid* (i.e., fluid and melt inclusions) could be used to determine whether rocks in which they are contained were deposited from aqueous solutions or crystallized from a melt (e.g., Correns, 2003; Bodnar, 2018). Significantly earlier than Sorby's work, the investigations of Scrope (1825) stand out (Fig. 3a). Through the study of volcanoes and volcanic products in south Italy (Sicily, and the Pontine and Aeolian Archipelagos), Central France (Auvergne, the Velay, and Vivarais areas), and north Germany (Eifel volcanic region), Scrope (1825) proposed that a wide range of igneous rocks could originate from the differentiation of a primary magma by "*some chemical process in an internal reservoir*" (see below). Moreover, this author further provided other speculations on the viscosity of magmas and their relationship with crystal and vapour composition. Years later, the chemist Robert von Bunsen also investigated the origin of granites and their water content. Through his investigations on the volcanic rocks of Iceland, von Bunsen (1851) showed evidence of the coexistence between felsic and mafic lavas. As Bunsen considered it impossible that potassic granites could be formed from the same primary magma as basalt, he proposed the existence of two primary magmas, basic and acid. Years later, Bunsen's reflections would also become part of the debate on the origin of granite from a geochemical point of view (von Bunsen, 1851, 1861) (see below).

The geochemical research on granites of the British metallurgist, geologist, and mining engineer John Arthur Phillips during the last decades of the 19th century was also remarkable. Phillips published several results of granite geochemical analyses, among other rock types and soils, and became one of the first scientists, together with H. C. Sorby, to use the polarizing microscope (Phillips, 1849, 1871, 1873, 1880, 1882). This instrument had been invented by W. H. Fox Talbot in 1834 by making use of William Nicol's single-vision 1828 calcite prism, and the work of Dana (1877) and Rosenbusch (1877a, 1877b) contributed to its popularity (Fig. 4a) (see below). The most complete whole-rock geochemical analyses published in the 19th century that we have been able to find are those by Phillips (1880), which included data for the *Silica*, *Alumina*, *Phosphoric anhydride*, *Titanic*, *Ferric oxide*, *Ferrous oxide*, *Manganous oxide*, *Lime*, *Magnesia*, *Potassa*, and *Soda* contents of granites cropping out in several quarries in England, Scotland, and Ireland. Other 19th century examples of whole-rock geochemical analyses of granites are the studies of the microscopic structure and chemical composition of Irish granites (Hull, 1874), as well as the structural, mineralogical, and geochemical investigations of granite quarries throughout England (Harris, 1888). On the other hand, the first known geochemical analysis of specific granite-forming minerals, namely feldspar, black mica, and beryl, were those presented to the Royal Irish Academy by Samuel Haughton, professor of geology at Trinity College (Dublin) (Haughton, 1853, 1855, 1862). In the United States, since the establishment of the United States Geological Survey (USGS) in 1879, several projects also reported the properties and the major element compositions of granites (among other rock types) and their mineral assemblages throughout the country, with Frank Wigglesworth Clarke as the chief chemist (e.g., Clarke, 1868, 1887; Clarke and Chatard, 1884; Kinahan, 1887; Van Hise, 1890; Turner, 1899; Mathews, 1900).

Several other works described granitic rocks around the world during the last decades of the 19th century. Although it would be impossible to address all of these in this review, those focused on the magmatism vs. transformism debate, are referred to below. Notable is also the pioneering work of McMahon (1887) on the Gneissose-Granite of the Himalayas, the summary of the geology of southern India by Newbold (1850), and the geological interpretations and petrographical descriptions of granitoid rocks made by G. F. Scott Elliot along the Nile River summarized by Raisin (1893) (Fig. 6).

4. From the late 19th century, part I: global flood of knowledge

"The "facts" of today are the hypotheses of yesterday"
Reginald Aldworth Daly, 1914. *Igneous Rocks and Their Origi*

With the development of geochemistry, research on granitic rocks shifted from being purely observational to analytical. The observational aspect, however, also flourished thanks to the emergence and optimisation of the polarizing microscope and the concomitant increase of petrographical studies during the late 19th and early 20th centuries (Fig. 4). As a result of the new ideas on the origin and significance of granites and other igneous rocks, the first problems with their classification became central to discussions among scientists worldwide. Until that moment, the term *granite* had been used to refer to any kind of massive crystalline rock with a broadly felsic composition. However, that broad use was no longer acceptable from the late 19th century, since interpretations of the origin of granitic rocks were directly correlated with their textural properties and chemical compositions (Fig. 4b-e).

Among many other works, two textbooks on petrography are believed to have changed the course of the study of igneous rocks (e.g., Cross, 1902; Pitcher, 1997a, 1997b): *Lehrbuch der Petrographie* (Zirkel, 1866) and *Die mikroskopische Physiographie der massigen Gesteine* (Rosenbusch, 1877a), with the latter considered to contain the first published global classification of igneous rocks. In this classification, several sub-types of granites and syenites were proposed in addition to the definition of granite *sensu stricto*: a rock containing quartz and orthoclase, small amounts of plagioclase (oligoclase or albite), and micas and/or amphibole. For granitic rock containing biotite but no muscovite or amphibole, Rosenbusch (1877a) used the expression *"granite"* (e.g., Marmo, 1967a, 1967b).

Several other references stand out for furthering the knowledge of granite petrology during the late 19th and early 20th centuries. A good example is the textbook of Cossa (1881) (Fig. 4b), which influenced the Italian school of mineralogy and petrology by providing instructions for thin section preparation and the use of the polarizing microscope, as well as a complete set of colour plates representing different granite-forming minerals and textures. Furthermore, the work of Teall (1888) (Fig. 4c, d), from the British school (understanding *school* as a group of individuals with a common scientific tradition, thought, and/or views about a given subject), also provided numerous petrographic descriptions, geochemical analyses, and raised valuable points about the classification of igneous rocks, which he did not attempt to apply into his textbook: "*the more rocks are studied the less they seem to me to adapt themselves to any classification at all*" (Teall, 1888) (Fig. 4c, d). In fact, these and many other schools of thought have played a significant role on the evolution of our knowledge of granitic rocks by enhancing the magnitude of scientific revolutions. Instead of convincing individual scholars, a set of inconsistencies, arguments, and alternative explanations may eventually become convincing enough so that a whole school topples at once and completely changes its view. In these scenarios, paradigm shifts may be harder to accomplish, but when they happen, they are larger. The concept of schools of thought may be compared to the assortative mating phenomenon of Human Evolution theory (e.g., Bons et al., 2019), i.e., the innate tendency to mate and have children with like persons, which creates regions with particular (genetic) traits and sharp boundaries between them. In science, these regions may be

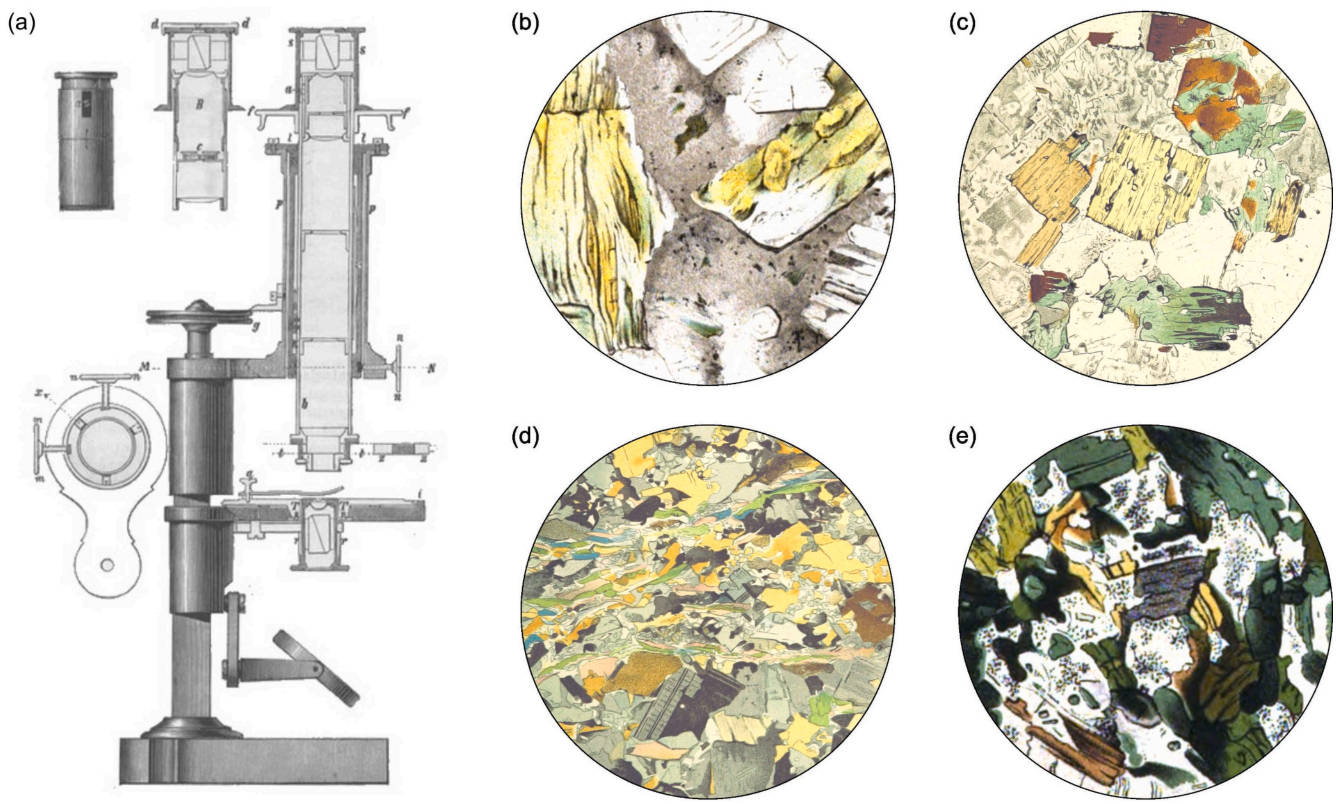

Fig. 4. (a) One of the first known schematic drawings of a polarizing microscope specifically designed for the study of rock thin sections (H. Rosenbusch model, *Serial Number 131*) (Dana, 1877; after Rosenbusch, 1873, and Zirkel, 1873). (b-e) Microscopic illustrations of granitoid textures published in some of the most influential works on igneous petrography of the late 19th century. (b) Cossa (1881), Tavola IV, Fig. 5: *thin section of a diorite in which chlorite (yellow) sheets are observed to be normally displaced at the flake plane* (light grey colours correspond to quartz and feldspar); magnification: 180 (location not provided). (c) Teall (1888), plate 35: *quartz (white), feldspar (grey), dark mica (biotite, yellow), chlorite (green), and apatite (brown) – Shap biotite-granite (granitite) (Devonian) intrusive in Ordovician strata (Cumbria, NW England); magnified 30 diameters*. (d) Teall (1888), plate 42: *feldspar (dark grey), white mica (brown and yellow), and quartz (light grey) – Pre-Carboniferous (Upper Ordovician) schistose Wicklow granite intrusive in Lower Palaeozoic strata (Leinster, Ireland); magnified 25 diameters*. (e) Rosenbusch (1873), Tafel VII, Fig. 40: *Biotite-granite close to Schlierbach (Heidelberg); quartz and feldspar in white, biotite in green and brown* (magnification not provided). Note that plate descriptions and indications on magnification in this caption are those originally published by the authors. See text for further references. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

understood as schools of thought and, yet not helpful for evolution to reach optimum fitness, it is a protective mechanism for preserving genomes (or, in science, common scientific traditions, thoughts, and views about a given subject).

One year later after Teall's (1888) work, another textbook published by the director of the Geological Survey of France, August Michel-Lévy, attempted to provide a new classification scheme for igneous rocks (Michel-Lévy, 1889). This new classification, the first of many following versions and revisions that would be published in the later decades, was based on previous observations and textural interpretations (Michel-Lévy, 1878a, 1878b, 1889; Fouqué and Michel-Lévy, 1879, 1882), as well as on the initial proposal of Rosenbusch (1877a, 1877b). Concerning granites, Michel-Lévy (1889) proposed a classification for the *Famille des Granites* based on their depth of emplacement, including: *Profondeur* (*granites*, *granulites*, and *granites à amphibole*), *Filons* (*granulites* and *microgranulites*), and *Épanchements* (among others, *microgranulites*, *micropegmatites*, *porphyres globulaires*) (see Section 5). The same classification scheme (i.e., deep, vein-type, and eruptive rocks) was also followed for the *Famille des Syenites*, the terminology of which was reduced and significantly simplified by Michel-Lévy (1889) after Rosenbusch (1877a, 1877b).

For the Russian school, the work of Feodor Yulievich Levinson-Lessing, Professor at the University of St. Petersburg, was particularly influential. Among other contributions, *Petrographisches Lexicon* (*Petrographic Lexicon*) (Levinson-Lessing, 1893a, 1895) and *Tablitzy dlya Mikroskopicheskikh Opredeleni Porodoobraznykh Mineralov* (Levinson-Lessing, 1893b; translated into English by Cole and Gregory, 1893) provided Russian scientists with new techniques that were emerging in western Europe for the study and interpretation of rocks under the microscope, including granites and granite-forming minerals.

In the United States, the work of Joseph Paxon Iddings was extremely influential within different departments and faculties of geology and petrology. Iddings spent two years (1879–1880) at the University of Heidelberg with Prof. Rosenbusch conducting petrographic investigations that resulted in several publications on the significance, formation and classification of granitoids and other igneous rocks (e.g., Hague and Iddings, 1885; Rosenbusch and Iddings, 1888; Iddings, 1890, 1892a, 1892b, 1893a, 1893b). Among his works, Iddings (1893a, 1893b, 1898a, 1898b) presented the largest dataset ever published of geochemical analyses of igneous rocks from the Los Andes cordillera, the Yellowstone National Park, and Christiania region, and included a large set of compositional plots. Furthermore, *The Origin of Igneous Rocks* (Iddings, 1892b) became as influential as it was controversial for the scientific community since, besides providing new ideas on the origin and classification of igneous rocks, it questioned the assumptions and interpretations of granites that had previously been made by Scrope (1825), Darwin (1844), von Bunsen (1851), or Durocher (1859) (see Section 5).

The large amount of observational, analytical, and (embryonic) experimental data on igneous rocks, and specifically on granites, gave rise to several classification issues. For example, confusion stemmed from the inclusion of a wide range of granite-looking rocks within the general term *granite*, but this term itself was not yet properly restricted (e.g., granites *sensu stricto*, granite-porphyries, granophyres, quartz porphyries, pitchstones, rhyolites, feldspar-bearing high-grade micas-chists, and migmatites). The subclassification of these rocks according to their relative age or area of occurrence further added more layers of complexity to this problem (e.g., Johnstone, 1887; Harker, 1896; Daly, 1910). The emergence of petrography as a subfield of petrology also produced an increase in the detail of the investigations on granites and thus a magnification of their differences, leading to complex sub-classifications often based on very slight changes in the modal abundance or texture of mineral assemblages (e.g., Michel-Lévy, 1889; Cross, 1898). Further confusion was related to the different approaches to the classification of granites proposed, adapted, and modified by petrologists from different schools in a brief period of time, among others: (1) the mode of occurrence (e.g., *Dikes*, *Necks* or *Plugs*, *Sills*, *Laccoliths*, *Bysmaliths*, and *Bathyliths*; Chamberlin and Salisbury, 1904), (2) their timing relative to orogenesis (e.g., *Synkinematic*, *Late-kinematic*, *Post-Kinematic*; Sederholm, 1891), (3) their petrogenesis and chemical and mineralogical features (e.g., the CIPW System or the *Persalane*, *Dosalane*, *Salfemane*, *Dofemane*, and *Perfemane* rock groups; Iddings, 1898b; Cross et al., 1902; Lœwinson-Lessing, 1911; Young, 1999), or (4) a combination of the above (e.g., Daly, 1905). The minutes and publications derived from meetings of the American Academy of Arts and Sciences, the Royal Society of Edinburgh, and the Mineralogical Society of Great Britain and Ireland are illustrative of these developements. For more information about these and other historical classifications of igneous rocks, some of which still cause debate among scientists, the reader is referred to Section 6.1 and to the exceptional reviews of Cross (1898), Iddings (1898b), Tomkeieff (1939), Barbarin (1990, 1999), and Pitcher (1997a, 1997b). Regarding the magmatic, metamorphic, or metasomatic origin of granites (e.g., Walton, 1960; Marmo, 1967a, 1967b; Kresten, 1988; Clarke, 1996), this issue is addressed in more detail in the following section.

5. From the late 19th century, part II: magmatism vs. transformism

"Are there Granites and Granites after all?"
Herbert Harold Read, 1947. *Granites and Granites. Geological Society of America Memoir 28: Origin of Granite*

The research on granitic rocks saw its most polarized controversy from the late 19th to the late 20th centuries. As a result of the growing number of inconsistencies derived from field observations, structural interpretations, and geochemical investigations (named *anomalies* in Fig. 5), chemists, physicists, and geologists were divided among *magmatists* and *transformists*. The debate on whether granites are of magmatic, metamorphic, or metasomatic origin, and the related structural and petrogenetical implications of each potential hypothesis, governed more than one century of widespread debate in almost all the geological societies, schools of thought, and geological surveys. Given the significant number of reviews that have already addressed this granite controversy (Walton, 1960; Marmo, 1967a, 1967b; Pitcher, 1987; Clarke, 1996; Pitcher, 1997a, 1997b; Brown, 2013), we focus the present section on two of the main debated issues: the *space* or *room* problem (e.g., Keilhau, 1838), and the origin of granitic melts (e.g., Tuttle and Bowen, 1958).

About the *room* problem, Read (1948) wrote: "*it is the room problem that lies at the heart of the granite problem, and the room problem is a matter to be dealt with by field geology*". The *room* problem, in fact, dates back to 1837 when Charles Lyell, Marie Elisabeth Lyell, and Baltazar M. Keilhau visited Norway and provided contrasting interpretations on the origin of the granites cropping out close to the city of Oslo (e.g., Holtedahl, 1963; Marmo, 1967a, 1967b; Hestmark, 2011) (see Section 3; Figs. 1b, 6). At that time, the idea of magmatism implied that the space needed for the formation of a body of granite was exactly the same of that occupied by the granite itself once formed. In contrast to this, *room* was not needed for the formation of granites according to the *transformist* views, which suggested that granites were formed by the replacement or transformation in the solid state of pre-existing rocks (Keilhau, 1838). The apparently unattainable dimensions required for the formation of granites as explained by *magmatists* led the *transformists* to gain traction in the late 19th century, and a wide range of arguments invoking *granitization* were reported to explain the formation of granitic rocks worldwide. Concepts such as pseudomorphism (variations in mineralogy, texture or composition of a granite simulating primary sedimentary or volcanic structures and/or mineral phases; Bowes, 1953; Stringham, 1953), gradation and continuity (the process by which a pre-existing rock passes gradationally into granite; Anderson, 1937; Goodspeed, 1948; Eckelmann and Poldervaart, 1957), or relict stratigraphy (the occurrence of pre-existing layers within a granite that maintain a relative stratigraphic position; Misch, 1949; Pitcher, 1952) were used as arguments for a metasomatic or metamorphic origin of granitoid rocks. The formation of rapakivi granites through replacement of red sandstones in the Fennoscandian Peninsula suggested by Backlund (1938), or the formation of gabbro and diorite as mafic fronts resulting from the expulsion of matter during granitization of metagreywackes (Reynolds, 1943, 1947), are good examples of the aforementioned concepts.

However, years before granitization had gained popularity and was eventually refuted, several geologists attempted to solve the *room* problem from a magmatic point of view by means of *assimilation*. Within this framework, granites from Oslo were again the source for the interpretations of Kjerulf (1855, 1879). This author agreed with previous interpretations of Lyell (1838, 1841) regarding a plutonic origin for the Oslo granites despite acknowledging the *room* problem pointed out by Keilhau (1838). Kjerulf (1879) suggested that the space needed for the emplacement of granites was progressively gained by the assimilation of sedimentary rocks, rather than created through forceful intrusion by displacing the surrounding strata. Other contemporaneous influential petrologists from the French and Finnish schools further developed the ideas of assimilation and anatexis (i.e., partial melting of rocks) (e.g., Michel-Lévy, 1888, 1893; Sederholm, 1897, 1907; Lacroix, 1898).

Authors from the French school based their interpretations on pioneering investigations of the mid-19th century that addressed the origin of granites from an extreme *transformist* perspective. For example, Boué (1824) first proposed igneous liquefaction as a process for turning metamorphic schists into igneous rocks, and the French chemist Sainte-Claire Deville first suggested the existence of *agents minéralisateurs* (i.e., mineralizing agents) that chemically transform the rocks through which they diffuse (see Holmes, 1945). Virlet D'Aoust (1844a, 1844b) coined the term *imbibition*, a precursor of *granitization*, to describe the process by which igneous materials could soak into metasedimentary rocks further transforming them into granites. Later, investigations by Delesse (1861) further provided insights for the French school of transformism: "plutonic rocks are formed from metamorphic rocks; they represent the extreme term of general metamorphism; they are the effect rather than the cause of metamorphism". This author further suggested that granitized plutonic rocks may become so mobile that they could be squeezed towards higher levels of the crust to form intrusive granites.

Occupying the middle ground between the endmembers of extreme magmatism and transformism, Michel-Lévy (1888, 1893) suggested that intrusive granite masses pervasively altered their surrounding strata, promoting the formation of more granite rocks. According to this interpretation, which was based on the ideas of Virlet D'Aoust (1844b), the upwelling rate of a given granitic intrusion was determined by the rate of absorption of the roof and walls of the reservoir, where granitic material assimilates the surrounding rocks that progressively sink and are transformed into granite gneiss, gneissose granite and, finally, granite (Michel-Lévy, 1888, 1893). Furthermore, the investigations of Lacroix (1898) in the granitic rocks from the Pyrenees (Fig. 1f) emphasized the contact zones with the surrounding schists. From field and mineralogical observations along the Garonne River in the Haute-

Ariège, Lacroix obtained strong evidence regarding the occurrence of granitic intrusions and their relationship to the assimilation and metamorphism of surrounding rocks. This author attributed strong feldspatisation of metamorphic aureoles to the migration of a *granite substance* into the country rock, in the presence of mineralizing agents, as well as the possible removal of certain elements in the exomorphic contact zone under the same intrusion conditions (Lacroix, 1896, 1898; Daly, 1898). From this work, the Pyrenees turned out to be the flagship for the *transformist* ideas of the French school, being defined as a district in which remarkable rock transformations could be clearly seen. A geological excursion to the Pyrenees led by Prof. Lacroix within the framework of the Eighth International Geological Congress (Paris, year 1900) (see summary in Adams, 1901) further fostered the discussion on the origin of the Pyrenean granites, which remained open until the late 20th century (e.g., Guitard, 1960, 1970; Autran et al., 1970).

In Finland, the spread of transformism was mainly lead by the head of the Finnish Geological Survey, Jakob Johannes Sederholm (Sederholm, 1907, 1911, 1926). From observations on Precambrian rocks of southern Finland, Sederholm encountered difficulties in explaining different outcrop features in terms of classical magmatism, which led him to introduce the terms *palingenesis* (i.e., *rebirth*) and *anatexis* (i.e., *to melt down*) to account for peculiar mixed rocks, migmatites (Sederholm, 1907): "*because the mixture of different constituents is the characteristic feature of all these different rocks, I would suggest for them the name migmatites*". The term *palingenesis* was also used by Sederholm (1907) to explain the inception of the granitization phenomenon, where the (re-)melting of older granites formed granite melts that were later on intruded at higher levels while granitizing their adjacent rocks, thereby not requiring *room*. Sederholm (1926) also defined migmatites as an intermediate rock type between igneous and metamorphic end members, which were commonly found in migmatitic terrains together with other rock varieties such as *arterites*, *agmatites*, *eruptive breccias*, *banded-gneisses*, *ptygmatitic migmatites*, and *diktyonites* (see comparisons between Finnish and Scottish rocks in Read, 1925).

The interpretation by French and Finnish schools regarding the formation of granites and their relationship with migmatites did not necessitate a choice between either magmatic emplacement through forceful intrusion or extreme transformism by mysterious replacement reactions driven by fluids. A coupled process under high-temperature conditions, where minor intrusions of granitic magma caused the transformation of surrounding strata into more granitic rocks, was more acceptable given the knowledge of that epoch, and furthermore reduced the *room* problem by several orders of magnitude. The growing inconsistencies between field observations (Michel-Lévy, 1888; Lacroix, 1898; Read, 1925; Sederholm, 1926) and the tenets of magmatism questioned the theories involving forceful intrusions as the origin of granitic rocks. "*Granites are very big things, not hand specimens*", noted Read (1948) several years later, when introducing the *room* problem in the well-known review *Granites and Granites*.

Despite maintaining traditional views on magmatism, some geologists were forced to acknowledge the existence and importance of metasomatic granites during the early 20th century. This was the case of the Finnish geologist Pentti Eskola. About Sederholm, Eskola wrote (see Eskola's prologue in Sederholm, 1967): "*one may ask how he, a pupil of Harry Rosenbusch, the extreme magmatist, became the announcer of granitization*". Sederholm's (1891) classification of granitic rocks (see Section 4) according to their time of formation relative to orogenesis was, nevertheless, adapted by Eskola (1932). In this classification, Groups I, II, and III of Sederholm (1891) were defined in Eskola (1932) and later on refined in Eskola (1955) as: (I) Synkinematic granites, of metasomatic origin with gneissose texture, which are associated with greatly differentiated complexes varying through all calci-alkalic members from peridotites to granites, (II) Late-kinematic granites, of metasomatic origin with aplitic texture, which were formed at a later stage of the orogeny and thus crosscut the country rock and some of its deformation structures, and (III) Post-kinematic granites, of magmatic origin and completely devoid of gneissosity. This latter type of granite, often characterized in Finland by rapakivi textures, was the only *true* magmatic granite in Eskola's opinion (Eskola, 1955): "*the rapakivi plutons are the purest magmatic granites in our country. From them we can follow all gradations to metasomatic granites*" (see Marmo, 1967a, 1967b; Pitcher, 1997a, 1997b; Eklund et al., 2008).

At the other end of the spectrum are the observations reported by advocates of magmatism of the English and German schools regarding the origin of granites. One of the best examples are the geochemical investigations of Rosenbusch (1877b) on the contact metamorphic slates surrounding the Barr-Andlau Pluton in the northern Vosges (France). From a series of geochemical analyses along sampling profiles from distal towards proximal areas of the margin of the granite, the author concluded that metamorphism adjacent to granitic bodies always took place without significant chemical changes. Another exceptional example refuting the existence of granitization were the observations of Callaway (1894) in a paper entitled *Is granite ever metamorphic?* In this work, the author investigated contact zones between granites and surrounding schists in Great Britain, which were believed to show transitional or gradational contacts. At three investigated localities, Callaway (1894) refuted the former interpretations about a metamorphic or metasomatic origin of the exposed granites by showing evidence of granitic veins or intrusive and "net" contacts between granites and sedimentary country rocks. However, Callaway (1894) did not account for the *room* problem. Hans Cloos, from the German school, attempted to solve the *room* problem and suggested that large batholiths posing controversial space problems were in truth large intrusive sheets (Cloos, 1923). This interpretation involved less *room* needed to form such structures, although vertical or horizontal crustal extension was necessary to accommodate the intrusive sheets following crustal discontinuities.

Previous work by Daly (1912), who also advocated for the forceful intrusion of granitic magmas, was influential to the understanding of the *room* problem. Based on the occurrence of *intrusion breccias* observed along the margins of large granitic masses along the North American Cordillera, Daly (1912) coined the term *magmatic stoping* and defined it as "*the successive engulfment of suites of blocks broken out of the roof and walls of the batholith*". Pitcher et al. (1958) later proposed lateral magmatic widening as the mechanism of emplacement for the relatively large Donegal granite in northwest Ireland. Numerous investigations on this area had already been published, suggesting either a magmatic (Haughton, 1862) or metamorphic (Scott, 1861) origin. However, Pitcher et al. (1958) provided new meaningful observations and detailed geological mapping of different granite units, acknowledging that a "metamorphic" origin appeared reasonable for one part, and an "igneous" origin for another. Pitcher et al. (1958) found that discontinuous metasedimentary horizons in the country rocks were also present within the granite as a *relict* or *ghost* stratigraphy, a phenomenon that had classically been used as an argument for granitization. However, they attributed it to a *syn*-plutonic origin for these horizons, which developed a strong marginal lineation during compression caused by sequential pulses of a plexus of wedge-like granite sheets (see a review in Cobbing, 2000).

Contrasting positions were taken by geologists since the late 19th century, but the *room* problem within the magmatism vs. transformism debate was not polarized on a geographical basis. There were as many *extreme magmatists* in the French and Finnish schools as there were *extreme transformists* in the English and German schools. For example, investigations by Currier (1937, 1947), member of the United States Geological Survey, and Reynolds (1943, 1947, 1958), Fellow of the Royal Society of Edinburgh, promoted a metamorphic or metasomatic origin of granites (e.g., by Lewis, 2021).

The origin of granitic magmas was the second major question in the magmatism vs. transformism debate and, unlike the *room* problem, was solely pursued within the magmatic school of thought. If granites were magmatic, then the origin of granitic magmas and the conditions at which they formed, including their water content, were key issues to be understood. The origin of this discussion dates back to the birth of geochemistry and experimental petrology, which marked the onset of numerous investigations on the order of crystallization of mineral phases and their physicochemical conditions of growth (see Section 3). The presence of water in granitic magmas was acknowledged following the work by Sorby (1858) on fluid inclusions in granites, and by Scheerer (1862) on melting of hydrous salts as a magma analogue. However, before reaching this stage, the controversy on the origin of granitic magmas was focused on the fusion of rocks: dry, or wet? (see Chapter 6 in Young, 2018). The leading advocates for the dry fusion were the Frenchmen Baptiste Xavier Fournet and Joseph Marie Durocher (e.g., Fournet, 1844, 1845; Durocher, 1859). Wet fusion (involving the presence of H_2O and other volatile phases) was accepted later during the second half of the 19th century. This theory had major implications for the understanding of how granitic magmas form and, more specifically, for the physicochemical laws governing the process of magmatic differentiation.

The concept of magmatic differentiation was proposed and subsequently investigated by, among others, Scrope (1825), von Bunsen (1851, 1861), Iddings (1893b, 1896), and Harker (1896, 1909) (see Section 3). However, it only started to gain advocates since the petrographic and geochemical insights provided in the seminal work of Brögger (1894) (see Pitcher, 1997a, 1997b). From field observations and geochemical analyses of the granites cropping out in southern Norway, Brögger (1894) suggested that the sequence of mineral phase crystallization reflected the differentiation of the original magma, from basic to acid: "*the oldest rocks are the most basic, the youngest are the most acid, and between the two extremes I have found a continuous series*". At that time, it was already known that, under wet conditions, a granitic melt could be formed at much lower temperatures than an equivalent anhydrous melt, which had major implications for the research on the order of crystallization of mineral phases, or "crystallization series" (e.g., Fouqué and Michel-Lévy, 1882; Brögger, 1894; Iddings, 1896). Understanding of the specific order in which mineral phases are formed during the cooling and solidification of the magma, was based on the relative melting points of minerals. It was known that the crystallization temperature of micas was lower than that of feldspar, and still lower than that of quartz (see Chapter 6 in Young, 2018). On this basis, works from the late 18th century had already suggested that quartz, the phase with the highest melting temperature, should crystallize before the more fusible feldspar and, therefore, euhedral quartz crystals should show imposed faces on the subsequent feldspar crystals rather than the opposite (e.g., Kirwan, 1793, 1800). By the end of the 19th century, however, it was known that that the actual order was precisely the reverse, as demonstrated by von Bunsen (1861): "*No one seems to have considered that the temperature at which a body solidifies for itself is never the temperature at which it becomes solid from its solutions in other bodies*".

Later on, the order of crystallization in granitic magmas was further investigated by Guthrie (1884), who first suggested the idea of eutectics, Vogt (1884, 1888), regarded as the founder of the modern experimental petrology, and Rosenbusch (1910), who maintained that molten material with a composition of primary magma exists within the Earth's interior, where it continually differentiates. Moreover, according to Rosenbusch (1910), variations in differentiation could occur because of variations in temperature and pressure during crystallization. This latter idea served as the basis for the seminal experimental work of Norman L. Bowen on the crystallization of silicate melts and its relation to natural associations of igneous rocks (see a review in Grove and Brown, 2018). Bowen investigated crystallization processes in different silicate melts and binary, ternary, or composite systems. Among other findings, those related to different binary and ternary systems, as well as the invaluable insights into the fractional crystallization of basalt under anhydrous conditions, represented a milestone for igneous petrology in the early 20th century (e.g., Bowen, 1912, 1913, 1916). Later, Bowen started to work with Frank Tuttle, who during the 1940s conceptualized and built an apparatus to simulate varying conditions in the Earth's crust. The *hot-seal hydrothermal quenching apparatus*, painstakingly described in Tuttle (1948) and nowadays stored at the Carnegie Institution for Science Earth and Planets Laboratory Archives (Washington DC, USA), represented the inception of a plethora of investigations on mineral systems including volatile components, which had been sparse until that moment (e.g., Goranson, 1936). At that time, the origin of granite was viewed differently by field researchers with strong backgrounds in structural geology and metamorphic petrology, who favoured a non-magmatic origin of granite, and those with backgrounds in experimental petrology. Two quotations from leading researchers in these fields are illustrative: "*the best geologist is he who has seen the most rocks*" (Read, 1939), and "*look as one will at the rocks he cannot see them in process of formation*" (Bowen, 1948). In this framework, the seminal work of Tuttle and Bowen (1958) on the *haplogranite* system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O (Ab-Or-Qtz-H_2O) demonstrated that granitic rocks could be formed from granitic magmas. Only a few years later, Winkler and von Platen (1961) experimentally tested high-grade metamorphism and anatexis of different greywackes, finding that tonalitic or granodioritic compositions were a final stage in the anatectic process. This milestone offered an even more convincing hypothesis for the formation of granitic melts and ultimately granitic rocks, significantly contributing to the understanding of their genesis. Granite, therefore, turned out to be strictly magmatic for most experimental petrologists (see Bailey and Macdonald, 1976), whereas other geologists maintained opposite views on the basis of field and petrographic evidence (see Walton, 1960; Marmo, 1967a; Vernon, 1986; Pitcher, 1987; Clarke, 1996; Pitcher, 1997a, 1997b; Brown, 2013).

6. The granite concept since the Plate Tectonics theory

"Some granites are cooler than others"
Vhairi Mackintosh. *Cosmos Magazine - 2 Jul 2018*

Alfred Wegener's continental drift theory (Wegener, 1912) is widely understood as the precursor to the Plate Tectonics theory. However, it is worth noting that, long before that moment, Benjamin Franklin already pointed out that the movement of continents across the Earth's surface should be driven by some internal force: "*Thus the surface of the globe would be a shell, capable of being broken and disordered by the violent movements of the fluid on which it rested*" (Franklin, 1782). The initial ideas of Franklin and Wegener were initially met with great scepticism due to the lack of plausible mechanisms (Oreskes, 1999), which were not discovered and accepted until the 1960s–1970s. Processes such as mantle convection, seafloor spreading, and slab pull and ridge push, provided reliable explanations for the large-scale movement of the Earth's lithosphere, and agreed with observations from seafloor mapping, paleomagnetic analysis, geochemical compositions, and large-scale tectonics (Dietz, 1961; Hess, 1962; Vine and Matthews, 1963; Wilson, 1965, 1975; McKenzie and Parker, 1967; Ringwood, 1974; Anderson, 1982; Tatsumi, 1986; McKenzie, 1989). Plate tectonics is thus a scientific revolution not only for granite science but for the understanding of the past, present and future behaviour of our planet; its influence on the knowledge of granitic rocks has therefore been crucial during the last 60 yr. (Fig. 5). One of the most important contributions was, for example, to distinguish granites from different tectonic settings and sometimes with different sources, mineralogy or compositions, such as in orogenic, anorogenic, and mid-ocean ridge environments (e.g., Chappell and White, 1974; Pitcher, 1983, 1987; Pearce et al., 1984; Maniar and Piccoli, 1989; Brown, 1994).

However, the Plate Tectonics theory did not directly end the magmatism vs. transformism debate, since many inconsistencies concerning granitic magma generation, segregation and emplacement were still debated (Fig. 5). These inconsistencies are exceptionally well documented in the work of Pitcher (1987), where it is first acknowledged that "*the advent of the Plate Tectonic Hypothesis has emphasised the relationship between cause, process and the regional geological environment*" but, later, it is stated that "*whilst many granites are essentially magmatic and intrusive others are metamorphic and replacive*". However, Plate Tectonics did contribute to increasing the explanatory power of magmatism and decreasing that of transformism (Fig. 5). The magmatism vs. transformism debate lasted until the late 20th century, with some investigations published based on studies of different regions of eastern Europe as the last witnesses of this long-lasting discussion (Korzhinskii, 1962; Dobretsov and Shafeev, 1991; Stumbea, 2003; Sedova et al., 2013; Aranovich, 2017). The magmatism paradigm prevailed, and granite research entered progressively, for a second time (see *Section 3*), the current paradigm-governed, stasis period of normal science (Kuhn, 1970) (Fig. 5). Accordingly, most current investigations into granitic rocks (see below in this Section) are part of a reductionist science trend, based on detailed studies about specific fields and sub-fields that offer their findings as part of a wider knowledge gap (Tex, 1990; Clarke, 1996; Petford et al., 1997).

The last half-century of research on granitic rocks, since the acceptance of the Plate Tectonics theory and the establishment of the magmatism paradigm, has mostly consisted, in Kuhn's words, of "puzzle solving"; which is, for clarity, to address problems that are believed in advance to have a solution (Fig. 5). This period has further fostered the proposal of tens of genetic and non-genetic classifications, some of them still used and some others already proven to be only valid for the context where they were proposed (see Section 6.1). Publications that categorically support a non-magmatic origin for igneous-looking rocks are almost absent in the modern literature. Noteworthy abundant are, however, investigations that tentatively attribute a non-magmatic origin to granite-looking rocks, suggesting that: (1) rocks showing very different field appearances (gneiss, trondhjemite, and mica schist among others) may be derived from similar precursors by mineralogical and chemical changes induced by deformation and metasomatism, and (2) deformation and metasomatism can also give a very similar appearance to previously different rocks (e.g., Hanor and Duchač, 1990; Almond et al., 1997; Elburg et al., 2001, 2012; Martin, 2006; Zirner et al., 2015). These investigations reflect how neglected ideas may eventually become central for explaining inconsistencies in new paradigms that have more explanatory power (Fig. 5). This phenomenon can be compared, as with the concept of the schools of thought (see Section 4), with Evolution theory. In this case, reusing old, neglected ideas to solve new problems is analogous to the role of refuges during evolution (Fig. 5), where old genomes may persist in isolated places without following the main evolutionary trend and may subsequently join the mainstream again.

It is currently widely accepted by the scientific community that granites *sensu stricto* are plutonic (Hutton, 1794; Walton, 1960; Le Maitre et al., 2002) silica-rich felsic rocks that contain modal quartz (Q), alkali feldspar (A), and plagioclase (P) in the following proportions: $20 < Q < 60$ and A: $P = 90$: 10 to 35: 65, and that they may contain one or more types of mica, amphibole, and many other accessory minerals (Streckeisen, 1974; Le Maitre et al., 2002). However, metasomatic *pseudo-granites* are also proposed to still exist, as recently demonstrated for the Himalayan banded tourmaline leucogranites, formed by metasomatism of a psammitic country-rock (Dyck and Larson, 2023), or the granites in the Mt. Painter Inlier that are alteration products of metasedimentary rocks of the Radium Creek Group (Weisheit et al., 2013).

Current research on granitic rocks can roughly be divided in two major approaches (see below): (1) observational and analytical and (2) experimental and numerical modelling. Although it is beyond the scope of this work to thoroughly review the bountiful literature of these two approaches, below we provide a summary of their main milestones and current debates (see Sections 6.2 and 6.3).

6.1. The classification(s) of granites

Naming and categorizing igneous rocks, including granites, has been highly controversial for geologists for the past two centuries. Since the acceptance of the Plate Tectonics theory, more than 30 non-petrogenetic and petrogenetic classifications of granitic rocks have been proposed (see the reviews of Barbarin, 1990, 1999; Frost et al., 2001; Bonin et al., 2020; Garcia-Arias, 2020). However, widespread agreement on the most suitable classification has not been yet reached. As pointed out by Garcia-Arias (2020), this long-lasting pursuit probably lies in the intrinsic "imperfection" of the existing chemical classification systems, which, if perfect, should provide names that convey all relevant information about a given sample: modal mineralogy, texture, chemical composition and genesis. For example, the widely accepted non-genetic classification of Streckeisen (1974) can be easily applied in the field and does not require determination of the other minerals (besides quartz and feldspars) that are present in the rock, nor how these rocks formed. However, this is also a limiting factor because the classification does not consider the abundance and composition of other mineral phases that may have significant petrological implications. Another example is the petrogenetic classification of Chappell and White (1974) that, although widely adopted, is not always straightforward when indicator minerals are absent, such as cordierite for S-type, amphibole for I-type, and orthopyroxene (or pigeonite or fayalite) for C-type granites (Ague and Brimhall, 1988; Barbarin, 1990; Kilpatrick and Ellis, 1992; Frost et al., 2001). Other drawbacks of these "alphabet" genetic classification schemes are that they often use a single parameter to infer a unique source. For example, peraluminous granites are equated to S-types, and therefore deemed to have a sedimentary source, whereas other origins and pathways may lead to the same composition (Alonso-Perez et al., 2009). Moreover, the classification of granites according to these multiple schemes is sometimes seen as a goal in itself, which is an approach that contributes little to our understanding of granite petrogenesis.

In this section, most used classifications are summarized, including details of their major strengths and potential pitfalls. Classifications of granitic rocks here reviewed are based on a wide number of variables including, among others, mineralogical modal compositions, petrographic features, accessory mineral phases, nature and abundance of enclaves, major or trace element compositions, and isotope geochemistry. The principal non-petrogenetic classifications of granitic rocks are presented in Table 1 (Streckeisen, 1974; De la Roche et al., 1980; Debon and Le Fort, 1988; Middlemost, 1994; Frost et al., 2001; Barton and Young, 2002; Frost and Frost, 2008; Enrique and Esteve, 2019; Glazner et al., 2019). They are based on either mineralogical modal abundances or major element compositions, and have the major advantage of being non-genetic. It is explicitly stated in Le Maitre et al. (2002) that the Subcommission on Igneous Petrology of the IUGS was based on Streckeisen (1974) and Le Bas and Streckeisen (1991) to provide nomenclature and classification to all *igneous and igneous-looking rocks*. Most authors now agree to use the modal classifications recommended by the IUGS (e.g., Streckeisen, 1974; Middlemost, 1994; Le Maitre et al., 2002), which use subdivisions and nomenclatures based on a limited number of variables, and are generally widely accepted (e.g., Frost et al., 2019; Bonin et al., 2020; Garcia-Arias, 2020). However, other petrologists have recently questioned and reformulated these schemes (e.g., Glazner et al., 2019).

The principal petrogenetic classifications of granitic rocks are summarized in Table 2 (Didier and Lameyre, 1969; Capdevila and Floor, 1970; Capdevila et al., 1973; Tauson and Kozlov, 1973; Chappell and White, 1974, 2001; Orsini, 1976, 1979; Ishihara, 1977, 2004; White and Chappell, 1977; Loiselle and Wones, 1979; Lameyre, 1980; Pupin, 1980, 1985; Keqin et al., 1982; Lameyre and Bowden, 1982; Yang, 1982; Pitcher, 1983, 1987; Pearce et al., 1984; Nachit et al., 1985; Rossi and Chevremont, 1987; Maniar and Piccoli, 1989; Barbarin, 1990, 1999; Castro et al., 1991; Didier and Barbarin, 1991; Kilpatrick and Ellis, 1992; Tischendorf and Förster, 1992) and have already been exhaustively discussed in Barbarin (1999) and Frost et al. (2001). These classification schemes gained popularity with the advent of modern geochemical methods, which provided evidence of the relationships between the mineralogical, chemical, and/or isotopic composition of granitoid rocks and their petrogenesis or tectonic setting (e.g., Pearce et al., 1984;

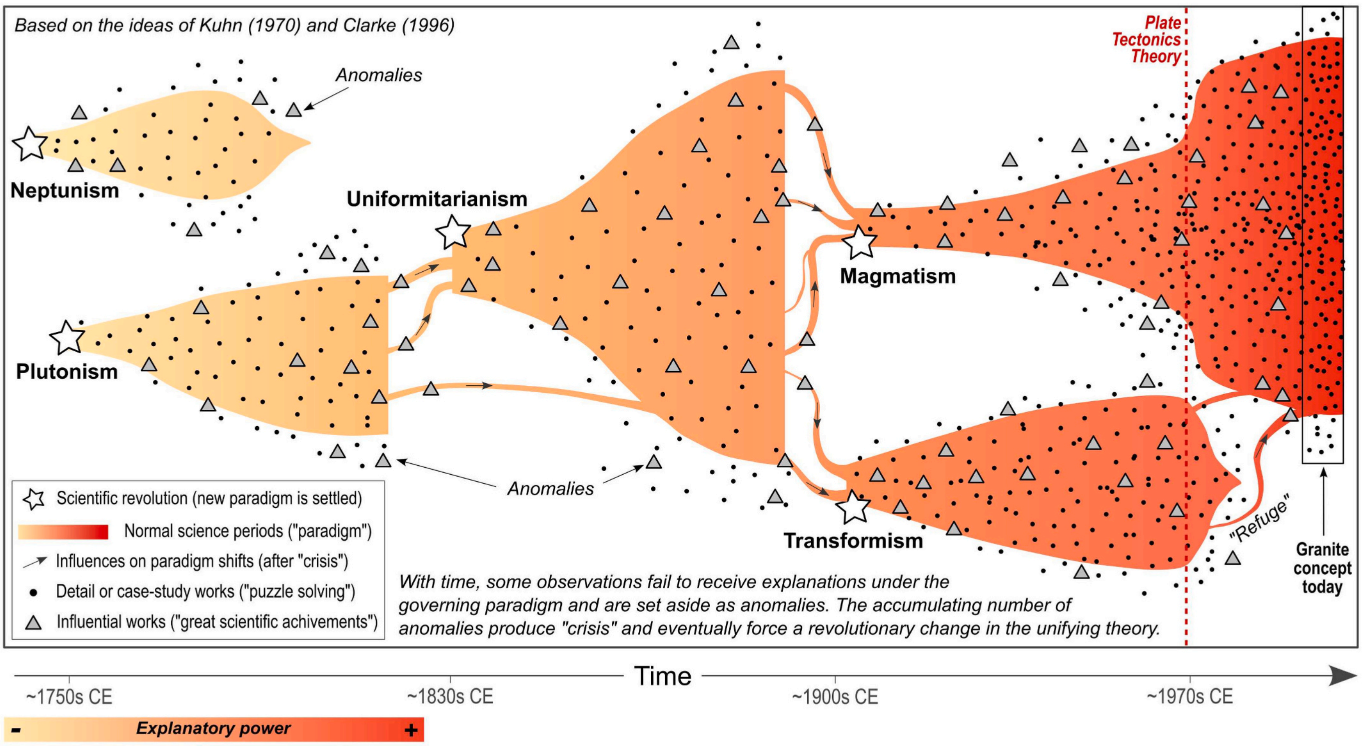

Fig. 5. Schematic timeline of the historical development of the granite concept through time, after the ideas of Kuhn (1970) and Clarke (1996). Each new paradigm about the origin of granites is settled (i.e., established) through a "scientific revolution" after "great scientific achievements". Scientific revolutions are followed by a period of "normal" science (paradigm-governed), where specific investigations or case studies are carried out through "puzzle solving" (i.e., investigating problems that are believed in advance to have a solution; stasis periods according to Bak, 1996). As more inconsistencies and new ideas emerge (anomalies falling outside the explanatory power of a given theory), the paradigms experience a crisis and collapse progressively, which forces a new revolutionary change ("avalanche" in the sandpile analogy of Bak, 1996). Ideas from preceding paradigms are often used to foster the explanatory power of the newly settled ones. See text for further explanations.

Maniar and Piccoli, 1989). In some cases, petrogenetic granite classifications were devised as bimodal schemes that progressively gained complexity by means of new sub-divisions and/or petrogenetic constrains. The two original I- and S-type granite endmembers, initially proposed by Chappell and White (1974) and subsequently complemented by the A-, M-, C- and H-types (Chappell and White, 2001; White and Chappell, 1977; Loiselle and Wones, 1979; Castro et al., 1991), are a good example of this growing complexity.

6.2. *Observational and analytical approaches for investigating granitic rocks*

Observational and analytical approaches of current research on granitic rocks encompass field-based, mineralogical, geophysical, and geochemical investigations (e.g., Liesa et al., 2021; Dahlquist et al., 2022; Milani et al., 2022; Song and Xu, 2022; Turner et al., 2022), commonly related to geothermal energy (e.g., Singh et al., 2020; Klee et al., 2021; Chandrasekharam et al., 2022) and the exploration for ore deposits (e.g., Harlaux et al., 2021; Lehmann, 2021; Zhang et al., 2021; Wang et al., 2022a, 2022b). Global investigations are generally represented by multidisciplinary approaches at the interface between structural geology and petrology. The observational approach for the study of granitoid rocks often starts with geological-structural mapping through classical fieldwork (e.g., Cobbing, 2000; IGME-BRGM, 2009; Casini et al., 2015; Tavazzani et al., 2017; Errandonea-Martin et al., 2018; Secchi et al., 2021; Russo et al., 2022) and, in high-altitude or inaccessible areas, remote sensing-based technologies (e.g., Watts and Harris, 2005; Haselwimmer et al., 2011; Karimzadeh and Tangestani, 2021). Recently, the historical importance and future directions of geological mapping have been reviewed by Butler et al. (2024). Another fundamental and widely applied observational mesoscale approach for the study of granites is the mapping, measurement, and quantification of fabrics (Bouillin et al., 1993; Bouchez, 1997; Moyen et al., 2003; Carreras et al., 2004). At the microscopic scale, beyond optical petrography, Electron Back Scatter Diffraction (EBSD) analyses with Scanning Electron Microscope (SEM) have also become a popular observational approach in the study of tectonic fabrics and sub-fabrics present in granitic rocks (e.g., Peternell et al., 2010; Mamtani and Renjith, 2015; Ávila et al., 2022), which may provide insights into the stress, strain, temperature, and pressure conditions of granitoid deformation (Hirth and Tullis, 1992; Stipp et al., 2002; Cross et al., 2017; Gomez-Rivas et al., 2020).

Geophysical imaging of granite bodies may also be classified as an observational approach. Among others, electric (e.g., Olhoeft, 1981; Jover, 1986), magnetic (e.g., Schwarz, 1991; Maré and Thomas, 1997; Kadioglu et al., 1998), and seismic surveys (Wenzel et al., 1987; Améglio and Vigneresse, 1999) have been conducted during the past decades. Moreover, high-resolution seismic reflection profiles and the 3D inversion of gravity data have provided valuable insights into the deep geometry and the internal structure of granitoid masses (e.g., Mair and Green, 1981; Evans et al., 1994), as well as the large-scale crustal architecture of different orogens worldwide (Muñoz, 1992; Mortimer et al., 2002; Korsch et al., 2012; Ayarza et al., 2021). Gravity survey data and methods such as 2D forward modelling and 3D inversion can be considered as the most used and insightful geophysical imaging techniques for granitic rocks (e.g., Vigneresse, 1990, 1995, 1999; Améglio et al., 1997). Since differences in gravity signatures are based on density contrasts between granitoids (generally with lower density, thus showing negative gravity signatures) and surrounding rocks (Vigneresse, 1990; Améglio and Vigneresse, 1999; Wang et al., 2011),

Table 1
Summary of the main non-petrogenetic classifications of granitoid rocks, including the parameters or properties utilised for categorizing, a broad summary of the resulting classes, and their potential problems and pitfalls.

Reference (chronological order)	Parameters considered	Classification at glance	Potential pitfalls
Lacroix (1933)	Major element composition	Calc-alkaline hyperaluminic Calc-alkaline Alkaline	In disuse – Terminology and sub-classes have been improved and/or updated
Shand (1948); Barton and Young (2002)	Major element composition (Aluminium Saturation Index)	Peralkaline; Metaluminous; Weakly/Strongly peraluminous	In use - Terminology and sub-classes have been improved and/or updated
Streckeisen (1974)	Major element composition (volumetric % normative composition of quartz, K-felspar, plagioclase feldspar)	Widely used, applicable in the field, inexpensive. Recommended by the International Union of Geological Sciences	Other minerals than quartz and feldspars are not considered.
De la Roche et al. (1980)	Major element composition (Multicationic chemical parameters R1 and R2; Oxide percentages converted to millications)	Incorporates all of the major elements that are relevant to both the rock mineralogy and petrology. Similar nomenclature as in Streckeisen (1974)	Not suitable for granitic rocks because K-feldspar and albite plot at the same point (see Batchelor and Bowden, 1985)
Debon and Le Fort (1988)	Major element composition (Oxide percentages converted to millications)	Applicable in two steps: sample nomenclature and identification through cationic values, and sample association to magmatic three possible groups (Aluminous / Alumino-Cafemic / Cafemic). First step with similar nomenclature as in Streckeisen (1974)	In disuse - Terminology and sub-classes have been improved and/or updated. According to Bonin et al. (2020), it should be resurrected and used as the most ideal classification
Middlemost (1994)	Major element composition (% alkali and silica content)	Recommended by the International Union of Geological Sciences – Similar nomenclature as in Streckeisen (1974)	Other minerals than quartz and feldspars are not considered
Frost et al. (2001)	Major element composition (Fe-number, Modified alkali–lime index, and Aluminium Saturation Index)	Three-tiered classification scheme that uses familiar chemical parameters to successively distinguish among (i) magnesian and ferroan, (ii) alkaline, alkali-calcic, calc-alkaline and calcic, and (iii) peraluminous, metaluminous and peralkaline types	Not (yet) widely applied. Terminology and sub-classes have been improved and/or updated - See Frost and Frost (2008)
Frost and Frost (2008)	Major element composition (Alkalinity Index & Aluminium Saturation Index)	Introduction of the alkalinity index and feldspathoid silica-saturation index allows to apply the three-tiered classification scheme of Frost et al. (2001) to all alkaline rocks, including feldspathoid-bearing rocks	Not (yet) widely applied.
Enrique and Esteve (2019)	Major element composition (SiO_2, CaO, and K_2O)	Chemical approximation to the normative QAP diagram. Similar nomenclature as in Streckeisen (1974)	Other minerals than quartz, feldspars, and feldspathoids are not considered. Sodium not considered.
Glazner et al. (2019)	Major element composition	Based on the QAP system but adding quantitative data to rock names	See numerous comments in Frost et al. (2019) and Hogan (2019)

these techniques have allowed the identification of the shape and extension at depth of outcropping granite bodies in, e.g., the Congo Craton (Shandini and Tadjou, 2012), the Pennine area (Kimbell et al., 2010), the Pyrenees (Ayala et al., 2021), and the Arabian Shield (Mukhopadhyay et al., 2021). Furthermore, they have allowed the detection of concealed subsurface igneous masses of contrasting size and composition in many regions where, for example, granitic basement rocks are located beneath thick sedimentary sequences (Cooper Basin in Central Australia, Meixner et al., 2014; Middle and High Atlas in northern Africa, Elabouyi et al., 2022; or Northland in New Zealand, Stagpoole et al., 2016), and even in the subsurface of the Moon (Andrews-Hanna et al., 2013, 2014) and Mars (Kiefer, 2004).

Regarding analytical approaches, whole-rock geochemical data are commonly used for the petrogenetic and non-petrogenetic classification of granitic rocks (see Tables 1 and 2 and Section 6.4). Moreover, geochemical investigations on accessory minerals of granites have gained popularity during the recent decades due to their potential use for correlation, dating, and unravelling the temperature and pressure conditions of granite formation. Zircon, for example, is an outstanding U—Pb geochronometer due to, among others, its high closure temperature and the long-lasting stability of its atomic structure (e.g., Davis et al., 2003; Harley and Kelly, 2007). U—Pb zircon geochronology has therefore been applied to granitic rocks worldwide to obtain insights into major orogenic events (e.g., Aguilar et al., 2014; Heilbron et al., 2017). However, in some cases, the robustness of zircon can be a hindrance to determine the magmatic age of granites, as the mineral is not always reset during anatexis (Bea et al., 2021). In these cases, U—Pb dating of monazite and titanite (Elburg et al., 2003) can be more informative. The trace element and isotopic composition of igneous zircons, as well as of micro-zircon inclusions in accessory minerals, are furthermore considered as petrogenetic indicators (e.g., Belousova et al., 2002; Bell and Kirkpatrick, 2022; Guo et al., 2022; Yang et al., 2024). Recently, zircon oxygen isotopic signature and water content have also been suggested as a potential tool to distinguish I- and S-type granites (Mo et al., 2023).

Beyond zircon, other accessory minerals are also targets of geochronological investigations on granites. U—Pb dating of apatite crystals can provide accurate geochronological data, although it is recommended to apply it in combination with other geochronological data for comparison and data validation (e.g., Ferreira et al., 2019; Van Daele et al., 2020). In fact, two main possible pitfalls must be considered when carrying out U—Pb dating of apatite-bearing granitoid rocks. First, its closure temperature of ~450–550 °C (e.g., Schoene and Bowring, 2007), which is significantly lower than that of zircon (~<900 °C; e.g., Cherniak and Watson, 2003). And second, its potential crystal-plastic deformation and recrystallization, which causes chemical changes in the trace element composition substantially decreasing the U/Pb ratio (Ribeiro et al., 2020). Another useful method generally applied to zircon and apatite crystals to gain insights into the exhumation paths of granitic rocks is the measurement of fission-tracks, i.e., regions of high density of crystalline defects formed due to the damage inferred by fission decay of ^{238}U (Reiners and Brandon, 2006). Other methods applied to diverse accessory minerals for constraining the crystallization age of granitic rocks are, for example, cassiterite U—Pb and muscovite Ar—Ar dating on granite-related ore deposits, such as skarn- and greisen-type deposits (Chen et al., 2018; Tichomirowa et al., 2019; Bui et al., 2022), in-situ Lu—Hf geochronology of apatite through laser ablation tandem inductively coupled mass spectrometry (LA-ICP-MS/MS), as well as the

Table 2
Summary of the main petrogenetic classifications attempted for granitoid rocks (updated after Barbarin, 1999), including the parameters or properties employed for categorizing, a broad summary of the resulting classes, and their potential problems and pitfalls.

Reference (chronological order)	Parameters considered	Classification at glance	Potential pitfalls
Didier and Lameyre (1969); Didier and Barbarin (1991)	Mineralogy and associated enclaves	C-type (crustal granitoids; leucogranites) M-type (mixed or mantle granitoids; monzonites and granodiorites)	In disuse - Diagnostic minerals and enclave types may not be present
Capdevila and Floor (1970); Capdevila et al. (1973)	Petrographic features	*Mesocrustaux / Mixtes / Basicrustaux*	In disuse - Diagnostic minerals and textures may not be present
Tauson and Kozlov (1973)	Trace element composition [Discrimination diagrams]	Plumasitic leucogranites / Ultra-metamorphic granites / Palingenic granites / Plagio-granites / Agpaitic leucogranites	In disuse - Outdated terminology
Chappell and White (1974, 2001); White and Chappell (1977); Loiselle and Wones (1979); Castro et al. (1991); Kilpatrick and Ellis (1992)	Major element composition and Mineralogy	I-type (Igneous source) / A-type (Anorogenic) / S-type (Sedimentary source) / M-type (Mantle-derived) / C-type (Charnockitic) / H-type (Hybrid source)	Granitoids rarely come from single sources. Diagnostic minerals may not be present for some sources. See text for further pitfalls and other comments in Frost et al. (2001)
Orsini (1976, 1979)	Petrographic features	*Aluminic subalkaline / Hypoaluminic Subalkaline / Calc-alkaline*	In disuse - Diagnostic minerals and textures may not be present
Ishihara (1977, 2004)	Fe-Ti oxides content, associated mineralization, δ^{34}S and δ^{18}O values	Depending on the occurrence or absence of magnetite (magnetite-andIllmenite-series, respectively)	Processes that can control the stability of magnetite in granitic rocks are not fully considered. See comments in Frost et al. (2001)
Lameyre (1980); Lameyre and Bowden (1982)	Mineralogy	Based on the QAP system and the four major series, differentiates among: Leucogranites (Crustal fusion) / Calc-alkaline series / Tholeiitic series / (Per)Alkaline series	In disuse - not accepted nowadays to link QAP compositions with possible magmatic sources
Pupin (1980, 1985)	Zircon morphology, petrographic features, accessory minerals	Types 1–7 grouped in Crustal, Mixed, and Mantle granites on the basis of zircon typological populations and their "Typological Evolutionary Trend" (TET).	In disuse - Diagnostic minerals and zircon morphology may not be present
Keqin et al. (1982)	Associated mineralization	Transformation type (Continental Crust) / Syntexis type (transitional Crust) / Mantle-derived type	In disuse - outdated terminology
Yang (1982)	Petrographic features	Metamorphic type / Crustal type / Mixed source type / Mantle-derived type	In disuse - Diagnostic minerals and textures may not be present
Pitcher (1983, 1987)	Geodynamic setting	Hercynotype / Caledonian type / Andinotype / West Pacific type / Nigeria type	In disuse - outdated terminology
Pearce et al. (1984)	Trace element composition [Discrimination diagrams]	Distinction among tectonic environments on the basis of (among others) Rb-Ta-Nb-Y relationships: Ocean ridge granites / Volcanic arc granites / Within-plate granites / Collisional granites	Not applicable to post-collisional granitoids because they plot over the range of classification fields
Nachit et al. (1985)	Biotite composition [Discrimination diagrams]	Distinction among magmatic series on the basis of Al and Mg contents of biotite: *Alumino-potassiques / Calcoalcalines et subalcalines / Alcalines et hyperalcalines*	In disuse - Processes that can control the composition of biotite in granitic rocks are not fully considered
Rossi and Chevremont (1987)	Mineralogy (mafic minerals)	Depending on the mafic mineral content, distinction among: *Aluminopotassique / Monzonitique / Calcoalcaline / Tholeitique / (Per)Alcaline*	Diagnostic minerals and textures may not be present
Maniar and Piccoli (1989)	Major element composition [Discrimination diagrams]	Distinction among tectonic environments (Island arc granitoids, Continental arc granitoids, Continental collision granitoids, Postorogenic granitoids, Rift-related granitoids, Continental epeirogenic uplift granitoids, and Oceanic plagiogranites	Not applicable to post-collisional granitoids because they plot over the range of classification fields
Barbarin (1990, 1999)	Petrographic features, Mineralogy, Major element composition	Three main groups that are further subdivided and correlated to major tectonic settings: Crustal / Mixed / Mantle	It compresses the wide range of bulk compositions of granitoids into six rock types. See comments in Frost et al. (2001)
Tischendorf and Förster (1992)	Major and trace element composition [Discrimination diagrams]	Distinction among granitoids tectonic environment on the basis of K2OxRb / MgO – Na2OxZrxY diagram (Ocean ridge, Volcanic arc, Within plate, and Collisional)	In disuse – Processes such as magma mixing and wall rock assimilation are not considered

recently developed in-situ triple quadrupole inductively coupled plasma mass spectrometry (LA-QQQ-ICPMS) Rb—Sr dating of mica (Zack and Hogmalm, 2016; Wang et al., 2022a, 2022b).

Isotopic investigations also constitute a wide category within the analytical approaches addressing the origin and significance of granitic rocks. Investigations on whole-rock radiogenic isotope ratios, such as ^{87}Sr/^{86}Sr, ^{143}Nd/^{144}Nd, and the various Pb isotope ratios, currently play a major role on granite petrogenetic investigations, including the origin and composition of magma sources, the mantle-crust interactions, crustal melting processes, and the identification of the geotectonic setting (e.g., McCulloch and Chappell, 1982; Foden et al., 2002; Farina et al., 2014; Zametzer et al., 2022). Moreover, the study of radiogenic isotopes in single mineral grains or mineral separates, such as ^{87}Sr/^{86}Sr on K-feldspar (e.g., Siebel et al., 2005) and ^{176}Hf/^{177}Hf on zircon (e.g., Chagondah et al., 2023), also provide very meaningful insights into the assimilation of wallrock material and magma mixing processes during granite petrogenesis. In this framework, analytical profiles through zircon and feldspar crystals, namely crystal isotope stratigraphy (Davidson et al., 1998), may help to reveal both the magmatic history and post-magmatic subsolidus re-equilibration of a given granite.

Reconstructions of the temperature and pressure conditions of granite formation have also a strong analytical basis that targets many accessory minerals. Among others, the two-feldspar, hornblende-plagioclase, pyroxene-ilmenite, pyroxene-biotite, garnet-hornblende, muscovite-biotite, and garnet-biotite methods are based on mineral compositions and activity models to infer the temperature and/or pressure of crystallization, although they are strongly dependent on other factors (see Anderson, 1996; Anderson et al., 2008). When present in granitoid rocks, garnet also represents a useful tool in petrogenetic studies for unravelling the pressure (e.g., garnet-biotite-plagioclase-quartz mineral assemblage) and temperature (e.g., garnet-biotite mineral assemblage) of crystallization (e.g., Dahlquist et al., 2007). Furthermore, titanite, a common accessory mineral in mainly metaluminous granites, can also be used as an empirical geobarometer when crystallized under near-solidus conditions together with a particular mineral assemblage (Erdmann et al., 2019). Additionally, significant advances in barometric and thermometric estimations of granite formation have been made from diffusion modelling coupled to determinations of titanium concentrations in zircon (Schiller and Finger, 2019) and (more commonly) in quartz, the latter also known as Titanium-in-quartz thermobarometry (Wark and Watson, 2006; Huang and Audétat, 2012). A noteworthy finding from Titanium-in-quartz thermobarometry is the significantly low formation temperature (474–561 °C) obtained by Ackerson et al. (2018) for the Tuolumne Intrusive Suite in the Sierra Nevada Batholith, California. Although low-temperature magma storage had already been inferred from volcanic rocks, for example in the Taupo Volcanic zone (Rubin et al., 2017), results from Ackerson et al. (2018) may represent one of the paradigm-shifts of the 21st century regarding the knowledge of granitic rocks, with major implications on their petrogenesis. However, these findings have also been suggested to be problematic (Clemens et al., 2020). Furthermore, beyond investigations of granite petrogenesis, the post-magmatic evolution on granitoid rocks has also been investigated through studies on hydrothermal minerals. This wide topic includes chemical and stable isotope analyses on quartz veins and related ores hosted in granitic rocks (Sun and Eadington, 1987; Bhattacharya et al., 2014), as well as microthermometry and microanalysis of fluid inclusions (Wagner et al., 2016; Tang et al., 2021).

6.3. Experimental and numerical modelling approaches for investigating granitic rocks

Approaches that address the origin and significance of granitic rocks from an experimental or numerical modelling background may be classified in three different perspectives. Chronologically ordered, they correspond to the origin of melt (i.e., fluid present or absent partial melting and melt segregation), its ascent and emplacement (i.e., continuous or episodic ascent, and mode of emplacement in different tectonic settings), and the post-magmatic tectono-thermal evolution (i.e., brittle and ductile deformation, metamorphism, and metasomatism) (e.g., Petford et al., 2000). After the pioneering experimental work of Tuttle and Bowen (1958) on the *haplogranite* system Qz-Ab-Or-H_2O, experimental melting of upper crustal rocks and crystallization of granite became very popular and was carried out at a wide range of physicochemical conditions. This includes low (1–2 kbar; e.g., Clemens et al., 1986; Rusak et al., 2021) to high (10–15 kbar and even up to 40 kbar; e.g., Green and Lambert, 1965; Huang and Wyllie, 1975) pressures and from granite solidus (500–800 °C; e.g., Johannes, 1984; Shchekina et al., 2020; Bartoli and Carvalho, 2021) to high (1400 °C; e.g., Clemens et al., 1986) temperatures, in runs that span from few hours (e.g., Green and Lambert, 1965) to several weeks or months (e.g., Maaløe and Wyllie, 1975). Such experiments have also shown that equating peraluminous felsic melts to a crustal (S-type) origin is flawed, as medium-pressure (1.2–0.7 GPa) fractionation of metaluminous mafic melts may lead to peraluminous derivative liquids (Alonso-Perez et al., 2009). The origin of granitic rocks by partial melting of the continental crust was also addressed in the models of Clemens and Vielzeuf (1987) that showed that the wide range of melting temperatures at which a given melt can be produced is a function of the composition of the rocks that are being melted. For example, the presence of micas and amphiboles is known to partially drive, through their high temperature breakdown, the amount of melt that is segregated at a given temperature (Clemens et al., 1986; Petford et al., 2000; Gao et al., 2016 and the references thereof). This fact explains, in turn, the wide range of temperature needed to produce a given melt fraction during fluid-absent melting, depending on the rock type (e.g., Petford, 1995; Petford et al., 2000). For further information, the reader is referred to the experimental results on melt origin, composition, and formation conditions of Clemens et al. (1986) on the anorogenic, alkaline A-type Watergums Granite in southeastern Australia, Clemens and Wall (1988) on the influence of pressure-temperature conditions, volatile fugacity and melt chemistry on the mineral assemblages of S-type granites with original melt chemistry, and the reviews of Castro (2014, 2020) on I-type granites from active continental margins (Cordilleran I-type) and intra-continental orogens (Caledonian I-type). Numerically, the computer programs and calculation packages *Perplex* (Connolly, 1990), *Thermocalc* (Andersson et al., 2002), *RCrust* (Mayne et al., 2016), and *Melts* (Ghiorso and Sack, 1995) are also commonly used for calculating granitic melt volumes and/or compositions.

Other relevant studies addressing the origin of granitic magmas are those focused on melt segregation in migmatitic terrains (e.g., Vigneresse et al., 1996; Vigneresse and Burg, 2000; Leitch and Weinberg, 2002; Bons et al., 2004; Cruden and Weinberg, 2018), which are thought to be the main sources of crustal magmas. Segregation is understood as a melt transport mechanism but, unlike magma ascent and emplacement (see below), it operates at the small scale (centimetres to decimetres) and mostly within the magma source region. The structures that indicate melt segregation are diverse in size and morphology, and can be formed by processes operating from ~10 μm to form initial melt pockets up to several decimetres to develop granitic patches, layers, pods, or veinlets in a metamorphic host (Brown et al., 1995; Clemens and Petford, 1999; Rosenberg and Handy, 2005; Brown, 2013). Numerous experiments have attempted to replicate melt segregation in migmatitic terrains under both hydrostatic conditions (e.g., Laporte, 1994) or during pure shear (Butler, 2010 and references therein) and simple shear (Katz et al., 2006 and references therein) deformation. The experiments that were carried out until the mid-1990s are exceptionally well summarized in the review of Rushmer (1996). From that moment on, however, many other works have provided insights into this issue (e.g., Bagdassarov et al., 1996; Pickering and Johnston, 1998; Rosenberg and Handy, 2005; Druguet and Carreras, 2006). For further reviews on this topic, readers with a strong background in experimental petrology are referred to the works of Brown (2001), Clemens and Stevens (2016), and Collins et al. (2020).

The experimental and numerical modelling approaches of granitic magma ascent and/or emplacement dynamics have been central for perhaps the most controversial debate involving granites during the last decades: dykes vs. diapirs as the main magma ascent mechanism. This debate is summarized in the work of Petford and Clemens (2000): "*How are granite magmas transported from their source regions in the deep crust, through 10–40 km of overlying solid rock and emplaced close to the Earth's surface?*" Before the 1990s, the widely accepted mechanism for magma ascent from melt extraction and segregation zones was diapirism (see review by Cruden and Weinberg, 2018). This process was believed to be driven by the density difference between a melt volume and its surrounding country rocks and, for decades, represented a feasible explanation for the shape, size, and deformation of both granite batholiths themselves and surrounding rocks. Pioneering investigations on modelling the magma ascent through diapirism were those of Grout (1945). Using a glass tank containing viscous material as analogue for magma, and soft wet clays, corn syrup, or syrup diluted with water as analogue of the surrounding rocks, Grout (1945) showed the diverse shape of the rising masses and deformation structures in the surrounding material were related to the amount, type, and temperature of analogue materials. Subsequently, numerous experiments were undertaken to investigate the diapiric ascent of granitic magmas (Berner et al., 1972; Ramberg, 1972; Cruden, 1988, 1990; Weinberg, 1992; Weinberg and Podladchikov, 1994), establishing diapirism as a plausible mechanism for the ascent and emplacement of granitic magmas (see the reviews by Weinberg, 1996; Cruden and Weinberg, 2018). Noteworthy, this diapir-driven ascent paradigm fostered the publication of several works where granites were drawn in cross-sections as large, downwards-extending or balloon-shaped masses at different depths of the crust. In some cases, granites are nowadays still illustrated like this (Peng et al., 2015; Gamal El Dien et al., 2019; Xie et al., 2019; Salih and Rahman, 2021; de Lira Santos et al., 2022; He et al., 2023). However, several problems related to this type of graphical representation of granites had already been pointed out by Lane (1931) and further debated until recent times (e.g., Clemens and Mawer, 1992; Hutton, 1992; Petford, 1996; Cruden, 1998; Vigneresse and Clemens, 2000). In fact, numerous works have suggested that magmatic ascent by diapirism cannot overcome the high effective viscosity of the crust (which would need to be at least one order of magnitude lower than that predicted; Miller et al., 1988; Cruden and Weinberg, 2018), nor the crustal brittle-ductile transition (~10–20 km depending on the temperature of the crust). These arguments thus restricted diapirism, if present, to the lower crust (Barnichon et al., 1999; Vigneresse, 2004). However, it is worth noting that diapir-driven ascent dynamics are still invoked nowadays for the exhumation of UHP eclogite rocks to the surface of deep-seated subduction zones (e.g., Little et al., 2011; Chatterjee and Jagoutz, 2015; Massonne and Fockenberg, 2022).

Another plausible mechanism of "bulk" ascent of granitic magmas through the crust is the magmatic stoping (Daly, 1912). This mechanism has been suggested to operate at all crustal levels and to be mainly controlled by thermal fracturing, and involves the incorporation of blocks of country rock into the magma and the development of irregular contacts. Some of these blocks may remain within the molten material as stoped blocks and xenoliths, whereas others may be assimilated by the magma, changing its geochemical composition (e.g., Dumond et al., 2005; Žák et al., 2006; Pignotta and Paterson, 2007; Clarke and Erdmann, 2008). However, theoretical work by Marsh (1982, 1984, 2007) has shown that large-scale magma transport cannot be achieved through magmatic stoping because of the rapid cooling and freezing of granite magma, restricting magmatic stoping to a more local heat and mass transfer mechanism (e.g., Cruden and Weinberg, 2018). It has also been argued that the interplay between multiple space-making mechanisms could provide a solution for the *room* problem, including magmatic stoping, ductile shortening of host rocks, and downward return flow (Paterson and Miller, 1998a, 1998b; Paterson et al., 2008). From the 1990s, experimental and numerical modelling of granitic magma ascent in igneous-volcanic plumbing systems shifted the paradigm to dyke-driven, channelled magma ascent dynamics (see the reviews of Petford, 1996; Petford et al., 2000; Petford and Clemens, 2000; Vigneresse and Clemens, 2000; Menand, 2011). Emplacement of granitic magma that ascends through dykes is nowadays attributed to dyke arresting and sill-like horizontal propagation followed by vertical inflation of the pluton (Cruden, 1998; Cruden and Weinberg, 2018; Galland et al., 2018). Under this paradigm, debate has also been raised on the interplay between the steps of initial melt formation, segregation, accumulation, and its final emplacement. The assumption of complex fracture networks where small, tributary fractures feed larger ones, known as the 'rivulets-feeding-rivers' model, has been perhaps the dominant theory (Brown and Solar, 1998; Weinberg, 1999), although some theoretical arguments and field evidence speak against it (e.g., Bons et al., 2009). For example, the connected melt networks expected for the 'rivulets-feeding-rivers' model (e.g., the classical Port Navalo migmatites, France) have been suggested to more likely represent different generations of melt-filled veins and dykes (Bons et al., 2009). Within this framework, the discontinuous connectivity of melt-filled fractures in a stepwise accumulation model (Maaløe, 1987; Bons and van Milligen, 2001; Bons et al., 2001) has more explanatory power in terms of spatial and temporal scales involving the formation of a granitic pluton. For further reviews that address the origin and propagation of granitic magmas through dykes or dyke-diapir interaction, the reader is referred to the work of Clemens (1998), Bons et al. (2009), Cao et al. (2016), Cruden and Weinberg (2018) and references therein. Moreover, given the bountiful literature on the topic and the multiple possible explanations for the ascent of granitic magmas through the crust, we think it is appropriate to ask here: has the *room* problem been resolved?

Investigations on the physical and chemical processes acting during the post-magmatic evolution of granites are generally focused on metamorphism, deformation, and hydrothermal and metasomatic alteration, as well as on the interplay and/or overprinting of these processes. These phenomena, although unrelated to granite genesis, are important because they control the final aspect and geochemical composition that geologists find while studying or sampling granites (e.g., Elburg et al., 2001). Among others, the metamorphic, metasomatic, hydrothermal, and tectonic post-magmatic evolution of a given granite at subsolidus conditions are included in this scope. Since granites are an important rock type being considered to host nuclear waste storage facilities (e.g., Mccarthy et al., 1978; Metz et al., 2005) and can act as reservoir storage rocks in geothermal and petroleum systems (Landes et al., 1960; Zheng et al., 2021), a significant number of experiments on fracture initiation and propagation have been conducted in granites (see a review in Zhuang and Zang, 2021). Moreover, other experimental studies on the post-magmatic evolution of granites are those focused on hydrothermal alteration and metasomatic reactions. Hydrothermal alteration in granitic rocks can occur as a result of either the interaction with magmatic fluids exsolved during crystallization processes (e.g., Berni et al., 2020), or with hydrothermal fluids of metamorphic or meteoric origin (e.g., Savage et al., 1987). Significant knowledge of the interplay between ore genesis, element mobility, and hydrothermal fluid flow has been gained from experimental studies on granite-hosted ore deposits such as, among others, tungsten (Wang et al., 2021) and gold (Pokrovski et al., 2014) (see a review in Candela, 1992). Furthermore, of significant interest for potential application in geo-energy are the experiments of Truche et al. (2021), where it is demonstrated that the production of molecular hydrogen (H_2) during the alteration of peralkaline granites can be similar to, if not faster than, those formerly suggested during the serpentinization of ultramafic rocks.

Experimental and numerical modelling studies focused on the post-magmatic evolution of granitoid rocks can be roughly classified in two main research subfields that commonly appear intimately related in the literature: structural geology and metamorphic petrology. Within the structural geology subfield, rock mechanics testing of deformational (micro- to macro-) structures are divided according to the temperature and pressure conditions under which they act. Generally, at shallow crustal levels, granites behave as a brittle material where a given stress state can produce fractures, i.e., discrete planar discontinuities along which cohesion and continuity are lost (Lajtai, 1998; Gudmundsson, 2011; Parisio et al., 2019). Testing fracturing processes affecting granitic rocks is generally carried out for geo-energy applications and ore deposits research (Zheng et al., 2021; Chandrasekharam et al., 2022). In this framework, numerical approaches that evaluate the brittle behaviour of granites under different injection flow rates and pressure and temperature ranges in enhanced geothermal systems are common (e.g., Shao et al., 2015; Guo et al., 2018; Cheng et al., 2021). Furthermore, other studies have also attempted to simulate the influence of the orientation, geometry, aperture, and roughness of natural fracture systems on the fluid flow and heat transfer mechanisms in natural granitic geothermal reservoirs (e.g., Liu et al., 2020; Chabani et al., 2021). Within the ore deposits field, artificial (i.e., human-induced) hydrofracturing is often used in mining operations as a rock preconditioning method aimed at the fragmentation of ore bodies (Katsaga et al., 2015; He et al., 2016; Bons et al., 2022), and natural fractures are furthermore key structures because they exert a critical control on hydrothermal fluid flow and the formation of orebodies. Mineral precipitates that fill fractures in granites, forming veins, thus constitute very important ore sources of, among others, key elements for the energy transition such as antimony, tungsten, lithium, or cobalt (Alderton et al., 1980; Li et al., 2018; Chauvet, 2019; Slack et al., 2022). For a comprehensive review of the structural controls on ore deposits related to granitoid rocks from a numerical modelling approach, the reader is referred to Zhang et al. (2011).

At deep crustal levels, where temperature and lithostatic pressure are higher than those related to the brittle behaviour, ductile flow controls deformation processes affecting most rock types, including granitic rocks (e.g., Gomez-Rivas et al., 2020 and references therein). Numerical modelling of ductile structures has provided meaningful insights to unravel whether granite microstructures reflect igneous histories, post-magmatic deformations, or a combination of both (e.g., Paterson et al., 1989; Holness et al., 2018). Within this framework, numerical modelling platforms such as ELLE (Jessell et al., 2001; Bons et al., 2008) and other computational approaches (e.g., Bäckström et al., 2008; Zhang et al., 2019) have contributed to the understanding of tectonic structures and microstructures commonly found in granites (e.g., Griera et al., 2011; Llorens et al., 2013). Moreover, Finch et al. (2020) simulated the development of C′ shear bands, which dip in the direction of shear at an angle of 15–35° to the shear zone boundary, and described how changes in the proportions of the weak phase influence the formation of S—C fabrics, C′ and C″ shear bands. Finch et al. (2022) also modelled and described the wide range of interference patterns that can be developed when co-planar shearing overprints ductile simple shear in the opposite direction, providing insights into strain accommodation during the formation of these hybrid structures in granitic rocks.

In the metamorphic petrology subfield, numerical modelling of post-magmatic processes affecting granitic rocks is mainly related to the theoretical determinations of pressure-temperature-deformation-time (P-T-D-t) paths. Metamorphism is commonly recorded in granites that, after undergoing this process, become named metagranites or orthogneisses (Bucher and Frey, 2002; Schmid et al., 2004; Fettes and Desmons, 2011) and are often present as gneiss-dome systems or metamorphic core complexes (see reviews in Teyssier and Whitney, 2002; Yin, 2004). P-T-D-t estimations on metagranites allow relating the spatial and temporal evolution of pressure and temperature with a given number of deformation phases. Although the temperature and pressure may be estimated from observational (e.g., mineral assemblages and reaction textures; Eskola, 1920; Okrusch and Frimmel, 2020) and analytical approaches (e.g., geothermometry and geobarometry; Anderson et al., 2008), numerical modelling is required for the calculation of pseudosections and thermal modelling. However, these approaches are outside the scope of the present work since they are not different from the P-T-D-t paths of other rock types. For examples of P-T-D-t determinations using pseudosection and thermal modelling in metagranites, the interested reader is referred to the recent works of Massonne (2015), Jung et al. (2019) and Schorn (2022). Mineral transformations, grain coarsening, and grain recrystallization are also common textural re-equilibration processes that may take place during the cooling or metamorphism of granitic rocks. Although these processes may not alter the geochemical composition of rocks, they cause important textural changes that could be confused with primary magmatic features (see reviews by Higgins, 2011; Holness and Vernon, 2015).

6.4. *Research on granites during the Digital Age*

The aforementioned observational, analytical, experimental, and numerical modelling approaches for the study of granitic rocks have greatly benefited during the past few years from Open Access, FAIR (Findable, Accessible, Interoperable, Reusable) initiatives for data management (Wilkinson et al., 2016; Stall et al., 2019). However, until recently, geochemical data of granitic rocks were typically published with non-standardized approaches and, in some cases, lack of sample metadata. This has significantly reduced the data value and longevity in large areas of Australia, Europe, South America, and easternmost Asia (Figs. 6, 7) (e.g., Chamberlain et al., 2021).

These FAIR geochemical initiatives, which offer to the end user a standardized template for data download, can be roughly divided among geographically constrained compilations and worldwide-focused databases (Fig. 6; Table 3). Examples of the regional compilations are the North American Volcanic and Intrusive Rock Database (NAVDAT, http://www.navdat.org/; Walker et al., 2006), the Finnish Lithogeochemical Rock Geochemistry Database (RGDB; Rasilainen et al., 2007), and the Geochemical Database of Japanese Islands for Basement Rocks (DODAI; Haraguchi et al., 2018) (Fig. 7; Table 3). Worldwide-focused geochemical databases offer a user-friendly search engine through which users can filter data by sample location, chemical composition, or tectonic setting. Among others, the Geochemistry of Rocks of the Oceans and Continents database (GEOROC; Georg-August-Universität Göttingen, http://georoc.eu) and the community-driven Petrological Database (PetDB; EarthChem; www.earthchem.org/petdb) are data-rich examples (Figs. 6, 7; Table 3). An excellent compilation of the aforementioned databases was carried out by Gard et al. (2019), which has allowed to graphically represent the worldwide distribution and the geochemical composition of more than 25,000 whole-rock analyses on fresh granitoid samples (Figs. 6, 7; Table 3) in a user-friendly, Geographical Information System (GIS)-based resource; the Global Granite Geochemistry and Outcrop Database (GGGOD; González-Esvertit et al., 2024). This tool allows the visualization, plotting, and spatial analysis of all granitoid compositions available Open Access.

When comparing the GGGOD Database with the global distribution of granitic rocks (modified from the Open Access Global Lithological Map, GLIM, Universität Hamburg; Hartmann and Moosdorf, 2012) (Figs. 6, 7; Table 3), high granite sample concentrations stand out in northern Canada and Alaska (Fig. 7a) and Japan (Fig. 7e). In contrast, Mainland Australia (Fig. 7b), Europe (Fig. 7c), South America (Fig. 7d), and easternmost Asia (Fig. 7e) show limited data. Most (if not all) the granitic rocks cropping out in these areas have, however, already been studied, analyzed, and/or interpreted in the literature. Therefore, the efforts for sample collection and analysis of these granites can be considered as futile in terms of their subsequent reusability in later investigations, such as the present and other potential review works on granitic rocks (e.g., Piwowar et al., 2007).

7. Concluding remarks

The origin and significance of granitic rocks have been two of the most controversial and long-lived topics in the history of Earth Sciences. Here we have reviewed the role that granitic rocks have played on our knowledge of the behaviour of the Earth's system for more than two centuries, including the *Neptunism*, *Plutonism*, *Uniformitarianism*, *Transformism*, and *Magmatism* paradigms. Consecutive *stasis* periods of reductionist science, or "puzzle solving" periods, have successively led to the accumulation of inconsistencies, or anomalies, generally related to the field occurrence, mineralogy, geochemistry, petrology, and geophysical imaging of granitic rocks. These anomalies have produced, in turn, successive scientific revolutions towards new paradigms with more explanatory power than the preceding ones. During some periods of the history of Earth Science, two paradigms have coexisted leading to an increase in the degree of scientific discussion and to radicalization of the main arguments. Major innovations, such as the invention of the petrographic microscope, the birth of geochemistry, and the development of experimental petrology, have fostered the accumulation of anomalies, driving research on granitic rocks towards new challenges and settling new uncertainties. These anomalies have been mostly derived from observational approaches, highlighting the importance of field-based geological investigations. During the current paradigm, tens of petrogenetic and non-petrogenetic classification schemes have been proposed and, for the first time, a worldwide-scale approach for the study of granites is being underpinned by the Open Access and FAIR initiatives for sharing spatial and geochemical data. Yet today, there are still several controversies to be resolved, which will require new analytical methods and more complex theoretical frameworks. The role

Fig. 6. Global distribution of Open Access, FAIR geochemical data from fresh granitoid samples compared to the global distribution of granitoid outcrops. Type localities and influential works published during the 18th and 19th centuries are indicated. Geochemical data is compiled from FAIR, Open Access initiatives (dataset modified after Gard et al., 2019). Granitic rock outcrops redrawn from the Global Lithological Map (GLIM, Universität Hamburg; Hartmann and Moosdorf, 2012). Basemap: *ESRI® Ocean*. See outcrop photographs of selected outcrops in Fig. 1 and detail maps of selected sectors in Fig. 7.

of the *schools*, or the places where granite scientist have been trained, will be important for the generation of new hypotheses as well as the anomalies that will break them down.

Finally, it is worth noting from the references and quotations included in this review that, as in many other areas of inquiry, granite research has historically been dominated by wealthy, mostly male researchers in high income, geopolitically stable countries from Europe and North America. From the 20th century onwards, a diversification trend can be observed in terms of who is involved in the research on granites and where. However, this diversification has not succeeded in eradicating past and present economical, geopolitical, and gender imbalances. The evolution of the knowledge of granites reflects, in fact, the general evolution of geoscientific knowledge. Yet today, terms as *parachute science* or *helicopter research*, where local communities are not involved in the design, execution, and dissemination of research in a given area, are a common practice to be tackled.

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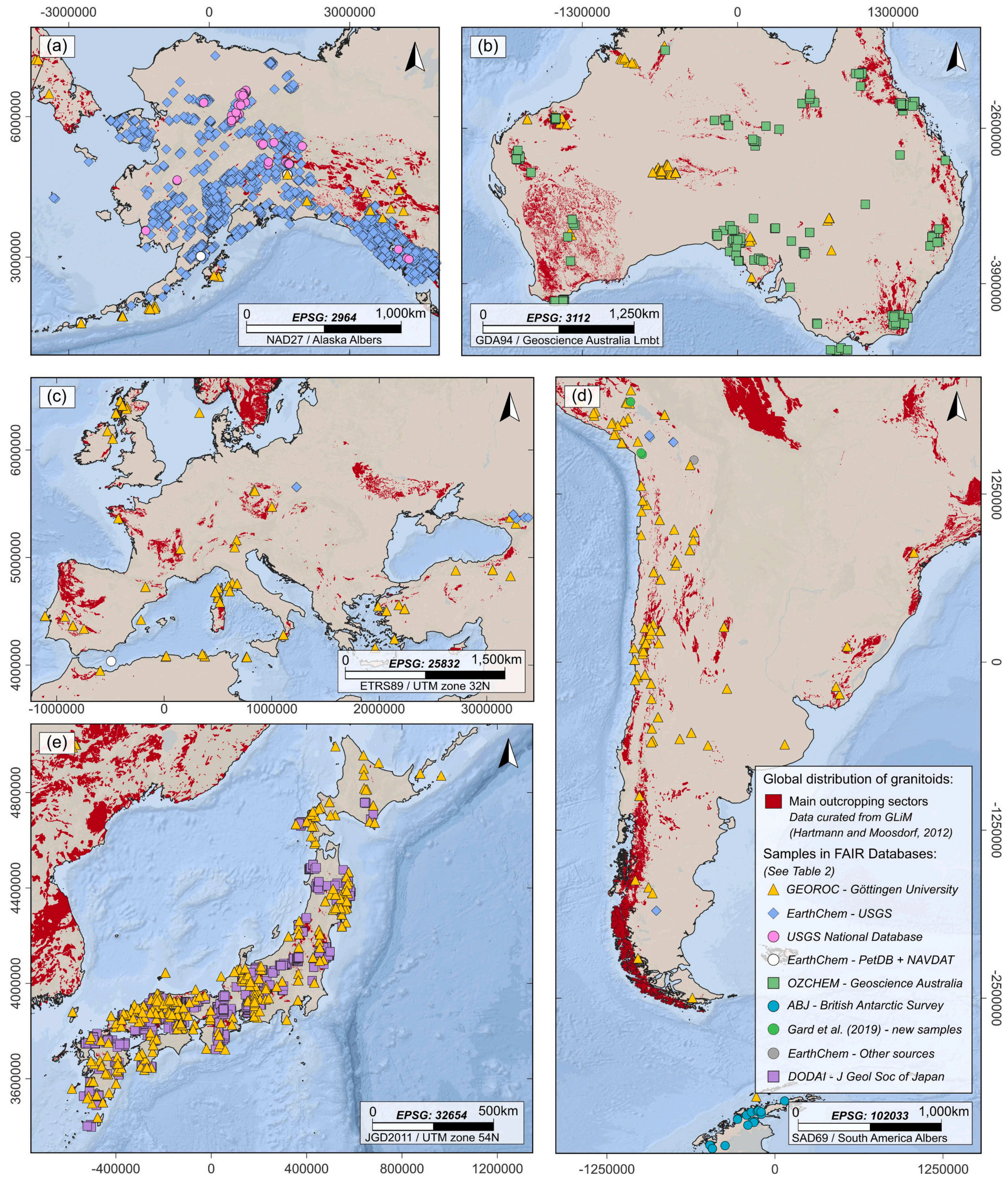

Fig. 7. Distribution of Open Access, FAIR geochemical data from fresh granitic rock samples compared to the global distribution of granitoid outcrops in (a) Alaska and northwestern Canada, (b) Mainland Australia, (c) Europe and north Africa, (d) southern South America and northern Antarctic Peninsula, and (e) east Asia (Korea Peninsula, Japan, eastern China, and eastern Russia). See locations in Fig. 6 (note that the Geographic Reference System has been changed into various Projected Coordinate Reference Systems that best represent land surface, indicated in each region). Geochemical data is compiled from the Open Access, FAIR initiatives listed in Table 3 (dataset modified after Gard et al., 2019). Granitoid outcrop distribution has been redrawn from the Global Lithological Map (GLIM, Universität Hamburg; Hartmann and Moosdorf, 2012). Basemap: *ESRI® Ocean*.

Table 3
Summary of the FAIR, Open Access databases that host geochemical data from fresh granite samples formerly published in scientific literature ($n = 26{,}459$). See Figs. 6 and 7 for the spatial distribution of samples (raw dataset curated after Gard et al., 2019).

Database Acronym	Host institution	Reference	n*
Geographically constrained databases:			
DODAI [Japan]	Journal of the Geological Society of Japan (Open Access)	Geochemical database of Japanese islands for basement rocks; Haraguchi et al. (2018). doi:https://doi.org/10.5575/geosoc.2018.0027	1606
OZCHEM [Australia]	Geoscience Australia, Australian Government	Geoscience Australia's national whole-rock geochemical database. http://pid.geoscience.gov.au/dataset/ga/65464	298
USGS [USA]	United States Geological Survey (USGS)	USGS National Geochemical Database. https://usgs.gov	85
CDoGS [Canada]	Natural Resources Canada, Government of Canada	Canadian Database of Geochemical Surveys. https://geochem.nrcan.gc.ca/	8
ABJ [Antarctica]	British Antarctic Survey	A. Burton-Johnson compilation; published in Gard et al. (2019). doi: https://doi.org/10.5281/zenodo.2592822	160
NLGA [Canada and PM]	Dept. of Energy, Industry and Technology, Government of Newfoundland and Labrador	Newfoundland and Labrador Geoscience Atlas. https://geoatlas.gov.nl.ca/	4219
PETLAB	Geological and Nuclear Sciences Limited (GNS), New Zealand	New Zealand's national rock, mineral and geoanalytical database; Strong et al. (2016). https://pet.gns.cri.nz/	567
Non-geographically constrained databases:			
EarthChem - USGS	Lamont-Doherty Earth Observatory of Columbia University, City College of New York, Kansas University, and South Dakota School of Mines and Technology. Funded by US National Science Foundation.	EarthChem Portal - USGS National Geochemical Database. https://earthchem.org	10,023
EarthChem – PetDB and NAVDAT		EarthChem Portal - Petrological Database of the Ocean Floor (PetDB) and North American Volcanic and Intrusive Rock Database (NAVDAT). https://earthchem.org	5006
EarthChem - others		EarthChem Portal. https://earthchem.org	23
GEOROC	Göttingen University - Formerly hosted at Max Planck Institute for Chemistry in Mainz	Geochemistry of Rocks of the Oceans and Continents; Lehnert et al. (2000). https://georoc.eu/	4087
Gard et al. (2019) – new samples	Zenodo Data Repository (Open Access)	Gard, M., Hasterok, D., and Halpin, J. (2019). Global whole-rock geochemical database compilation (Version 1.0.0). doi:https://doi.org/10.5281/zenodo.2592823	377

See Figs. 6 and 7 for sample location and distribution.
* *n refers to the number of available fresh granitoid samples with associated whole-rock geochemical data.*

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Declaration of competing interest

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Data availability

Data is available in the Global Granite Geochemistry and Outcrop Database (GGGOD) - https://doi.org/10.20350/digitalCSIC/16505

References

Ackerson, M.R., Mysen, B.O., Tailby, N.D., Watson, E.B., 2018. Low-temperature crystallization of granites and the implications for crustal magmatism. Nature 559, 94–97. https://doi.org/10.1038/s41586-018-0264-2.

Adams, F.D., 1901. The excursion to the pyrenees in connection with the eighth international geological congress. J. Geol. 9, 28–46. https://doi.org/10.1086/620878.

Ague, J.J., Brimhall, G.H., 1988. Regional variations in bulk chemistry, mineralogy, and the compositions of mafic and accessory minerals in the batholiths of California. GSA Bull. 100, 891–911. https://doi.org/10.1130/0016-7606(1988)100<0891:RVIBCM>2.3.CO;2.

Aguilar, C., Liesa, M., Castiñeiras, P., Navidad, M., 2014. Late Variscan metamorphic and magmatic evolution in the eastern Pyrenees revealed by U–Pb age zircon dating. J. Geol. Soc. Lond. 171, 181–192. https://doi.org/10.1144/jgs2012-086.

Alderton, D.H.M., Pearce, J.A., Potts, P.J., 1980. Rare earth element mobility during granite alteration: evidence from Southwest England. Earth Planet. Sci. Lett. 49, 149–165. https://doi.org/10.1016/0012-821X(80)90157-0.

Almond, D.C., Osman, A.A., Ahmed, F., 1997. The Arba'at Granite, Sudan: a mineralised, Pan-African intrusion enhanced by hydrothermal metasomatism. J. Afr. Earth Sci. 24, 335–350. https://doi.org/10.1016/S0899-5362(97)00048-1.

Alonso-Perez, E., Müntener, O., Ulmer, P., 2009. Igneous garnet and amphibole fractionation in the roots of island arcs: experimental constraints on andesitic liquids. Contrib. Mineral. Petrol. 157 (4), 541–558.

Améglio, L., Vigneresse, J.L., 1999. Geophysical imaging of the shape of granitic intrusions at depth: a review. Geol. Soc. Lond. Spec. Publ. 168, 39–54. https://doi.org/10.1144/GSL.SP.1999.168.01.04.

Améglio, L., Vigneresse, J.L., Bouchez, J.L., 1997. Granite Pluton geometry and emplacement mode inferred from combined fabric and gravity data. In: Bouchez, J. L., Hutton, D.H.W., Stephens, W.E. (Eds.), Granite: From Segregation of Melt to Emplacement Fabrics. Springer, Netherlands, Dordrecht, pp. 199–214. https://doi.org/10.1007/978-94-017-1717-5_13.

Anderson, W., 1778. An account of a large Stone near Cape Town. In a letter from Mr. Anderson to Sir John Pringle, Bart. PRS; with a Letter from Sir William Hamilton, KB, FRS to Sir John Pringle, on having seen pieces of the said Stone. Philos.Trans. R. Soc. Lond. 68, 102–106.

Anderson, J.G.C., 1937. The Etive granite complex. Q. J. Geol. Soc. 93, 487–533. https://doi.org/10.1144/GSL.JGS.1937.093.01-04.17.

Anderson, D.L., 1982. Hotspots, polar wander, Mesozoic convection and the geoid. Nature 297, 391–393. https://doi.org/10.1038/297391a0.

Anderson, J.L., 1996. Status of thermobarometry in granitic batholiths. Earth Environ. Sci. Trans. R. Soc. Edinb. 87, 125–138. https://doi.org/10.1017/S0263593300006544.

Anderson, J.L., Barth, A.P., Wooden, J.L., Mazdab, F., 2008. Thermometers and thermobarometers in granitic systems. Rev. Mineral. Geochem. 69, 121–142. https://doi.org/10.2138/rmg.2008.69.4.

Andersson, J.-O., Helander, T., Höglund, L., Shi, P., Sundman, B., 2002. Thermo-Calc & DICTRA, computational tools for materials science. Calphad 26, 273–312. https://doi.org/10.1016/S0364-5916(02)00037-8.

Andrews-Hanna, J.C., Asmar, S.W., Head, J.W., Kiefer, W.S., Konopliv, A.S., Lemoine, F. G., Matsuyama, I., Mazarico, E., McGovern, P.J., Melosh, H.J., Neumann, G.A., Nimmo, F., Phillips, R.J., Smith, D.E., Solomon, S.C., Taylor, G.J., Wieczorek, M.A., Williams, J.G., Zuber, M.T., 2013. Ancient igneous intrusions and early expansion of the moon revealed by GRAIL gravity gradiometry. Science 339, 675–678. https://doi.org/10.1126/science.1231753.

Andrews-Hanna, J.C., Besserer, J., Head III, J.W., Howett, C.J.A., Kiefer, W.S., Lucey, P. J., McGovern, P.J., Melosh, H.J., Neumann, G.A., Phillips, R.J., Schenk, P.M., Smith, D.E., Solomon, S.C., Zuber, M.T., 2014. Structure and evolution of the lunar Procellarum region as revealed by GRAIL gravity data. Nature 514, 68–71. https://doi.org/10.1038/nature13697.

Ansted, D.T., 1849. The Gold-seeker's Manual. D. Appleton & Company.

Aranovich, L.Ya., 2017. The role of brines in high-temperature metamorphism and granitization. Petrology 25, 486–497. https://doi.org/10.1134/S0869591117050022.

Armstrong, P., 1985. Charles Darwin in Western Australia: A Young Scientist's Perception of an Environment. University of Western Australia Press.

Autran, A., Fonteilles, M., Guitard, G., 1970. Relations entre les intrusions de granitoides, l'anatexie, et le métamorphisme regional considertes principalment du point de vue de l'eau: cas de la Chaine Hercynienne des Pyrénées Orientales., ercynienne des Pyrénées Orientales. Bull. Soc. Géol. Fr. 7 (4), 673–731.

Ávila, C.F., Archanjo, C.J., Platt, J.P., Fossen, H., 2022. Rheology, shear zone width, microstructural evolution and tectonics of a zippered strike-slip shear zone: the Senador Pompeu shear zone, northern Borborema Province, Brazil. J. Struct. Geol. 104776. https://doi.org/10.1016/j.jsg.2022.104776.

Ayala, C., Rey-Moral, C., Rubio, F., Soto, R., Clariana, P., Martín-León, J., Bellmunt, F., Gabàs, A., Macau, A., Casas, A.M., Martí, J., Pueyo, E.L., Benjumea, B., 2021. Gravity data on the Central Pyrenees: a step forward to help a better understanding of the Pyrenean structures. J. Maps 17, 750–759. https://doi.org/10.1080/17445647.2021.2001386.

Ayarza, P., Martínez Catalán, J.R., Martínez García, A., Alcalde, J., Andrés, J., Simancas, J.F., Palomeras, I., Martí, D., DeFelipe, I., Juhlin, C., Carbonell, R., 2021. Evolution of the Iberian Massif as deduced from its crustal thickness and geometry of a mid-crustal (Conrad) discontinuity. Solid Earth 12, 1515–1547. https://doi.org/10.5194/se-12-1515-2021.

Backlund, H.G., 1938. The problems of the Rapakivi granites. J. Geol. 46, 339–396.

Bäckström, A., Antikainen, J., Backers, T., Feng, X., Jing, L., Kobayashi, A., Koyama, T., Pan, P., Rinne, M., Shen, B., Hudson, J.A., 2008. Numerical modelling of uniaxial compressive failure of granite with and without saline porewater. Int. J. Rock Mech. Min. Sci. 45, 1126–1142. https://doi.org/10.1016/j.ijrmms.2007.12.001.

Bagdassarov, N.S., Dorfman, A.M., Dingwell, D.B., 1996. Modelling of melt segregation processes by high-temperature centrifuging of partially molten granites—I. Melt extraction by compaction and deformation. Geophys. J. Int. 127, 616–626. https://doi.org/10.1111/j.1365-246X.1996.tb04042.x.

Bailey, E.B., Hartley, H.B., 1960. Charles Lyell, F. R. S. (1797-1875). Notes Rec. R. Soc. Lond. 14, 121–138. https://doi.org/10.1098/rsnr.1959.0007.

Bailey, D.K., Macdonald, R., 1976. The Evolution of the Crystalline Rocks. Academic Press, New York xii.

Bailey, E.B., Tait, D., 1921. Edinburgh's Place in Scientific Progress. British Association for the Advancement of Science, Chambers, Edimburgh.

Bak, P., 1996. How Nature Works. Springer, New York, NY. https://doi.org/10.1007/978-1-4757-5426-1.

Baker, V.R., 1998. Catastrophism and uniformitarianism: logical roots and current relevance in geology. Geol. Soc. Lond. Spec. Publ. 143, 171–182. https://doi.org/10.1144/GSL.SP.1998.143.01.15.

Bakewell, R., 1823. Travels: Comprising Observations Made during a Residence in the Tarentaise and Various Parts of the Grecian and Pennine Alps, and in Switzerland and Auvergne, in the Years 1820, 1821, and 1822. Longmans, Hurst, Rees, Orme and Brown.

Baldridge, W.S., 1984. The Geological Writings of Goethe: despite his keen powers of observation, Goethe's ideas on geology reflected the biases of his time. Am. Sci. 72, 163–167.

Barbarin, B., 1990. Granitoids: Main petrogenetic classifications in relation to origin and tectonic setting. Geol. J. 25, 227–238. https://doi.org/10.1002/gj.3350250306.

Barbarin, B., 1999. A review of the relationships between granitoid types, their origins and their geodynamic environments. Lithos 46, 605–626. https://doi.org/10.1016/S0024-4937(98)00085-1.

Barnichon, J.D., Havenith, H., Hoffer, B., Charlier, R., Jongmans, D., Duchesne, J.C., 1999. The deformation of the Egersund–Ogna anorthosite massif, south Norway: finite-element modelling of diapirism. Tectonophysics 303, 109–130. https://doi.org/10.1016/S0040-1951(98)00247-9.

Barrow, J., 1801. An Account of Travels into the Interior of Southern Africa in the Years 1797 and 1798. T. Cadell Jun. and W. Davies, London.

Bartoli, O., Carvalho, B.B., 2021. Anatectic granites in their source region: A comparison between experiments, thermodynamic modelling and nanogranitoids. In: Lithos, 9th Hutton Symposium on the Origin of Granites and Related Rocks, 402–403, p. 106046. https://doi.org/10.1016/j.lithos.2021.106046.

Barton, M.D., Young, S., 2002. Non-pegmatitic deposits of beryllium: mineralogy, geology, phase equilibria and origin. Rev. Mineral. Geochem. 50, 591–691. https://doi.org/10.2138/rmg.2002.50.14.

Batchelor, R.A., Bowden, P., 1985. Petrogenetic interpretation of granitoid rock series using multicationic parameters. Chem. Geol. 48, 43–55. https://doi.org/10.1016/0009-2541(85)90034-8.

Baudin, N., 1974. The Journal of Post Captain Nicolas Baudin, Commander-in-Chief of the Corvettes Géographe and Naturaliste. Assigned by Order of the Government to a Voyage of Discovery. Libraries Board of South Australia.

Bea, F., Morales, I., Molina, J.F., Montero, P., Cambeses, A., 2021. Zircon stability grids in crustal partial melts: implications for zircon inheritance. Contrib. Mineral. Petrol. 176, 18. https://doi.org/10.1007/s00410-021-01772-x.

Bell, E.A., Kirkpatrick, H.M., 2022. Micro-zircon inclusions in accessory minerals reveal more complete magma compositional evolution records. Contrib. Mineral. Petrol. 177, 113. https://doi.org/10.1007/s00410-022-01979-6.

Belousova, E., Griffin, W., O'Reilly, S.Y., Fisher, N., 2002. Igneous zircon: trace element composition as an indicator of source rock type. Contrib. Mineral. Petrol. 143, 602–622. https://doi.org/10.1007/s00410-002-0364-7.

Berner, H., Ramberg, H., Stephansson, O., 1972. Diapirism theory and experiment. Tectonophysics 15, 197–218. https://doi.org/10.1016/0040-1951(72)90085-6.

Berni, G.V., Wagner, T., Fusswinkel, T., 2020. From a F-rich granite to a NYF pegmatite: magmatic-hydrothermal fluid evolution of the Kymi topaz granite stock, SE Finland. Lithos 364–365, 105538. https://doi.org/10.1016/j.lithos.2020.105538.

Bhattacharya, S., Panigrahi, M.K., Sachan, H.K., Kharya, A., 2014. Oxygen isotope ratio of quartz veins from the auriferous Ramagiri–Penakacherla schist belt and surrounding granitoids in the Eastern Dharwar craton: a case for a possible link between gold mineralization and granite magmatism. Ore Geol. Rev. 63, 201–208. https://doi.org/10.1016/j.oregeorev.2014.04.023.

Bodnar, R.J., 2018. The evolution of melt inclusion research: From Sorby to today. 2018, V52A-08.

Bonin, B., Bébien, J., Masson, P., 2002. Granite: a planetary point of view. Gondwana Res. 5, 261–273. https://doi.org/10.1016/S1342-937X(05)70722-X.

Bonin, B., Janoušek, V., Moyen, J.-F., 2020. Chemical variation, modal composition and classification of granitoids. Geol. Soc. Lond. Spec. Publ. 491, 9–51. https://doi.org/10.1144/SP491-2019-138.

Bonney, T.G., 1888. On some results of pressure and of the intrusion of granite in stratified palæozoic rocks near Morlaix, in Brittany. Q. J. Geol. Soc. 44, 11–19. https://doi.org/10.1144/GSL.JGS.1888.044.01-04.04.

Bonney, T.G., 1899. The lost volume of Hutton's theory of the Earth. Nature 60, 220. https://doi.org/10.1038/060220a0.

Bons, P.D., van Milligen, B.P., 2001. New experiment to model self-organized critical transport and accumulation of melt and hydrocarbons from their source rocks. Geology 29, 919. https://doi.org/10.1130/0091-7613(2001)029<0919:NETMSO>2.0.CO;2.

Bons, P.D., Dougherty-Page, J., Elburg, M.A., 2001. Stepwise accumulation and ascent of magmas: accumulation and ascent of magmas. J. Metamorph. Geol. 19, 627–633. https://doi.org/10.1046/j.0263-4929.2001.00334.x.

Bons, P.D., Arnold, J., Elburg, M.A., Kalda, J., Soesoo, A., van Milligen, B.P., 2004. Melt extraction and accumulation from partially molten rocks. In: Lithos, Selected Papers Presented at the Symposium: "Interaction between Mafic and Felsic Magmas in Orogenic Suites: Dynamics of Processes, Nature of End-Members, Effects", 78, pp. 25–42. https://doi.org/10.1016/j.lithos.2004.04.041.

Bons, P.D.D., Koehn, D., Jessell, M.W. (Eds.), 2008. Microdynamics Simulation, Lecture Notes in Earth Sciences. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-44793-1.

Bons, P.D., Becker, J.K., Elburg, M.A., Urtson, K., 2009. Granite formation: stepwise accumulation of melt or connected networks? Earth Environ. Sci. Trans. R. Soc. Edinb. 100, 105–115. https://doi.org/10.1017/S175569100901603X.

Bons, P.D., Bauer, C.C., Bocherens, H., de Riese, T., Drucker, D.G., Francken, M., Menéndez, L., Uhl, A., van Milligen, B.P., Wißing, C., 2019. Out of Africa by spontaneous migration waves. PLoS One 14 (4), e0201998.

Bons, P.D., Cao, D., de Riese, T., González-Esvertit, E., Koehn, D., Naaman, I., Sachau, T., Tian, H., Gomez-Rivas, E., 2022. A review of natural hydrofractures in rocks. Geol. Mag. 159, 1–26. https://doi.org/10.1017/S0016756822001042.

Bouchez, J.L., 1997. Granite is never Isotropic: An Introduction to AMS Studies of Granitic Rocks. In: Bouchez, J.L., Hutton, D.H.W., Stephens, W.E. (Eds.), Granite: From Segregation of Melt to Emplacement Fabrics, Petrology and Structural Geology. Springer, Netherlands, Dordrecht, pp. 95–112. https://doi.org/10.1007/978-94-017-1717-5_6.

Boué, A., 1824. Mémoire géologique Sur le Sud-Ouest de la France.

Boué, A., 1844. Mémoire à l'appui d'un essai de Carte géologique du globe terrestre, présenté, le 22 septembre 1843, à la réunion des naturalistes d'Allemagne à Gratz. Bull. Soc. Géol. France 1 (supplement), 296–371.

Bouillin, J.-P., Bouchez, J.-L., Lespinasse, P., Pêcher, A., 1993. Granite emplacement in an extensional setting: an AMS study of the magmatic structures of Monte Capanne (Elba, Italy). Earth Planet. Sci. Lett. 118, 263–279. https://doi.org/10.1016/0012-821X(93)90172-6.
Boussingault, J.B., 1849. Viajes científicos a los Andes Ecuatoriales: ó Coleccion de Memorias Sobre física, química é Historia Natural de la Nueva Granada, Ecuador y Venezuela. Lasserre.
Bowen, N.L., 1912. The binary system; na 2 Al 2 Si 2 O 8 (nephelite, carnegieite); CaAl 2 Si 2 O 8 (anorthite). Am. J. Sci. s4-33, 551–573. https://doi.org/10.2475/ajs.s4-33.198.551.
Bowen, N.L., 1913. The melting phenomena of the plagioclase feldspars. Am. J. Sci. s4-35, 577–599. https://doi.org/10.2475/ajs.s4-35.210.577.
Bowen, N.L., 1916. Das ternäre system: Diopsid-Anorthit-Albit. Z. Anorg. Allg. Chem. 94, 23–50. https://doi.org/10.1002/zaac.19160940103.
Bowen, N.L., 1948. The Granite Problem and the Method of Multiple Prejudices. Geological Society of America Memoir.
Bowes, D.R., 1953. The transformation of tillite by migmatization at Mount Fitton, South Australia. Q. J. Geol. Soc. 109, 455–481. https://doi.org/10.1144/GSL.JGS.1953.109.01-04.18.
Breislak, S., 1811. Introduzione alla geologia. Stamperia Reale.
Brögger, W.C., 1894. The basic eruptive rocks of gran. (a preliminary notice.). Q. J. Geol. Soc. 50, 15–38. https://doi.org/10.1144/GSL.JGS.1894.050.01-04.05.
Brown, M., 1994. The generation, segregation, ascent and emplacement of granite magma: the migmatite-to-crustally-derived granite connection in thickened orogens. Earth Sci. Rev. 36, 83–130. https://doi.org/10.1016/0012-8252(94)90009-4.
Brown, M., 2001. Orogeny, migmatites and leucogranites: a review. J. Earth Syst. Sci. 110, 313–336. https://doi.org/10.1007/BF02702898.
Brown, M., 2013. Granite: from genesis to emplacement. GSA Bull. 125, 1079–1113. https://doi.org/10.1130/B30877.1.
Brown, M., Solar, G.S., 1998. Shear-zone systems and melts: feedback relations and self-organization in orogenic belts. J. Struct. Geol. 20, 211–227. https://doi.org/10.1016/S0191-8141(97)00068-0.
Brown, M., Averkin, Y.A., McLellan, E.L., Sawyer, E.W., 1995. Melt segregation in migmatites. J. Geophys. Res. Solid Earth 100, 15655–15679. https://doi.org/10.1029/95JB00517.
Bucher, K., Frey, M., 2002. Metamorphic rocks. In: Bucher, K., Frey, M. (Eds.), Petrogenesis of Metamorphic Rocks. Springer, Berlin, Heidelberg, pp. 17–48. https://doi.org/10.1007/978-3-662-04914-3_2.
Bui, D.C., Qiu, H.-N., Ngo, X.D., Bai, X.-J., Wu, Y., 2022. Dating of granite-related tin mineralisation at Quy Hop, Vietnam: constraints from zircon and cassiterite U–Pb and muscovite 40Ar/39Ar geochronology. Ore Geol. Rev. 143, 104785. https://doi.org/10.1016/j.oregeorev.2022.104785.
Burchfield, J.D., 1974. Darwin and the dilemma of geological time. Isis 65, 301–321. https://doi.org/10.1086/351300.
Butler, S.L., 2010. Porosity localizing instability in a compacting porous layer in a pure shear flow and the evolution of porosity band wavelength. Phys. Earth Planet. Inter. 182, 30–41. https://doi.org/10.1016/j.pepi.2010.06.004.
Butler, R.W.H., Torvela, T., Williams, L., 2024. An introduction to geological mapping of our world and others. Geol. Soc. Lond. Spec. Publ. 541. https://doi.org/10.1144/SP541-2023-201. SP541-2023–201.
Callaway, C., 1894. Is granite ever metamorphic? Science 23 (581), 157. https://doi.org/10.1126/science.ns-23.581.157.
Candela, P.A., 1992. Controls on ore metal ratios in granite-related ore systems: an experimental and computational approach. Earth Environ. Sci. Trans. R. Soc. Edinb. 83, 317–326. https://doi.org/10.1017/S0263593300007999.
Cao, W., Kaus, B.J.P., Paterson, S., 2016. Intrusion of granitic magma into the continental crust facilitated by magma pulsing and dike-diapir interactions: numerical simulations. Tectonics 35, 1575–1594. https://doi.org/10.1002/2015TC004076.
Capdevila, R., Floor, P., 1970. Les différents types de granites hercyniens et leur distribution dans le nord ouest de l'Espagne. Bol. Geol. Min. T 225. LXXXI.-II-III Ano 215.
Capdevila, R., Corretge, G., Floor, P., 1973. Les granitoides varisques de la Meseta iberique. Bull. Soc. Géol. France S7-XV, 209–228. https://doi.org/10.2113/gssgfbull.S7-XV.3-4.209.
Carreras, J., Druguet, E., Griera, A., Soldevila, J., 2004. Strain and deformation history in a syntectonic pluton. The case of the Roses granodiorite (Cap de Creus, Eastern Pyrenees). Geol. Soc. Lond. Spec. Publ. 224, 307–319. https://doi.org/10.1144/GSL.SP.2004.224.01.19.
Casini, L., Cuccuru, S., Maino, M., Oggiano, G., Puccini, A., Rossi, P., 2015. Structural map of Variscan northern Sardinia (Italy). J. Maps 11, 75–84. https://doi.org/10.1080/17445647.2014.936914.
Castro, A., 2014. The off-crust origin of granite batholiths. Geosci. Front. Thematic Sect. 5, 63–75. https://doi.org/10.1016/j.gsf.2013.06.006.
Castro, A., 2020. The dual origin of I-type granites: the contribution from experiments. Geol. Soc. Lond. Spec. Publ. 491, 101–145. https://doi.org/10.1144/SP491-2018-110.
Castro, A., Moreno-Ventas, I., de la Rosa, J.D., 1991. H-type (hybrid) granitoids: a proposed revision of the granite-type classification and nomenclature. Earth Sci. Rev. 31, 237–253. https://doi.org/10.1016/0012-8252(91)90020-G.
Chabani, A., Trullenque, G., Parashar, R., Pomart, A., Attali, R., Sass, I., 2021. Modelling of Fractured Granitic Geothermal Reservoirs: Use of Deterministic and stochastic methods in Discrete Fracture Networks and a Coupled Processes Modeling Framework. Presented at the Proceedings World Geothermal Congress 2021, Zenodo, Reykjavik, Iceland, May 21 – May 26, 2021. https://doi.org/10.5281/zenodo.5614479.
Chagondah, G.S., Hofmann, A., Elburg, M.A., Iaccheri, L.M., Kramers, J.D., Wilson, A.H., 2023. Petrogenesis of potassic granite suites along the southern margin of the Zimbabwe Craton. S. Afr. J. Geol. 126, 1–28. https://doi.org/10.25131/sajg.126.0004.
Chamberlain, K.J., Lehnert, K.A., McIntosh, I.M., Morgan, D.J., Wörner, G., 2021. Time to change the data culture in geochemistry. Nat. Rev. Earth Environ. 2, 737–739. https://doi.org/10.1038/s43017-021-00237-w.
Chamberlin, T.C., Salisbury, R.D., 1904. Geology, 3 vols. H. Holt, New York, p. 6.
Chandrasekharam, D., Baba, A., Ayzit, T., Singh, H.K., 2022. Geothermal potential of granites: case study- Kaymaz and Sivrihisar (Eskisehir region) Western Anatolia. Renew. Energy 196, 870–882. https://doi.org/10.1016/j.renene.2022.07.035.
Chappell, B.W., White, A.J.R., 1974. Two contrasting granite types. Pac. Geol. 8, 173–174.
Chappell, B.W., White, A.J.R., 2001. Two contrasting granite types: 25 years later. Aust. J. Earth Sci. 48, 489–499. https://doi.org/10.1046/j.1440-0952.2001.00882.x.
Chatterjee, N., Jagoutz, O., 2015. Exhumation of the UHP Tso Morari eclogite as a diapir rising through the mantle wedge. Contrib. Mineral. Petrol. 169, 3. https://doi.org/10.1007/s00410-014-1099-y.
Chauvet, A., 2019. Structural control of ore deposits: the role of pre-existing structures on the formation of mineralised vein systems. Minerals 9, 56. https://doi.org/10.3390/min9010056.
Chen, G.-N., Grapes, R., 2007. Granite Genesis: In Situ Melting and Crustal Evolution. Springer Netherlands, Dordrecht. https://doi.org/10.1007/978-1-4020-5891-2.
Chen, X., Liang, H., Richards, J.P., Huang, W., Zhang, J., Wu, J., Sotiriou, P., 2018. Age and granite association of skarn W mineralization at Niutangjie district, South China Block. Ore Geol. Rev. 102, 268–283. https://doi.org/10.1016/j.oregeorev.2018.09.003.
Cheng, Y., Zhang, Y., Yu, Z., Hu, Z., Ma, Y., Yang, Y., 2021. Experimental and numerical studies on hydraulic fracturing characteristics with different injection flow rates in granite geothermal reservoir. Energy Sci. Eng. 9, 142–168. https://doi.org/10.1002/ese3.816.
Cherniak, D.J., Watson, E.B., 2003. Diffusion in zircon. Rev. Mineral. Geochem. 53, 113–143. https://doi.org/10.2113/0530113.
Clarke, F.W., 1868. Contributions to Chemistry from the Laboratory of the Lawrence Scientific School; No. 5, On a new process in mineral analysis. Am. J. Sci. s2-45, 173–180. https://doi.org/10.2475/ajs.s2-45.134.173.
Clarke, F.W., 1887. ART. XVI.–Studies in the mica group. Am. J. Sci. (1880-1910) 34, 131.
Clarke, D.B., 1992. Granitoid Rocks. Springer, Dordrecht.
Clarke, D.B., 1996. Two centuries after Hutton's Theory of the Earth': the status of granite science. Trans. R. Soc. Edinb. Earth Sci. 87 (353–359), 8.
Clarke, F.W., Chatard, T.M., 1884. A Report of Work Done in the Washington Laboratory during the Fiscal Year 1883–84. U.S. Government Printing Office.
Clarke, D.B., Erdmann, S., 2008. Is stoping a volumetrically significant pluton emplacement process?: comment. GSA Bull. 120, 1072–1074. https://doi.org/10.1130/B26147.1.
Clemens, J.D., Mawer, C.K., 1992. Granitic magma transport by fracture propagation. Tectonophysics 204, 339–360. https://doi.org/10.1016/0040-1951(92)90316-X.
Clemens, J.D., Petford, N., 1999. Granitic melt viscosity and silicic magma dynamics in contrasting tectonic settings. J. Geol. Soc. Lond. 156, 1057–1060. https://doi.org/10.1144/gsjgs.156.6.1057.
Clemens, J.D., Stevens, G., 2016. Melt segregation and magma interactions during crustal melting: breaking out of the matrix. Earth Sci. Rev. 160, 333–349. https://doi.org/10.1016/j.earscirev.2016.07.012.
Clemens, J.D., Vielzeuf, D., 1987. Constraints on melting and magma production in the crust. Earth Planet. Sci. Lett. 86, 287–306. https://doi.org/10.1016/0012-821X(87)90227-5.
Clemens, J.D., Wall, V.J., 1988. Controls on the mineralogy of S-type volcanic and plutonic rocks. Lithos 21, 53–66. https://doi.org/10.1016/0024-4937(88)90005-9.
Clemens, J.D., 1998. Observations on the origins and ascent mechanisms of granitic magmas. J. Geol. Soc. 155 (5), 843–851.
Clemens, J.D., Holloway, J.R., White, A.J.R., 1986. Origin of an A-type granite; experimental constraints. Am. Mineral. 71, 317–324.
Clemens, J.D., Stevens, G., Bryan, S.E., 2020. Conditions during the formation of granitic magmas by crustal melting – Hot or cold; drenched, damp or dry? Earth Sci. Rev. 200, 102982. https://doi.org/10.1016/j.earscirev.2019.102982.
Cloos, H., 1923. Das Batholiten Problem, 1. Fortschritte der Geologie und Palaeontologie, Berlin, pp. 1–80.
Cobbing, J., 2000. The Geology and Mapping of Granite Batholiths. In: Lecture Notes in Earth Sciences. Springer, Berlin, Heidelberg. https://doi.org/10.1007/3-540-45055-6.
Cole, G.A.J., Gregory, J.W., 1893. Tables for the Determination of the Rock-Forming Minerals. Compiled by F. Loewinson-Lessing. Translated from the Russian by J.W. Gregory...with a Chapter on the Petrological Microscope, by...Grenville A.J. Cole. Macmillan and co, London and New Yok.
Collins, W.J., Murphy, J.B., Johnson, T.E., Huang, H.-Q., 2020. Critical role of water in the formation of continental crust. Nat. Geosci. 13, 331–338. https://doi.org/10.1038/s41561-020-0573-6.
Connolly, J.A.D., 1990. Multivariable phase diagrams; an algorithm based on generalized thermodynamics. Am. J. Sci. 290, 666–718. https://doi.org/10.2475/ajs.290.6.666.
Cooke, J.P., 1866. On danalite, a new mineral species from the granite of Rockport, Massachusetts. Am. J. Sci. s2-42 (124), 73–79. https://doi.org/10.2475/ajs.s2-42.124.73.
Cormack, W.E., Bruton, F.A., 1928. Narrative of a Journey across the Island of Newfoundland in 1822. Longmans, Green.

Correns, C.W., 2003. Fluid inclusions with gas bubbles as geothermometers. In: Dullo, W.-C. (Ed.), Milestones in Geosciences: Selected Benchmark Papers Published in the Journal Geologische Rundschau. Springer, Berlin, Heidelberg, pp. 123–133. https://doi.org/10.1007/978-3-662-08763-3_10.

Cortesi, G., 1819. Saggi Geologici Degli Stati di Parma e Piacenza. Majno.

Cossa, A., 1881. Ricerche Chimiche e Microscopiche Su Roccie e Minerali d'Italia (1875–1880). Vincenzo Bona.

Craig, G.Y., 1978. Episodes and engravings: James Hutton and John Clerk. Episodes J. Int. Geosci. 1, 3–5. https://doi.org/10.18814/epiiugs/1978/v1i1/001.

Crawford, J., 1824. XXIII.—Geological Observations made on a Voyage from Bengal to Siam and Cochin China. Extracted from a Letter to H. T. Colebrooke, Esq. M.G.S. Trans. Geol. Soc. Lond. 1, 406–408. https://doi.org/10.1144/transgslb.1.2.406.

Cross, W., 1898. The geological versus the petrographical classification of igneous rocks. J. Geol. 6, 79–91. https://doi.org/10.1086/608016.

Cross, W., 1902. The development of systematic petrography in the nineteenth century. J. Geol. 10, 451–499. https://doi.org/10.1086/621020.

Cross, W., Iddings, J.P., Pirsson, L.V., Washington, H.S., 1902. A quantitative chemico-mineralogical classification and nomenclature of igneous rocks. J. Geol. 10, 555–690. https://doi.org/10.1086/621030.

Cross, A.J., Prior, D.J., Stipp, M., Kidder, S., 2017. The recrystallized grain size piezometer for quartz: an EBSD-based calibration. Geophys. Res. Lett. 44, 6667–6674. https://doi.org/10.1002/2017GL073836.

Cruden, A.R., 1988. Deformation around a rising diapir modeled by creeping flow past a sphere. Tectonics 7, 1091–1101. https://doi.org/10.1029/TC007i005p01091.

Cruden, A.R., 1990. Flow and fabric development during the diapiric rise of magma. J. Geol. 98, 681–698. https://doi.org/10.1086/629433.

Cruden, A.R., 1998. On the emplacement of tabular granites. J. Geol. Soc. 1998 155 (5), 853–862. https://doi.org/10.1144/gsjgs.155.5.0853.

Cruden, A.R., Weinberg, R.F., 2018. Chapter 2 - Mechanisms of magma transport and storage in the lower and middle crust—magma segregation, ascent and emplacement. In: Burchardt, S. (Ed.), Volcanic and Igneous Plumbing Systems. Elsevier, pp. 13–53. https://doi.org/10.1016/B978-0-12-809749-6.00002-9.

Currier, L.W., 1937. The problem of the Chelmsford, Massachusetts, Granite. EOS Trans. Am. Geophys. Union 18, 260–261. https://doi.org/10.1029/TR018i001p00260.

Currier, L.W., 1947. Granitization and its significance as a regional metamorphic process in New England. J. Wash. Acad. Sci. 37, 75–86.

Dahlquist, J.A., Galindo, C., Pankhurst, R.J., Rapela, C.W., Alasino, P.H., Saavedra, J., Fanning, C.M., 2007. Magmatic evolution of the Peñón Rosado granite: petrogenesis of garnet-bearing granitoids. Lithos 95, 177–207. https://doi.org/10.1016/j.lithos.2006.07.010.

Dahlquist, J.A., Morales Cámera, M.M., Alasino, P.H., Tickyj, H., Basei, M.A.S., Galindo, C., Moreno, J.A., Rocher, S., 2022. Geochronology and geochemistry of Devonian magmatism in the Frontal cordillera (Argentina): geodynamic implications for the pre-Andean SW Gondwana margin. Int. Geol. Rev. 64, 233–253. https://doi.org/10.1080/00206814.2020.1845994.

Daly, R.A., 1898. Review of Le Granit des Pyrénées et ses phénomènes de contact-Premier memoir: Les contacts de la Haute-Ariège. J. Geol. 6, 759–763.

Daly, R.A., 1905. The classification of igneous intrusive bodies. J. Geol. 13, 485–508. https://doi.org/10.1086/621251.

Daly, R.A., 1910. Origin of the Alkaline rocks. GSA Bull. 21, 87–118. https://doi.org/10.1130/GSAB-21-87.

Daly, R.A., 1912. Geology of the North American Cordillera at the Forty-Ninth Parallel. US Government Printing Office.

Dana, E.S., 1877. A Text-Book of Mineralogy: With an Extended Treatise on Crystallography and Physical Mineralogy. Wiley.

D'Aoust, Virlet, 1844a. Sur Jes fiIons en general et le role qu'ils paraissent avoir joue dans l'operation du metamorphisme. Bull. Soc. Geol. Fr. 28 Serie, 1, 825–844.

D'Aoust, Virlet, 1844b. Note sur les roches d'imbibition. Bull. Soc. Geol. Fr. 28 Serie, 1, 845.

Darwin, C., 1844. Geological Observations on the Volcanic Islands Visited during the Voyage of H.M.S. Beagle, Together with some Brief Notes on the Geology of Australia and the Cape of Good Hope, ed. Smith Elder, London.

Darwin, C., 1845. The Voage of the Beagle. Henry Colburn, Great Malborough Street, London.

Darwin, C., 1846. Geological Observations on South America. Being the Third Part of the Geology of the Voyage of the Beagle, under the Command of Capt. Fitzroy, R.N. During the Years 1832 to 1836. Smith Elder and Co. ed, London.

Davidson, J.P., Tepley III, F.J., Knesel, K.M., 1998. Isotopic fingerprinting may provide insights into evolution of magmatic systems. EOS Trans. Am. Geophys. Union 79, 185–193. https://doi.org/10.1029/98EO00135.

Davis, D.W., Krogh, T.E., Williams, I.S., 2003. Historical development of zircon geochronology. Rev. Mineral. Geochem. 53, 145–181. https://doi.org/10.2113/0530145.

de Gimbernat, C., 1806. Mapa Geognostico de la Suiza. Segun las Observationes de Carlos de Gimbernat, 68 x 53 cm. Bayerische Staatsbibliothek München, Mapp.XXIV, 112.

de Gimbernat, C., 1808. Mapa Geognostico del Tirol, Lithographie, 49,7x 51,2 cm. Bayerische Staatsbibliothek München, Mapp. XXIV, p. 63.

De la Roche, H., Leterrier, J., Grandclaude, P., Marchal, M., 1980. A classification of volcanic and plutonic rocks using R1R2-diagram and major-element analyses — its relationships with current nomenclature. Chem. Geol. 29, 183–210. https://doi.org/10.1016/0009-2541(80)90020-0.

de Lira Santos, L.C.M., de Almeida Lages, G., Lima, H.M., de Araújo Neto, J.F., Santos, G. L., da Paixão, M.S., 2022. An overview on the Rhyacian–Orosirian (ca. 2.1–2.0 Ga) granitic magmatism of the Alto Moxotó Terrane and its implications for the crustal evolution of the Borborema Province, NE Brazil. J. Iber. Geol. 48, 225–239. https://doi.org/10.1007/s41513-022-00191-6.

de Saussure, H.B., 1779. Voyage Dans les Alpes, précédé d'un Essai Sur l'histoire Naturelles Des Environs de Geneve. Chez Samuel Fauche, Neuchâtel.

de Saussure, H.B., 1786. Voyages dans les Alpes. J. Cherbuliez.

Dean, D.R., 2009. Benjamin Franklin and geology. The revolution in geology from the renaissance to the enlightenment. Geol. Soc. Am. Mem. 203, 209–223.

Debon, F., Le Fort, P., 1988. A cationic classification of common plutonic rocks and their magmatic associations : principles, method, applications. Bull. Mineral. 111, 493–510. https://doi.org/10.3406/bulmi.1988.8096.

Degrandpré, L.M.J.O., 1801. Voyage a la Cote Occidentale d'Afrique, Fait Dans les années 1786 et 1787; Suivi d'un Voyage Fait Au Cap de Bonne-Espérance, Contenant la Description Militaire de Cette Colonie. 2 volumes. Dentu, Paris.

Delesse, A., 1861. Études Sur le métamorphisme Des Roches. F. Savy.

Delgadillo, J.M., 2013. Del Batolito a un monumento: Machu Picchu. Stud. Geol. Salmanticensia 49, 157–190.

Desmarest, N., 1774. Mémoire Sur l'origine & la Nature du Basalte à Grandes Colonnes Polygones, déterminées Par l'histoire Naturelle de Cette Pierre, observée en Auvergne.

Didier, J., Barbarin, B., 1991. The different types of enclaves in granites-Nomenclature. Enclaves Granite Petrol. 19–23.

Didier, J., Lameyre, J., 1969. Les granites du Massif Central Français: étude comparée des leucogranites et granodiorites. Contrib. Mineral. Petrol. 24, 219–238. https://doi.org/10.1007/BF00376049.

Dietz, R.S., 1961. Continent and ocean basin evolution by spreading of the sea floor. Nature 190, 854–857. https://doi.org/10.1038/190854a0.

Dobretsov, N.L., Shafeev, A.A., 1991. Anatexis and granitisation: Criteria and models. In: Anatexis and Granitisation : Criteria and Models, 42, pp. 45–52.

Domeyko, I., 1855. Jeolojía: sobre la situacion, criadero i minerales de las minas de plata de Tres puntas (provincia de Atacama). Anales de la Universidad de Chile ág 312-322. https://doi.org/10.5354/0717-8883.1855.22046.

Dott, R.H., 1998. Charles Lyell's debt to North America: his lectures and travels from 1841 to 1853. Geol. Soc. Lond. Spec. Publ. 143, 53–69. https://doi.org/10.1144/GSL.SP.1998.143.01.06.

Dott Jr., R., 1996. Lyell in America—his lectures, field work, and mutual influences, 1841-1853. Earth Sci. Hist. 15, 101–140. https://doi.org/10.17704/eshi.15.2.b4n1102556ju6736.

Druguet, E., Carreras, J., 2006. Analogue modelling of syntectonic leucosomes in migmatitic schists. J. Struct. Geol. 28, 1734–1747. https://doi.org/10.1016/j.jsg.2006.06.015.

Duke, 1853. On the granitic district of Inverary, Argyllshire. Q. J. Geol. Soc. 9, 360–366. https://doi.org/10.1144/GSL.JGS.1853.009.01-02.57.

Dumond, G., Yoshinobu, A.S., Barnes, C.G., 2005. Midcrustal emplacement of the Sausfjellet pluton, Central Norway: ductile flow, stoping, and in situ assimilation. GSA Bull. 117, 383–395. https://doi.org/10.1130/B25464.1.

Dumont, A.H., 1857. Carte géologique de l'Europe / par André Dumont... [WWW Document]. Gallica. URL. https://gallica.bnf.fr/ark:/12148/btv1b530931459 (accessed 10.8.22).

Durocher, J., 1859. Essay on Comparative Petrology. McGlashan & Gill.

Dyck, B., Larson, K.P., 2023. Metasomatic origin of the Himalayan banded tourmaline leucogranite. Contrib. Mineral. Petrol. 178, 37. https://doi.org/10.1007/s00410-023-02020-0.

Eckelmann, F.D., Poldervaart, A.W., 1957. Geologic evolution of the Beartooth Mountains, Montana and Wyoming. Geol. Soc. Am. Bull. 68, 1225.

Eklund, O., Väisänen, M., Ehlers, C., Kosunen, P., Kurhila, M., Lehtinen, M., Sorjonen-Ward, P., 2008. 100 Years of Migmatite - in Sederholms Footsteps.

Elabouyi, M., Yaagoub, D., Driouch, Y., Dahire, M., Qarqori, K., Manar, A., Ntarmouchant, A., Jeddi, M., Elkourchia, A., Laguenini, F., Mali, B., Hinaje, S., Belkasmi, M., 2022. The buried Variscan granites and associated structures in the High Moulouya basin from gravity data and their role during the Triassic-Liassic extensional tectonics (Moroccan Meseta-Atlas domain). J. Afr. Earth Sci. 193, 104597. https://doi.org/10.1016/j.jafrearsci.2022.104597.

Elburg, M.A., Bons, P.D., Dougherty-Page, J., Janka, C.E., Neumann, N., Schaefer, B., 2001. Age and metasomatic alteration of the Mt Neill Granite at Nooldoonooldoona Waterhole, Mt Painter Inlier, South Australia. Aust. J. Earth Sci. 48, 721–730. https://doi.org/10.1046/j.1440-0952.2001.485890.x.

Elburg, M.A., Bons, P.D., Foden, J., Brugger, J., 2003. A newly defined Late Ordovician magmatic-thermal event in the Mt Painter Province, northern Flinders Ranges, South Australia. Aust. J. Earth Sci. 50, 611–631. https://doi.org/10.1046/j.1440-0952.2003.01016.x.

Elburg, M.A., Andersen, T., Bons, P.D., Weisheit, A., Simonsen, S.L., Smet, I., 2012. Metasomatism and metallogeny of A-type granites of the Mt Painter–Mt Babbage Inliers, South Australia. Lithos 151, 83–104. https://doi.org/10.1016/j.lithos.2011.09.009.

Enrique, P., Esteve, S., 2019. A Chemical Approximation to the Modal QAPF and Normative Q' (F')-ANOR Classification of the Igneous Rocks based on their SiO2-CaO-K2O Content.

Enys, J.S., 1833. LII. Some remarks on the granite found near Penryn, and on the mode of working it. Lond. Edinburgh Dublin Philos. Mag. J. Sci. 2, 321–325. https://doi.org/10.1080/14786443308648050.

Erdmann, S., Wang, R., Huang, F., Scaillet, B., Zhao, K., Liu, H., Chen, Y., Faure, M., 2019. Titanite: a potential solidus barometer for granitic magma systems. Comptes Rendus Geosci. 351, 551–561. https://doi.org/10.1016/j.crte.2019.09.002.

Errandonea-Martin, J., Sarrionandia, F., Junguitu, J., Carracedo-Sánchez, M., Eguíluz, L., Ibarguchi, J.I.G., 2018. The composite Sierra Bermeja Pluton (southern Iberian Massif): science, heritage and geoconservation. J. Maps 15 (2), 101–111.

Eskola, P., 1920. The mineral facies of rocks. Nor. Geol. Tidsskr. 6, 52 pages.
Eskola, P., 1932. On the origin of granitic magmas. Z. Krist. Mineral. Petrogr. 42, 455. https://doi.org/10.1007/BF02938830.
Eskola, P., 1955. About the granite problem and some masters of the study of granite. Compte Rendu Soc. Géol. Finl. 28, 117–130.
Evans, D.J., Rowley, W.J., Chadwick, R.A., Kimbell, G.S., Millward, D., 1994. Seismic reflection data and the internal structure of the Lake District batholith, Cumbria, northern England. Proc. Yorks. Geol. Soc. 50, 11–24. https://doi.org/10.1144/pygs.50.1.11.
Fairbridge, R.W., 1998. History of Geochemistry. Geochemistry, Encyclopedia of Earth Science. Springer, Netherlands, Dordrecht, pp. 315–322. https://doi.org/10.1007/1-4020-4496-8_156.
Farina, F., Dini, A., Rocchi, S., Stevens, G., 2014. Extreme mineral-scale Sr isotope heterogeneity in granites by disequilibrium melting of the crust. Earth Planet. Sci. Lett. 399, 103–115. https://doi.org/10.1016/j.epsl.2014.05.018.
Ferreira, J.A., Bento dos Santos, T., Pereira, I., Mata, J., 2019. Tectonically assisted exhumation and cooling of Variscan granites in an anatectic complex of the Central Iberian Zone, Portugal: constraints from LA-ICP-MS zircon and apatite U–Pb ages. Int. J. Earth Sci. 108, 2153–2175. https://doi.org/10.1007/s00531-019-01755-1.
Fettes, D., Desmons, J. (Eds.), 2011. Metamorphic Rocks: A Classification and Glossary of Terms: Recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Metamorphic Rocks, Illustrated, edition. ed. Cambridge University Press, Cambridge.
Finch, M.A., Bons, P.D., Steinbach, F., Griera, A., Llorens, M.-G., Gomez-Rivas, E., Ran, H., de Riese, T., 2020. The ephemeral development of C′ shear bands: a numerical modelling approach. J. Struct. Geol. 139, 104091. https://doi.org/10.1016/j.jsg.2020.104091.
Finch, M.A., Bons, P.D., Weinberg, R.F., Llorens, M.G., Griera, A., Gomez-Rivas, E., 2022. A dynamic atlas of interference patterns in superimposed, opposite sense ductile shear zones. J. Struct. Geol. 165, 104739. https://doi.org/10.1016/j.jsg.2022.104739.
Finger, F., Clemens, J.D., 2002. Cadomian lower-crustal contributions to Variscan granite petrogenesis (South Bohemian Batholith, Austria): a Comment. J. Petrol. 43, 1779–1781.
Foden, J.D., Elburg, M.A., Turner, S.P., Sandiford, M., O'Callaghan, J., Mitchell, S., 2002. Granite production in the Delamerian Orogen, South Australia. J. Geol. Soc. Lond. 159, 557–575. https://doi.org/10.1144/0016-764901-099.
Fouqué, F., Michel-Lévy, A., 1879. Minéralogie micrographique roches éruptives françaises. Paris Impr. de A. Quantin.
Fouqué, F., Michel-Lévy, A., 1882. Synthèse Des minéraux et Des Roches. G. Masson, Paris.
Fournet, J., 1844. Sur l'état de surfusion du quartz dans les roches éruptives et dans les filons métallifères. éditeur inconnu.
Fournet, J.J.B.X., 1845. Simplification de l'étude d'une Certaine Classe de Filons.
Franklin, B., 1782. Letter of September 22, 1782 to the Abbe Soulavie: Quoted in: Van Doren, Carl, 1938, 1987 edition. Benjamin Franklin. published by Bramhall House, New York, p. 660.
Frost, B.R., Frost, C.D., 2008. A geochemical classification for feldspathic igneous rocks. J. Petrol. 49, 1955–1969. https://doi.org/10.1093/petrology/egn054.
Frost, B.R., Barnes, C.G., Collins, W.J., Arculus, R.J., Ellis, D.J., Frost, C.D., 2001. A geochemical classification for granitic rocks. J. Petrol. 42, 2033–2048. https://doi.org/10.1093/petrology/42.11.2033.
Frost, B.R., Frost, C.D., Anderson, J.L., Barnes, C.G., Wilson, M., 2019. A more informative way to name plutonic rocks—comment by Frost et al. GSA Today.
Füchsel, G.C., 1761. Historia Terrae et Maris, ex Historia Thuringiae, per Montium Descriptionem.
Galland, O., Bertelsen, H.S., Eide, C.H., Guldstrand, F., Haug, Ø.T., Leanza, H.A., Mair, K., Palma, O., Planke, S., Rabbel, O., Rogers, B., Schmiedel, T., Souche, A., Spacapan, J.B., 2018. Chapter 5 - Storage and transport of magma in the layered crust—formation of sills and related flat-lying intrusions. In: Burchardt, S. (Ed.), Volcanic and Igneous Plumbing Systems. Elsevier, pp. 113–138. https://doi.org/10.1016/B978-0-12-809749-6.00005-4.
Gamal El Dien, H., Li, Z.-X., Kil, Y., Abu-Alam, T., 2019. Origin of arc magmatic signature: a temperature-dependent process for trace element (re)-mobilization in subduction zones. Sci. Rep. 9, 7098. https://doi.org/10.1038/s41598-019-43605-9.
Gao, S., Luo, T.-C., Zhang, B.-R., Zhang, H.-F., Han, Y., Zhao, Z.-D., Hu, Y.-K., 1998. Chemical composition of the continental crust as revealed by studies in East China. Geochim. Cosmochim. Acta 62, 1959–1975. https://doi.org/10.1016/S0016-7037(98)00121-5.
Gao, P., Zheng, Y., Zhao, Z., 2016. Experimental melts from crustal rocks: a lithochemical constraint on granite petrogenesis. Lithos 266–267, 133–157. https://doi.org/10.1016/j.lithos.2016.10.005.
Garcia-Arias, M., 2020. The never-ending pursuit of a definitive chemical classification system for granites. J. Geosci. 65, 221–227. https://doi.org/10.3190/jgeosci.313.
Gard, M., Hasterok, D., Halpin, J.A., 2019. Global whole-rock geochemical database compilation. Earth Syst. Sci. Data 11, 1553–1566. https://doi.org/10.5194/essd-11-1553-2019.
Garrido, M.L., 2020. Aspectos geológicos en la Historia del Reino de Quito en la América Meridional (1844), de Juan de Velasco. Geogaceta 107–110.
Gemmellaro, C., 1823. Sopra alcuni pezzi di granito e di lave antiche trovati presso alla cima dell' Etna: Osservazioni fisiche. Dalla Tipografia del can. Longo per Salvatore Longo.
Ghiorso, M.S., Sack, R.O., 1995. Chemical mass transfer in magmatic processes IV. A revised and internally consistent thermodynamic model for the interpolation and extrapolation of liquid-solid equilibria in magmatic systems at elevated temperatures and pressures. Contrib. Mineral. Petrol. 119, 197–212. https://doi.org/10.1007/BF00307281.
Glazner, A.F., Bartley, J.M., Coleman, D.S., Cawood, A.J., Bond, C.E., 2019. A more informative way to name plutonic rocks. GSA Today 29, 4–10.
Gómez-Frutos, D., Castro, A., Gutiérrez-Alonso, G., 2023. Post-collisional batholiths do contribute to continental growth. Earth Planet. Sci. Lett. 603, 117978. https://doi.org/10.1016/j.epsl.2022.117978.
Gomez-Rivas, E., Butler, R.W.H., Healy, D., Alsop, I., 2020. From hot to cold - the temperature dependence on rock deformation processes: an introduction. J. Struct. Geol. 132, 103977. https://doi.org/10.1016/j.jsg.2020.103977.
González-Esvertit, E., Prieto-Torrell, C., Bons, P.D., Canals, A., Casas, J.M., Elburg, M.A., Gomez-Rivas, E., 2024. Global Granite Geochemistry and Outcrop Database (GGGOD) [Data Set]. DIGITAL.CSIC. https://doi.org/10.20350/digitalCSIC/16505.
Goodspeed, G.E., 1948. Origin of granites. In: Gilluly, J., Read, H.H., Buddington, A.F., Grout, F.F., Goodspeed, G.E., Bowen, N.L. (Eds.), Origin of Granite, 0. Geological Society of America. https://doi.org/10.1130/MEM28-p55.
Goranson, R.W., 1936. Silicate-water systems: the solubility of water in albite-melt. EOS Trans. Am. Geophys. Union 17, 257–259. https://doi.org/10.1029/TR017i001p00257-4.
Gortani, M., 1962. Italian pioneers in geology and mineralogy. Cahiers d'Histoire Mondiale. Journal of World History. Cuadernos de Historia Mundial 7, 503.
Green, D.H., Lambert, I.B., 1965. Experimental crystallization of anhydrous granite at high pressures and temperatures. J. Geophys. Res. 1896-1977 (70), 5259–5268. https://doi.org/10.1029/JZ070i020p05259.
Greene, J.C., 1973. Review of Charles Lyell, the years to 1841: the revolution in geology. J. Hist. Med. Allied Sci. 28, 297–300.
Griera, A., Bons, P.D., Jessell, M.W., Lebensohn, R.A., Evans, L., Gomez-Rivas, E., 2011. Strain localization and porphyroclast rotation. Geology 39, 275–278. https://doi.org/10.1130/G31549.1.
Grout, F.F., 1945. Scale models of structures related to batholiths. Am. J. Sci. 243, 260–284.
Grove, T.L., Brown, S.M., 2018. Magmatic processes leading to compositional diversity in igneous rocks: Bowen (1928) revisited. Am. J. Sci. 318, 1–28. https://doi.org/10.2475/01.2018.02.
Gudmundsson, A., 2011. Rock Fractures in Geological Processes. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511975684.
Guitard, G., 1960. Lineations, schistosite et phases de plissement durant l'orogenese hercynienne dans les terrains anciens des Pyrenees orientales, leurs relations avec le metamorphisme et la granitisation [with discussion]. Bull. Soc. Géol. France S7-II, 862–887. https://doi.org/10.2113/gssgfbull.S7-II.7.862.
Guitard, G., 1970. Le métamorphisme hercynien mésozonal et les gneiss oeillés du massif du Canigou (Pyrénées orientales). Mémoires Du Bureau de Recherches Géologiques et Minières (BRGM) 63, 353.
Guo, L.-L., Zhang, Y.-B., Zhang, Y.-J., Yu, Z.-W., Zhang, J.-N., 2018. Experimental investigation of granite properties under different temperatures and pressures and numerical analysis of damage effect in enhanced geothermal system. Renew. Energy 126, 107–125. https://doi.org/10.1016/j.renene.2018.02.117.
Guo, J.-L., Wang, Z., Zhang, W., Feng, L., Moynier, F., Hu, Z., Zhou, L., Liu, Y., 2022. Zirconium and its stable isotopes in igneous systems. Earth Sci. Rev. 104289. https://doi.org/10.1016/j.earscirev.2022.104289.
Guthrie, F., 1884. LII. On eutexia. Lond. Edinburgh Dublin Philos. Mag. J. Sci. 17, 462–482.
Hague, A., Iddings, J.P., 1885. On the Development of Crystallization in the Igneous Rocks of Washoe, Nevada, with Notes on the Geology of the District. U.S. Government Printing Office.
Hall, J., 1794. Observations on the Formation of Granite.
Hall, J., 1815. II. On the vertical position and convolutions of certain strata, and their relation with granite. Earth Environ. Sci. Trans. R. Soc. Edinb. 7, 79–108. https://doi.org/10.1017/S0080456800019268.
Hallam, A., 1983. Great Geological Controversies. Oxford University Press.
Hamilton, W., 1778. I. A letter from Sir William Hamilton, K. B. F. R. S. to Sir John Pringle, Bart. P. R. S. giving an account of certain traces of volcano on the banks of the Rhine. Philos. Trans. R. Soc. Lond. 68, 1–6. https://doi.org/10.1098/rstl.1778.0001.
Hanor, J.S., Duchač, K.C., 1990. Isovolumetric silicification of early Archean komatiites: geochemical mass balances and constraints on origin. J. Geol. 98, 863–877. https://doi.org/10.1086/629458.
Haraguchi, S., Ueki, K., Yoshida, K., Kuwatani, T., Mohamed, M., Horiuchi, S., Iwamori, H., 2018. Geochemical database of Japanese islands for basement rocks. J. Geol. Soc. Jpn. 124, 1049–1054. https://doi.org/10.5575/geosoc.2018.0027.
Harker, A., 1896. The classification of igneous rocks. Sci. Prog. 1894-1898 (4), 469–490.
Harker, A., 1909. The Natural History of Igneous Rocks. Methuen & Company.
Harlaux, M., Kouzmanov, K., Gialli, S., Clark, A.H., Laurent, O., Corthay, G., Prado Flores, E., Dini, A., Chauvet, A., Ulianov, A., Chiaradia, M., Menzies, A., Villón Durand, G., Kalinaj, M., Fontboté, L., 2021. The upper Oligocene San Rafael intrusive complex (Eastern Cordillera, Southeast Peru), host of the largest-known high-grade tin deposit. Lithos 400–401, 106409. https://doi.org/10.1016/j.lithos.2021.106409.
Harley, S.L., Kelly, N.M., 2007. Zircon tiny but timely. Elements 3, 13–18. https://doi.org/10.2113/gselements.3.1.13.
Harris, G.F., 1888. Granites and our Granite Industries. C. Lockwood and son.
Hartmann, J., Moosdorf, N., 2012. The new global lithological map database GLiM: a representation of rock properties at the Earth surface. Geochem. Geophys. Geosyst. 13. https://doi.org/10.1029/2012GC004370.

Haselwimmer, C.E., Riley, T.R., Liu, J.G., 2011. Lithologic mapping in the Oscar II Coast area, Graham Land, Antarctic Peninsula using ASTER data. Int. J. Remote Sens. 32, 2013–2035. https://doi.org/10.1080/01431161003645824.
Haughton, S., 1853. On the chemical composition and optical properties of the mica of the Dublin, Wicklow, and Carlow granites. Proc. R. Ir. Acad. 1836-1869 (6), 176–179.
Haughton, S., 1855. IV. Notes on mineralogy.—no. II. On the chemical composition of the granites of the south-east of Ireland. Lond. Edinburgh Dublin Philos. Mag. J. Sci. 10, 23–29. https://doi.org/10.1080/14786445508641924.
Haughton, S., 1858. Experimental researches on the granites of Ireland. Q. J. Geol. Soc. 14, 300–305. https://doi.org/10.1144/GSL.JGS.1858.014.01-02.39.
Haughton, S., 1859. On the black mica of the granite of Leinster and Donegal; and its probable identity with Lepidomelane. Q. J. Geol. Soc. 15, 129–131. https://doi.org/10.1144/GSL.JGS.1859.015.01-02.28.
Haughton, S., 1862. Experimental Researches on the Granites of Ireland: On the Granites of Donegal. Taylor & Francis.
Haughton, S., 1864. Experimental researches on the granites of Ireland.—Part IV. On the granites and syenites of Donegal, with some remarks on those of Scotland and Sweden. Q. J. Geol. Soc. 20, 116–117. https://doi.org/10.1144/GSL.JGS.1864.020.01-02.18.
He, Q., Suorineni, F.T., Oh, J., 2016. Review of hydraulic fracturing for preconditioning in cave mining. Rock Mech. Rock. Eng. 49, 4893–4910. https://doi.org/10.1007/s00603-016-1075-0.
He, H., Wang, T., Sui, Q., Duan, X., Ren, X., Hou, D., Xie, Y., Liu, S., Feng, P., Zhang, H., Chen, L., 2023. Geochronology and petrogenesis of the early paleozoic Jilongjie granites in the Central South China Block: implication for post-kinematic lithospheric delamination. Minerals 13, 734. https://doi.org/10.3390/min13060734.
Heilbron, M., Ribeiro, A., Valeriano, C.M., Paciullo, F.V., Almeida, J.C.H., Trouw, R.J.A., Tupinambá, M., Eirado Silva, L.G., 2017. The Ribeira Belt. In: Heilbron, M., Cordani, U.G., Alkmim, F.F. (Eds.), São Francisco Craton, Eastern Brazil: Tectonic Genealogy of a Miniature Continent, Regional Geology Reviews. Springer International Publishing, Cham, pp. 277–302. https://doi.org/10.1007/978-3-319-01715-0_15.
Herbert, S., 1991. Charles Darwin as a prospective geological author. Br. J. Hist. Sci. 24, 159–192. https://doi.org/10.1017/S0007087400027060.
Herbert, S., 2005. Charles Darwin, Geologist. Cornell University Press.
Herrgen, C., 1802. Descripcion geognóstica de las rocas que componen la parte solída del globo terrestre: extractada de varias obras alemanas de la escuela de Werner, y aumentada con observaciones hechas en la peninsula. La Imprenta Real (Madrid) 224.
Hess, H.H., 1962. History of Ocean Basins. In: Engel, A.E.J., James, H.L., Leonard, B.F. (Eds.), Petrologic Studies. Geological Society of America, p. 0. https://doi.org/10.1130/Petrologic.1962.599.
Hestmark, G., 2011. The meaning of "metamorphic" - Charles & Mary Lyell in Norway, 1837. Nor. Geol. Tidsskr. 91, 247–275.
Higgins, M.D., 2011. Textural coarsening in igneous rocks. Int. Geol. Rev. 53, 354–376. https://doi.org/10.1080/00206814.2010.496177.
Hirth, G., Tullis, J., 1992. Dislocation creep regimes in quartz aggregates. J. Struct. Geol. 14, 145–159. https://doi.org/10.1016/0191-8141(92)90053-Y.
Hogan, J.P., 2019. A more informative way to name plutonic rocks—comment by Hogan. GSA Today 29.
Holmes, A., 1945. Natural history of granite. Nature 155, 412–415. https://doi.org/10.1038/155412a0.
Holness, M.B., Vernon, R.H., 2015. The influence of interfacial energies on igneous microstructures. In: Charlier, B., Namur, O., Latypov, R., Tegner, C. (Eds.), Layered Intrusions. Springer, Netherlands, Dordrecht, pp. 183–228. https://doi.org/10.1007/978-94-017-9652-1_4.
Holness, M.B., Clemens, J.D., Vernon, R.H., 2018. How deceptive are microstructures in granitic rocks? Answers from integrated physical theory, phase equilibrium, and direct observations. Contrib. Mineral. Petrol. 173, 62. https://doi.org/10.1007/s00410-018-1488-8.
Holtedahl, O., 1963. Studies on the Igneous Rock Complex of the Oslo Region. XIX. Charles Lyell's Visit to Norway 1837 with Remarks on the History of the "Granite Problem" in the Oslo Region. Skrifter Utgitt Av Det Norske Videnskaps-Akademi i Oslo. I. Mat. Naturv. Klasse. Ny Serie. No. 12. Universitetsforlaget, Oslo.
Huang, R., Audétat, A., 2012. The titanium-in-quartz (TitaniQ) thermobarometer: a critical examination and re-calibration. Geochim. Cosmochim. Acta 84, 75–89. https://doi.org/10.1016/j.gca.2012.01.009.
Huang, W.-L., Wyllie, P.J., 1975. Melting reactions in the system NaAlSi3O8-KAlSi3O8-SiO2 to 35 kilobars, dry and with excess water. J. Geol. 83, 737–748. https://doi.org/10.1086/628165.
Hull, E., 1874. II.—Microscopic structure of Irish granites: no. 3. Granite of Ballyknockan, Co. Wicklow. Geol. Mag. 1, 2–5. https://doi.org/10.1017/S0016756800001746.
Hunt, R., 1849. On the structural character of rock, and of mineral deposits, as effected by electricity. Proc. Yorks. Geol. Soc. 3, 380–386. https://doi.org/10.1144/pygs.3.380.
Hutton, J., 1785. Theory of the Earth: Or an Investigation of the Laws observable in the Composition, Dissolution, and Restoration of Land upon the Globe. Royal Society of Edinburgh Scotland Foundation. ed.
Hutton, J., 1794. II. Observations on granite. Earth Environ. Sci. Trans. R. Soc. Edinb. 3, 77–85. https://doi.org/10.1017/S0080456800020305.
Hutton, J., 1795a. Theory of the Earth with Proofs and Illustrations in Four Parts. Part I, Foundation. ed. Royal Society of Edinburgh Scotland.
Hutton, J., 1795b. Theory of the Earth with Proofs and Illustrations in Four Parts. Part II, Foundation. ed. Royal Society of Edinburgh Scotland.
Hutton, J., 1899. Theory of the Earth with proofs and illustrations in four parts. Part III. Geol. Soc. 316.
Hutton, D.H.W., 1992. Granite sheeted complexes: evidence for the dyking ascent mechanism. Earth Environ. Sci. Trans. R. Soc. Edinb. 83, 377–382. https://doi.org/10.1017/S0263593300008038.
Iddings, J.P., 1890. The Mineral Composition and Geological Occurrence of Certain Igneous Rocks in the Yellowstone National Park. Philosophical Society of Washington.
Iddings, J.P., 1892a. On the Crystallization of Igneous Rocks. The Society.
Iddings, J.P., 1892b. The Origin of Igneous Rocks. Philosophical Society.
Iddings, J.P., 1893a. The volcanic rocks of the andes. J. Geol. 1, 164–175. https://doi.org/10.1086/606173.
Iddings, J.P., 1893b. Studies for students: genetic relationships among igneous rocks. J. Geol. 1, 833–844.
Iddings, J.P., 1896. Extrusive and intrusive igneous rocks as products of magmatic differentiation. Q. J. Geol. Soc. 52, 606–617. https://doi.org/10.1144/GSL.JGS.1896.052.01-04.38.
Iddings, J.P., 1898a. Chemical and mineral relationships in igneous rocks. J. Geol. 6, 219–237. https://doi.org/10.1086/608063.
Iddings, J.P., 1898b. On rock classification. J. Geol. 6, 92–111. https://doi.org/10.1086/608019.
IGME-BRGM, 2009. Mapa Geológico de Pirineos 1:400.000.
Ishihara, S., 1977. The magnetite-series and ilmenite-series granitic rocks. Min. Geol. 27, 293–305. https://doi.org/10.11456/shigenchishitsu1951.27.293.
Ishihara, S., 2004. The redox state of granitoids relative to tectonic setting and earth history: the magnetite–ilmenite series 30 years later. Earth Environ. Sci. Trans. R. Soc. Edinb. 95, 23–33. https://doi.org/10.1017/S0263593300000894.
Jessell, M., Bons, P., Evans, L., Barr, T., Stüwe, K., 2001. Elle: the numerical simulation of metamorphic and deformation microstructures. Comput. Geosci. 27, 17–30. https://doi.org/10.1016/S0098-3004(00)00061-3.
Johannes, W., 1984. Beginning of melting in the granite system Qz-Or-Ab-An-H2O. Contrib. Mineral. Petrol. 86, 264–273. https://doi.org/10.1007/BF00373672.
Johnstone, A., 1887. On the evolution and classification of igneous rocks. Trans. Edinb. Geol. Soc. 5, 412–420. https://doi.org/10.1144/transed.5.3.412.
Jover, O., 1986. Les massifs granitiques de Gu~ret et du Nord-Millevaches (Massifs Central franfais): Analyse structurale et module de mise en place.
Jung, S., Brandt, S., Bast, R., Scherer, E.E., Berndt, J., 2019. Metamorphic petrology of a high-T/low-P granulite terrane (Damara belt, Namibia) – Constraints from pseudosection modelling and high-precision Lu–Hf garnet-whole rock dating. J. Metamorph. Geol. 37, 41–69. https://doi.org/10.1111/jmg.12448.
Kadioglu, Y., Ates, A., Güleç, N.T., 1998. Structural Interpretation of Gabbroic Rocks in Agacoren Granitoid, Central Turkey: Field Observations and Aeromagnetic Data. https://doi.org/10.1017/s001675689800836x.
Karimzadeh, S., Tangestani, M.H., 2021. Evaluating the VNIR-SWIR datasets of WorldView-3 for lithological mapping of a metamorphic-igneous terrain using support vector machine algorithm; a case study of Central Iran. Adv. Space Res. 68, 2421–2440. https://doi.org/10.1016/j.asr.2021.05.002.
Katsaga, T., Riahi, A., DeGagne, D.O., Valley, B., Damjanac, B., 2015. Hydraulic fracturing operations in mining: conceptual approach and DFN modeling example. Min. Technol. 124, 255–266. https://doi.org/10.1179/1743286315Y.0000000022.
Katz, R.F., Spiegelman, M., Holtzman, B., 2006. The dynamics of melt and shear localization in partially molten aggregates. Nature 442, 676–679. https://doi.org/10.1038/nature05039.
Keilhau, M., 1828. Ein vorläufiges Wort über Contactbildungen. Ann. Phys. 90, 131–137. https://doi.org/10.1002/andp.18280900914.
Keilhau, M., 1838. Granitens og de ovrige saakaldte massive bjergarters samt de Krystallinske skiferes theori. Nyt. MaR. Naturvidenskab 1, 1–72.
Keilhau, M., 1843. Theory on granite. Edinb. New Philos. J. 24, 402. ed.
Keqin, X., Nai, S., Dezi, W., Shouxi, H., Yingchun, L., Shouyuan, J., 1982. On the origin and metallogeny of the granites in South China. In: Symposium on Geology of Granites and Their Metallogenetic Relations, pp. 1–3.
Kiefer, W.S., 2004. Gravity evidence for an extinct magma chamber beneath Syrtis Major, Mars: a look at the magmatic plumbing system. Earth Planet. Sci. Lett. 222, 349–361. https://doi.org/10.1016/j.epsl.2004.03.009.
Kilpatrick, J.A., Ellis, D.J., 1992. C-type magmas: igneous charnockites and their extrusive equivalents. Earth Environ. Sci. Trans. R. Soc. Edinb. 83, 155–164. https://doi.org/10.1017/S0263593300007847.
Kimbell, G.S., Young, B., Millward, D., Crowley, Q.G., 2010. The North Pennine batholith (Weardale Granite) of northern England: new data on its age and form. Proc. Yorks. Geol. Soc. 58, 107–128. https://doi.org/10.1144/pygs.58.1.273.
Kinahan, G.H., 1887. V.—Archæan rocks. Geol. Mag. 4, 503–507. https://doi.org/10.1017/S0016756800190430.
King, P.P., 1827. Narrative of a Survey of the Intertropical and Western Coasts of Australia: Performed Between the Years 1818 and 1822. J. Murray.
Kirwan, R., 1793. Examination of the supposed igneous origin of stony substances. Trans. R. Ir. Acad. 5, 51–82.
Kirwan, R., 1800. Observations on the Proofs of the Huttonian Theory of the Earth Adduced by Sir James Hall. G. Bonham.
Kjerulf, T., 1855. Das Christiania-Sihtrbecken, chemisch-geognostisch Untersucht. Fabritius, Christiania.
Kjerulf, T., 1879. Udsigt over del sydlige Norges geologi. WC Fabritius, Christiania (incl. atlas).
Klee, J., Potel, S., Ledésert, B.A., Hébert, R.L., Chabani, A., Barrier, P., Trullenque, G., 2021. Fluid-rock interactions in a paleo-geothermal reservoir (Noble Hills Granite,

California, USA). Part 1: granite pervasive alteration processes away from fracture zones. Geosciences 11, 325. https://doi.org/10.3390/geosciences11080325.
Klötzli, U.S., Koller, F., Scharbert, S., Höck, V., 2001. Cadomian lower-crustal contributions to variscan granite petrogenesis (South Bohemian Pluton, Austria): constraints from zircon typology and geochronology, whole-rock, and feldspar Pb–Sr isotope systematics. J. Petrol. 42, 1621–1642. https://doi.org/10.1093/petrology/42.9.1621.
Klötzli, U.S., Koller, F., Scharbert, S., Höck, V., 2002. Cadomian lower-crustal contributions to variscan granite petrogenesis (South Bohemian Pluton, Austria): a Reply. J. Petrol. 43, 1783–1786.
Korsch, R.J., Huston, D.L., Henderson, R.A., Blewett, R.S., Withnall, I.W., Fergusson, C. L., Collins, W.J., Saygin, E., Kositcin, N., Meixner, A.J., Chopping, R., Henson, P.A., Champion, D.C., Hutton, L.J., Wormald, R., Holzschuh, J., Costelloe, R.D., 2012. Crustal architecture and geodynamics of North Queensland, Australia: insights from deep seismic reflection profiling. Tectonophysics 572–573, 76–99. https://doi.org/10.1016/j.tecto.2012.02.022.
Korzhinskii, D.S., 1962. The role of alkalinity in the formation of charnockitic gneisses., Precambrian geology and petrology: general and regional problems. Trudy Vostochono-Sibirskogo Geol. Inst. 5, 50–61.
Kresten, P., 1988. Granitization - fact or fiction?. In: Geologiska Föreningen i Stockholm Förhandlingar, 110, pp. 335–340. https://doi.org/10.1080/11035898809452668.
Kuhn, T.S., 1970. The Structure of Scientific Revolutions. University of Chicago Press.
Lacroix, A., 1896. Les transformations endomorphiques du magma granitique dans la haute ariege, au contact des calcaires. Comptes Rendus l'Acad. Sci. Fr. 123, 1021–1023.
Lacroix, A., 1898. Le granite des Pyrénées et ses phénomènes de contact. In: Bull. Carte Gdol. France, 64. Librairie polytechnique.
Lacroix, A., 1933. In: Nancy, Berger-Levrault (Ed.), Classification des roches éruptives.
Lajtai, E.Z., 1998. Microscopic fracture processes in a granite. Rock Mech. Rock. Eng. 31, 237–250. https://doi.org/10.1007/s006030050023.
Lameyre, J., 1980. Les magmas granitiques: leurs comportements, leurs associations et leurs sources.
Lameyre, J., Bowden, P., 1982. Plutonic rock types series: discrimination of various granitoid series and related rocks. J. Volcanol. Geotherm. Res. 14, 169–186. https://doi.org/10.1016/0377-0273(82)90047-6.
Landes, K.K., Amoruso, J.J., Charlesworth Jr., L.J., Heany, F., Lesperance, P.J., 1960. Petroleum resources in basement rocks. AAPG Bull. 44, 1682–1691.
Lane, A.C., 1931. Size of batholiths. GSA Bull. 42, 813–824. https://doi.org/10.1130/GSAB-42-813.
Langer, W.H., 2001. Construction materials: Dimension stone. In: Buschow, K.H.J., Cahn, R.W., Flemings, M.C., Ilschner, B., Kramer, E.J., Mahajan, S., Veyssière, P. (Eds.), Encyclopedia of Materials: Science and Technology. Elsevier, Oxford, pp. 1546–1550. https://doi.org/10.1016/B0-08-043152-6/00276-X.
Laporte, D., 1994. Wetting behavior of partial melts during crustal anatexis: the distribution of hydrous silicic melts in polycrystalline aggregates of quartz. Contrib. Mineral. Petrol. 116, 486–499. https://doi.org/10.1007/BF00310914.
Le Bas, M.J., Streckeisen, A.L., 1991. The IUGS systematics of igneous rocks. J. Geol. Soc. Lond. 148, 825–833. https://doi.org/10.1144/gsjgs.148.5.0825.
Classification and nomenclature. In: Le Maitre, R.W., Streckeisen, A., Zanettin, B., Le Bas, M.J., Bonin, B., Bateman, P. (Eds.), 2002. Igneous Rocks. Cambridge University Press, Cambridge, pp. 3–42. https://doi.org/10.1017/CBO9780511535581.006.
Leddra, M., 2010. Time Matters: Geology's Legacy to Scientific Thought. John Wiley & Sons.
Lehmann, J.G., 1756. Versuch einer Geschichte von Flötz-Gebürgen: betreffend deren Entstehung, Lage, darinne befindliche Metallen. In: Mineralien und Foßilien, gröstentheils Aus Eigenen Wahrnehmungen, Chymischen und Physicalischen Versuchen, und Aus Denen Grundsätzen der Natur-Lehre Hergeleitet, und Mit nöthigen Kupfern Versehen. Klüter.
Lehmann, B., 2021. Formation of tin ore deposits: A reassessment. In: Lithos, 9th Hutton Symposium on the Origin of Granites and Related Rocks, 402–403, p. 105756. https://doi.org/10.1016/j.lithos.2020.105756.
Lehnert, K., Su, Y., Langmuir, C.H., Sarbas, B., Nohl, U., 2000. A global geochemical database structure for rocks. Geochem. Geophys. Geosyst. 1. https://doi.org/10.1029/1999GC000026.
Leitch, A.M., Weinberg, R.F., 2002. Modelling granite migration by mesoscale pervasive flow. Earth Planet. Sci. Lett. 200, 131–146. https://doi.org/10.1016/S0012-821X(02)00596-4.
Lesson, R.P., Duperrey, L.-I., 1830. Voyage autour du monde: Exécuté par Ordre du Roi, Sur la Corvette de Sa Majesté, La Coquille, pendant les années 1822, 1823, 1824 et 1825, sous le ministère et conformént aux instructions de S. E. M. le Marquis de Clermont-Tonnerre, ministre de la marine; et publié sous les auspices de son excellence Mgr le Cte de Chabrol, ministre de la marine et des colonies. Zoologie / par M. Lesson. Tome 2e, 1re Partie. Bertrand.
Levinson-Lessing, F.Y., 1893a. Petrographisches Lexicon. Part I. Unknown.
Levinson-Lessing, F.Y., 1893b. Tablitzy dlya Mikroskopicheskikh Opredeleni Porodoobraznykh Mineralov. Unknown - Available under request.
Levinson-Lessing, F.Y., 1895. Petrographisches Lexicon. Part II. Unknown.
Lewis, C.L.E., 2021. Two for the price of one: Doris Livesey Reynolds (1899–1985). Geol. Soc. Lond. Spec. Publ. 506, 187–200. https://doi.org/10.1144/SP506-2019-162.
Li, X.-Y., Gao, J.-F., Zhang, R.-Q., Lu, J.-J., Chen, W.-H., Wu, J.-W., 2018. Origin of the Muguayuan veinlet-disseminated tungsten deposit, South China: constraints from in-situ trace element analyses of scheelite. Ore Geol. Rev. 99, 180–194. https://doi.org/10.1016/j.oregeorev.2018.06.005.
Liesa, M., Aguilar, C., Castro, A., Gisbert, G., Reche, J., Muñoz, J.A., Vilà, M., 2021. The role of mantle and crust in the generation of calc-alkaline Variscan magmatism and its tectonic setting in the Eastern Pyrenees. Lithos 406–407, 106541. https://doi.org/10.1016/j.lithos.2021.106541.
Little, T.A., Hacker, B.R., Gordon, S.M., Baldwin, S.L., Fitzgerald, P.G., Ellis, S., Korchinski, M., 2011. Diapiric exhumation of Earth's youngest (UHP) eclogites in the gneiss domes of the D'Entrecasteaux Islands, Papua New Guinea. Tectonophysics 510, 39–68. https://doi.org/10.1016/j.tecto.2011.06.006.
Liu, H., Wang, H., Lei, H., Zhang, L., Bai, M., Zhou, L., 2020. Numerical modeling of thermal breakthrough induced by geothermal production in fractured granite. J. Rock Mech. Geotech. Eng. 12, 900–916. https://doi.org/10.1016/j.jrmge.2020.01.002.
Llorens, M.-G., Bons, P.D., Griera, A., Gomez-Rivas, E., 2013. When do folds unfold during progressive shear? Geology 41, 563–566. https://doi.org/10.1130/G33973.1.
Lœwinson-Lessing, F., 1911. The fundamental problems of petrogenesis, or the origin of the igneous rocks. Geol. Mag. 8, 248–257. https://doi.org/10.1017/S0016756800111161.
Loiselle, M.C., Wones, D.R., 1979. Characteristics and origin of anorogenic granites. Geol. Soc. Am. Abstr. Programs 11, 468.
Lunn, F., Brooke, H.J., Philips, J., Daubeny, C.G.B., 1835. Encyclopaedia of Chemistry, Mineralogy and Geology. R. Griffin & Co, London.
Lyell, C., 1830. Principles of Geology, Being an Attempt to Explain the Former Changes of the Earth's Surface, by Reference to Causes Now in Operation, vol. 1. John Murray, London.
Lyell, C., 1832. Principles of Geology, Being an Attempt to Explain the Former Changes of the Earth's Surface, by Reference to Causes Now in Operation, vol. 2. John Murray, London.
Lyell, C., 1833. Principles of Geology, Being an Attempt to Explain the Former Changes of the Earth's Surface, by Reference to Causes Now in Operation, vol. 3. John Murray, London.
Lyell, C., 1838. Elements of Geology. John Murray. ed, London.
Lyell, C., 1841. Notes on the Silurian Strata in the neighbourhood of Christiania in Norway. Read 30 June 1841. Proc. Geol. Soc. Lond. 3 (80), 465–467. Part II.
Lyell, C., 1849. A Second Visit to the United States of North America. Harper & Brothers.
Lyell, C., 1853. A Manual of Elementary Geology: Or, The Ancient Changes of the Earth and its Inhabitants as Illustrated by Geological Monuments. D. Appleton.
Lyell, C., 1857. Principles of Geology, second American edition. D. Appleton & Company.
Lyell, C., 1881. Life, Letters and Journals of Sir Charles Lyell, Bart. J. Murray.
Maaløe, S., 1987. The generation and shape of feeder dykes from mantle sources. Contrib. Mineral. Petrol. 96, 47–55. https://doi.org/10.1007/BF00375524.
Maaløe, S., Wyllie, P.J., 1975. Water content of a granite magma deduced from the sequence of crystallization determined experimentally with water-undersaturated conditions. Contrib. Mineral. Petrol. 52, 175–191. https://doi.org/10.1007/BF00457293.
Mackintosh, D., 1868. On a striking instance of apparent oblique lamination in granite. Q. J. Geol. Soc. 24, 278–279. https://doi.org/10.1144/GSL.JGS.1868.024.01-02.32.
Mair, J.A., Green, A.G., 1981. High-resolution seismic reflection profiles reveal fracture zones within a 'homogeneous' granite batholith. Nature 294, 439–442. https://doi.org/10.1038/294439a0.
Mamtani, M.A., Renjith, A.R., 2015. Using EBSD data to analyze effect of heat supplied by granite on CPO of quartz in deformed quartzite. J. Geol. Soc. India 86, 5–8. https://doi.org/10.1007/s12594-015-0275-7.
Maniar, P.D., Piccoli, P.M., 1989. Tectonic discrimination of granitoids. GSA Bull. 101, 635–643. https://doi.org/10.1130/0016-7606(1989)101<0635:TDOG>2.3.CO;2.
Marcou, J., 1853. A Geological Map of the United States, and the British Provinces of North America: With an Explanatory Text, Geological Sections, and Plates of the Fossils which Characterize the Formations. Gould and Lincoln.
Marcou, J., 1861. Carte géologique de la Terre. Construit Par J. M. Ziegler échelle 1: 23,000,000. J. Wurster, Winterthur.
Maré, L.P., Thomas, R.J., 1997. Palaeomagnetism and aeromagnetic modelling of the Mesoproterozoic Ntimbankulu pluton, Kwazulu-Natal, South Africa: mushroom-shaped diapir? J. Afr. Earth Sci. 25, 519–537. https://doi.org/10.1016/S0899-5362(97)00107-3.
Marmo, V., 1967a. On the granite problem. Earth Sci. Rev. 3, 7–29. https://doi.org/10.1016/0012-8252(67)90369-8.
Marmo, V., 1967b. On Granites: A Revised Study. Geologinen tutkimuslaitos.
Marsh, B.D., 1982. On the mechanics of igneous diapirism, stoping, and zone melting. Am. J. Sci. 282, 808–855. https://doi.org/10.2475/ajs.282.6.808.
Marsh, B.D., 1984. Mechanics and energetics of magma formation and ascension. In: Boyd Jr., F.R. (Ed.), Studies in Geophysics. Natl. Acad. Press, Washington, DC, pp. 67–83.
Marsh, B.D., 2007. Magmatism, Magma, and Magma Chambers, Crust and Lithosphere Dynamics. https://doi.org/10.1016/B978-044452748-6.00106-1.
Marsili, L.F., 1717. Map of the Sulphur Mines in the Meldola, Cesena, and Sarsina districts. To be Included in "Treatise on the Structure of the Earthy Globe" [Unfinished, unpublished].
Martin, R.F., 2006. A-type granites of crustal origin ultimately result from open-system fenitization-type reactions in an extensional environment. Lithos 91, 125–136. https://doi.org/10.1016/j.lithos.2006.03.012.
Marzari-Pencati, G., 1806. Corsa Pel Bacino del Rodano e per la LIguria d'Occidente. Paroni.
Marzari-Pencati, G., 1820. Cenni geologici e litologici sulle provincie venete e sul Tirolo, cui seguì un complemento (Notizie sopra un granito in massa sovrapposto [sul fiume Avisio]), in giacimento discordante, al calcare secondario. Suppl. al Nuovo Osservatore Veneziano 118 e, 127, pp. 1–6.
Masson, F., 1776. Mr Masson's Botanical Travels. An account of three journeys from the Cape into the interior parts of Africa. Philos.Trans. R. Soc. Lond. 66 (1), 268–317.

Massonne, H.-J., 2015. Derivation of P–T paths from high-pressure metagranites — Examples from the Gran Paradiso Massif, western Alps. Lithos 226, 265–279. https://doi.org/10.1016/j.lithos.2014.12.024.

Massonne, H.-J., Fockenberg, T., 2022. Melting of phengite-bearing eclogite at pressures of 4 and 9 GPa relevant to deep regions of a subduction zone. Earth Planet. Sci. Lett. 584, 117475. https://doi.org/10.1016/j.epsl.2022.117475.

Master, S., 2009. Plutonism versus Neptunism at the southern tip of Africa: the debate on the origin of granites at the Cape, 1776–1844. Earth Environ. Sci. Trans. R. Soc. Edinb. 100, 1–13. https://doi.org/10.1017/S1755691009016193.

Master, S., 2012. Darwin as a geologist in Africa - dispelling the myths and unravelling a confused knot. S. Afr. J. Sci. 108, 1–5.

Mathews, E.B., 1900. The granitic rocks of the Pikes Peak Quadrangle. J. Geol. 8, 214–240.

Mayer, W., 2009. The geological work of the Baudin expedition in Australia (1801–1803): the mineralogists, the discoveries and the legacy. Earth Sci. Hist. 28, 293–324. https://doi.org/10.17704/eshi.28.2.mr134w5l2507053n.

Mayne, M.J., Moyen, J.-F., Stevens, G., Kaislaniemi, L., 2016. Rcrust: a tool for calculating path-dependent open system processes and application to melt loss. J. Metamorph. Geol. 34, 663–682. https://doi.org/10.1111/jmg.12199.

Mccarthy, G.J., White, W.B., Roy, R., Scheetz, B.E., Komarneni, S., Smith, D.K., Roy, D. M., 1978. Interactions between nuclear waste and surrounding rock. Nature 273, 216–217. https://doi.org/10.1038/273216a0.

McCormick, C., 1886. The inclusions in the granite of craftsbury, VT. Proc. Acad. Natl. Sci. Phila. 38, 19–24.

McCulloch, M.T., Chappell, B.W., 1982. Nd isotopic characteristics of S- and I-type granites. Earth Planet. Sci. Lett. 58, 51–64. https://doi.org/10.1016/0012-821X(82)90102-9.

McKenzie, D., 1989. Some remarks on the movement of small melt fractions in the mantle. Earth Planet. Sci. Lett. 95, 53–72. https://doi.org/10.1016/0012-821X(89)90167-2.

McKenzie, D.P., Parker, R.L., 1967. The North Pacific: an example of tectonics on a sphere. Nature 216, 1276–1280. https://doi.org/10.1038/2161276a0.

McMahon, C.A., 1887. III.—The Gneissose-Granite of the Himalayas. Geol. Mag. 4, 212–220. https://doi.org/10.1017/S0016756800196530.

Meixner, A.J., Kirkby, A.L., Horspool, N., 2014. Using constrained gravity inversions to identify high-heat-producing granites beneath thick sedimentary cover in the Cooper Basin region of Central Australia. Geothermics 51, 483–495. https://doi.org/10.1016/j.geothermics.2013.10.010.

Menand, T., 2011. Physical controls and depth of emplacement of igneous bodies: a review. Tectonophysics 500, 11–19. https://doi.org/10.1016/j.tecto.2009.10.016.

Metz, B., Davidson, O., de Coninck, H.C., Loos, M., Meyer, L.. IPCC Special Report on Carbon Dioxide Capture and Storage. https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf.

Michel-Lévy, A., 1878a. Note sar l'association pegmatoïde de l'amphibole et du feldspath dans les amphibolites de Marmagne, près Aston. Bull. Mineral. 1, 41–42. https://doi.org/10.3406/bulmi.1878.2830.

Michel-Lévy, A., 1878b. Sur une roche à sphène, amphibole et wernérite granulitique des mines d'apatite de Bamble, près Brevig (Norwège). Bull. Mineral. 1, 43–46. https://doi.org/10.3406/bulmi.1878.1408.

Michel-Lévy, A., 1888. Études sur les schistes cristallins. Harrison and sons, printers.

Michel-Lévy, A., 1889. Structures et classification des roches éruptives. Librairie Polytechnique, Baudry et cie., éditeurs.

Michel-Lévy, A., 1893. Contribution à l'étude du Granite de Flamanville et Des Granites français en général. Baudry, Paris, France.

Middlemost, E.A.K., 1994. Naming materials in the magma/igneous rock system. Earth Sci. Rev. 37, 215–224. https://doi.org/10.1016/0012-8252(94)90029-9.

Milani, L., Lehmann, J., Bybee, G.M., Hayes, B., Owen-Smith, T.M., Oosthuizen, L., Delport, P.W.J., Ueckermann, H., 2022. Geochemical and geochronological constraints on the Mesoproterozoic Red Granite Suite, Kunene AMCG Complex of Angola and Namibia. Precambrian Res. 379, 106821. https://doi.org/10.1016/j.precamres.2022.106821.

Miller, C.F., Watson, E.B., Harrison, T.M., 1988. Perspectives on the source, segregation and transport of granitoid magmas. Earth Environ. Sci. Trans. R. Soc. Edinb. 79, 135–156. https://doi.org/10.1017/S0263593300014176.

Misch, P., 1949. Metasomatic granitization of batholithic dimensions; Part II, Static granitization in Sheku area, Northwest Yunnan (China). Am. J. Sci. 247, 372–406. https://doi.org/10.2475/ajs.247.6.372.

Mo, J., Xia, X.-P., Li, P.-F., Spencer, C.J., Lai, C.-K., Xu, J., Yang, Q., Sun, M.-D., Yu, Y., Milan, L., 2023. Water-in-zircon: a discriminant between S- and I-type granitoid. Contrib. Mineral. Petrol. 178, 5. https://doi.org/10.1007/s00410-022-01986-7.

Moro, A.L., 1740a. De'crostacei e degli altri marini corpi che si truovano su'monti. Appresso Stefano Monti.

Moro, A.L., 1740b. De' Crostacei: E Degli Altri Marini Corpi Che Si Truovano Su' Monti; Libri Due. Appresso Stefano Monti.

Mortimer, N., Davey, F.J., Melhuish, A., Yu, J., Godfrey, N.J., 2002. Geological interpretation of a deep seismic reflection profile across the Eastern Province and Median Batholith, New Zealand: Crustal architecture of an extended Phanerozoic convergent orogen. N. Z. J. Geol. Geophys. 45, 349–363. https://doi.org/10.1080/00288306.2002.9514978.

Moyen, J.-F., Nédélec, A., Martin, H., Jayananda, M., 2003. Syntectonic granite emplacement at different structural levels: the Closepet granite, South India. J. Struct. Geol. 25, 611–631. https://doi.org/10.1016/S0191-8141(02)00046-9.

Moyen, J.-F., Laurent, O., Chelle-Michou, C., Couzinié, S., Vanderhaeghe, O., Zeh, A., Villaros, A., Gardien, V., 2017. Collision vs. subduction-related magmatism: two contrasting ways of granite formation and implications for crustal growth. Lithos 277, 154–177. https://doi.org/10.1016/j.lithos.2016.09.018.

Mukhopadhyay, M., Saibi, H., Elawadi, E., Al-Arifi, N., 2021. Pulsed emplacement under the Uyaijah granite ring structure, eastern Saudi Arabia—results from 3D gravity-magnetic inversion. Arab. J. Geosci. 14, 2199. https://doi.org/10.1007/s12517-021-08647-2.

Muñoz, J.A., 1992. Evolution of a continental collision belt: ECORS-Pyrenees crustal balanced cross-section. In: McClay, K.R. (Ed.), Thrust Tectonics. Springer, Netherlands, Dordrecht, pp. 235–246. https://doi.org/10.1007/978-94-011-3066-0_21.

Nachit, H., Razafimahefa, N., Stussi, J.-M., Carron, J.-P., 1985. Composition chimique des biotites et typologie magmatique des granitoides. C. R. Acad. Sci. 301, 813–818.

Newbold, C., 1850. Summary of the geology of Southern India (Concluded from Vol. ix., p. 42). J. R. Asiat. Soc. G. B. Irel. 12, 78–96.

Nicholas, F.W., Nicholas, J., 2008. Charles Darwin in Australia. Cambridge University Press.

Okrusch, M., Frimmel, H.E., 2020. Metamorphic Facies and Facies Series. In: Okrusch, M., Frimmel, H.E. (Eds.), Mineralogy: An Introduction to Minerals, Rocks, and Mineral Deposits, Springer Textbooks in Earth Sciences, Geography and Environment. Springer, Berlin, Heidelberg, pp. 529–546. https://doi.org/10.1007/978-3-662-57316-7_28.

Oldroyd, D., 2014. A priori and a posteriori geological mapping. The geological maps of the world by Ami Boué (1843) and Jules Marcou (1861)—the Australasian aspects. Earth Sci. Hist. 33, 227–258. https://doi.org/10.17704/eshi.33.2.405041267083m00q.

Olhoeft, G.R., 1981. Electrical properties of granite with implications for the lower crust. J. Geophys. Res. Solid Earth 86, 931–936. https://doi.org/10.1029/JB086iB02p00931.

Orbigny, A.D., 1834. Voyage Dans l'Amérique méridionale, Paris : Chez P. Bertrand, éditeur, Libraire de la Société géologique de France, Rue Saint-André-Des-Arcs, 38, 33. ed. Chez V.e Levrault, des Juifs, Strasbourg.

Oreskes, N., 1999. The Rejection of Continental Drift : Theory and Method in American Earth Science. Oxford University Press, New York.

Ormerod, G.W., 1869. On some of the Results arising from the Bedding, Joints, and Spheroidal Structure of the Granite on the Eastern Side of Dartmoor, Devonshire*. Q. J. Geol. Soc. 25, 273–280. https://doi.org/10.1144/GSL.JGS.1869.025.01-02.48.

Orsini, J., 1976. Les granitoides hercyniens corso-sardes; mise en evidence de deux associations magmatiques. Bull. Soc. Géol. France 7, 1203–1206.

Orsini, J.B., 1979. Existence de trois associations magmatiques dans les granitoïdes post-viséen moyen (groupe des granodiorites-monzogranites) de la chaîne varisque française. CR Acad. Sci. Paris 289, 981–984.

Palassou, P.B., 1823. Nouveaux mémoires pour servir à l'histoire naturelle des Pyrénées et des pays adjacents.

Palin, R.M., Santosh, M., Cao, W., Li, S.-S., Hernández-Uribe, D., Parsons, A., 2020. Secular change and the onset of plate tectonics on Earth. Earth Sci. Rev. 207, 103172. https://doi.org/10.1016/j.earscirev.2020.103172.

Pallas, P.S., 1777. Reise durch verschiedene Provinzen des Russischen Reichs in einem ausführlichen Auszuge. J. G. Fleischer.

Pallas, P.S., 1812. Travels through the Southern Provinces of the Russian Empire, in the Years 1793 and 1794. John Stockdale, Piccadilly.

Parisio, F., Tarokh, A., Makhnenko, R., Naumov, D., Miao, X.-Y., Kolditz, O., Nagel, T., 2019. Experimental characterization and numerical modelling of fracture processes in granite. Int. J. Solids Struct. 163, 102–116. https://doi.org/10.1016/j.ijsolstr.2018.12.019.

Parker, R., 1973. Contributions of Peter Pallas to Science and Exploration in Russia. Dissertations and Theses. https://doi.org/10.15760/etd.1698.

Paterson, S.R., Miller, R.B., 1998a. Stoped blocks in plutons: paleo-plumb bobs, viscometers, or chronometers? J. Struct. Geol. 20 (9–10), 1261–1272. https://doi.org/10.1016/S0191-8141(98)00066-2.

Paterson, S.R., Miller, R.B., 1998b. Magma emplacement during arc-perpendicular shortening: an example from the Cascades crystalline core, Washington. Tectonics 17 (4), 571–586. https://doi.org/10.1029/98TC01604.

Paterson, S.R., Vernon, R.H., Tobisch, O.T., 1989. A review of criteria for the identification of magmatic and tectonic foliations in granitoids. J. Struct. Geol. 11, 349–363. https://doi.org/10.1016/0191-8141(89)90074-6.

Paterson, S.R., Pignotta, G.S., Farris, D., Memeti, V., Miller, R.B., Vernon, R.H., Žák, J., 2008. Is stoping a volumetrically significant pluton emplacement process? Discuss. Geol. Soc. Am. Bull. 120 (7–8), 1075–1079. https://doi.org/10.1130/B26148.1.

Patrin, M., 1791. Notice Minéralogique de la Daourie. Observations sur la physique, sur l'histoire naturelle et sur les arts. J. Phys. Tome XXXVIII Part. I, 225–245.

Pearce, J.A., Harris, N.B.W., Tindle, A.G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. J. Petrol. 25, 956–983. https://doi.org/10.1093/petrology/25.4.956.

Peng, T., Fan, W., Zhao, G., Peng, B., Xia, X., Mao, Y., 2015. Petrogenesis of the early Paleozoic strongly peraluminous granites in the Western South China Block and its tectonic implications. J. Asian Earth Sci. 98, 399–420. https://doi.org/10.1016/j.jseaes.2014.11.022.

Péron, F., de Freycinet, L.C.D., Lesueur, C.A., Petit, N.M., 1807. Voyage de découvertes aux terres australes, exécuté par ordre de Sa Majesté l'empereur et roi, sur les corvettes le Géographe, le Naturaliste, et la goëlette le Casuarina, pendant les années 1800, 1801, 1802, 1803 et 1804 .... [Historique.] publié par decret impérial, sous le ministère de M. de Champagny et Rédigé ... par M. F. Péron [et continué par M. Louis Freycinet]. [-Atlas par MM. Lesueur et Petit.]. De l'Imprimerie impériale.

Peternell, M., Hasalová, P., Wilson, C.J.L., Piazolo, S., Schulmann, K., 2010. Evaluating quartz crystallographic preferred orientations and the role of deformation partitioning using EBSD and fabric analyser techniques. J. Struct. Geol. 32, 803–817. https://doi.org/10.1016/j.jsg.2010.05.007.

Petford, N., 1995. Segregation of tonalitic-trondhjemitic melts in the continental crust: the mantle connection. J. Geophys. Res. Solid Earth 100, 15735–15743. https://doi.org/10.1029/94JB03259.

Petford, N., 1996. Dykes or diapirs? Earth Environ. Sci. Trans. R. Soc. Edinb. 87, 105–114. https://doi.org/10.1017/S0263593300006520.

Petford, N., Clemens, J.D., 2000. Granites are not diapiric! Geol. Today 16, 180–184. https://doi.org/10.1111/j.1365-2451.2000.00008.x.

Petford, N., Clemens, J.D., Vigneresse, J.-L., 1997. Application of information theory to the formation of granitic rocks. In: Bouchez, J.L., Hutton, D.H.W., Stephens, W.E. (Eds.), Granite: From Segregation of Melt to Emplacement Fabrics, Petrology and Structural Geology. Springer, Netherlands, Dordrecht, pp. 3–10. https://doi.org/10.1007/978-94-017-1717-5_1.

Petford, N., Cruden, A.R., McCaffrey, K.J.W., Vigneresse, J.-L., 2000. Granite magma formation, transport and emplacement in the Earth's crust. Nature 408, 669–673. https://doi.org/10.1038/35047000.

Phillips, J., 1849. XXXV. Thoughts on ancient metallurgy and mining in Brigantia and other parts of Britain, suggested by a page of Pliny's Natural history. Lond. Edinburgh Dublin Philos. Mag. J. Sci. 34, 247–260. https://doi.org/10.1080/14786444908646226.

Phillips, J.A., 1871. XIV. On the chemical composition and microscopic constitution of certain Cornish rocks. Lond. Edinburgh Dublin Philos. Mag. J. Sci. 41, 87–107. https://doi.org/10.1080/14786447108640451.

Phillips, J.A., 1873. II. On the composition and origin of the waters of a salt spring in Huel Seton mine, with a chemical and microscopical examination of certain rocks in its vicinity. Lond. Edinburgh Dublin Philos. Mag. J. Sci. 46, 26–36. https://doi.org/10.1080/14786447308640895.

Phillips, J.A., 1880. On concretionary patches and fragments of other rocks contained in granite*. Q. J. Geol. Soc. 36, 1–22. https://doi.org/10.1144/GSL.JGS.1880.036.01-04.03.

Phillips, J.A., 1882. Additional note on certain inclusions in granites. Q. J. Geol. Soc. 38, 216–217. https://doi.org/10.1144/GSL.JGS.1882.038.01-04.24.

Pickering, J.M., Johnston, D.A., 1998. Fluid-absent melting behavior of a two-mica metapelite: experimental constraints on the origin of black hills granite. J. Petrol. 39, 1787–1804. https://doi.org/10.1093/petroj/39.10.1787.

Pignotta, G.S., Paterson, S.R., 2007. Voluminous stoping in the Mitchell Peak granodiorite, Sierra Nevada batholith, California, USA. Can. Mineral. 45, 87–106. https://doi.org/10.2113/gscanmin.45.1.87.

Pissis, A., 1850. Descripcion jeolójica de la República de Chile. Facultades de Medicina i de Ciencias Físicas i Matemáticas.

Pitcher, W.S., 1952. The migmatitic Older Granodiorite of Thorr district, Co. Donegal. Q. J. Geol. Soc. 108, 413–446. https://doi.org/10.1144/GSL.JGS.1952.108.01-04.18.

Pitcher, W.S., 1983. Granite type and tectonic environment. In: Symposium on Mountain Building. Academic Press, London. Pp. 19–40. 19–40.

Pitcher, W.S., 1987. Granites and yet more granites forty years on. Geol. Rundsch. 76, 51–79. https://doi.org/10.1007/BF01820573.

Pitcher, W.S., 1997a. The Nature and Origin of Granite. Springer Science & Business Media.

Pitcher, Wallace Spencer, 1997b. The Historical Perspective: an Ever Changing Emphasis. The Nature and Origin of Granite. Springer, Netherlands, Dordrecht, pp. 1–18. https://doi.org/10.1007/978-94-011-5832-9_1.

Pitcher, W.S., Read, H.H., Cheesman, R.L., Pande, I.C., Tozer, C.F., 1958. The main donegal granite. Q. J. Geol. Soc. 114, 259–300. https://doi.org/10.1144/gsjgs.114.1.0259.

Piwowar, H.A., Day, R.S., Fridsma, D.B., 2007. Sharing detailed research data is associated with increased citation rate. PLoS One 2, e308. https://doi.org/10.1371/journal.pone.0000308.

Playfair, J., 1802. Illustrations of the Huttonian Theory of the Earth. Cadell and Davies,1802, UK.

Playfair, J., Hall, B., 1813. Account of the structure of Table Mountain and other parts of the peninsula of the Cape; drawn up by Prof. Playfair, from the observations made by Capt. Basil Hall, R.N.F.R.S. Edin. Trans R Soc Edinb. 7, 269–278.

Pokrovski, G.S., Akinfiev, N.N., Borisova, A.Y., Zotov, A.V., Kouzmanov, K., 2014. Gold speciation and transport in geological fluids: Insights from experiments and physical-chemical modelling. In: Garofalo, P.S., Ridley, J.R. (Eds.), Gold-Transporting Hydrothermal Fluids in the Earth's Crust. Geological Society of London, p. 0. https://doi.org/10.1144/SP402.4.

Porter, R., 1976. Charles Lyell and the principles of the history of geology. Br. J. Hist. Sci. 9, 91–103. https://doi.org/10.1017/S0007087400014692.

Pupin, J.P., 1980. Zircon and granite petrology. Contrib. Mineral. Petrol. 73, 207–220. https://doi.org/10.1007/BF00381441.

Pupin, J.P., 1985. Magmatic zoning of Hercynian granitoids in France based on zircon typology. Schweiz. Mineral. Petrogr. Mitt. 65, 29–56.

Raisin, C.A., 1893. II.—Contributions to the geology of Africa. Geol. Mag. 10, 436–443. https://doi.org/10.1017/S0016756800174084.

Ramberg, H., 1972. Mantle diapirism and its tectonic and magmagenetic consequences. Phys. Earth Planet. Inter. 5, 45–60. https://doi.org/10.1016/0031-9201(72)90073-8.

Ramond, L.-F., 1801. Voyages Au Mont-Perdu et Dans la Partie Adjacente Des Hautes-Pyrénées. Belin.

Ramsay, A.C., 1841. The Geology of the Island of Arran: From Original Survey. R. Griffin.

Rapprich, V., Valenta, J., Brož, M., Kadlecová, E., van Wyk de Vries, B., Petronis, M.S., Rojík, P., 2019. A crucial site in the argument between Neptunists and Plutonists: reopening of the historical adit in the Komorní hůrka (Kammerbühl) volcano after 180 years. Geoheritage 11, 347–358. https://doi.org/10.1007/s12371-018-0286-z.

Rasilainen, K., Lahtinen, R., Bornhorst, T., 2007. The Rock Geochemical Database of Finland Manual, Report of Investigation 164. ed, Geological Survey of Finland: Report of Investigation. Geological Survey of Finland.

Read, H.H., 1925. The Geology of the Country around Golspie, Sutherlandshire (Strath Fleet, Strath Brora, & Glen Loth): Including a Description of the Mesozoic Rocks of East Sutherland & Ross (Helmsdale, Brora, Golspie, Shandwick, and Ethie): (Explanation of Sheets 103). H.M. Stationery Office.

Read, H.H., 1939. Metamorphism and igneous action*. Nature 144, 729–731. https://doi.org/10.1038/144729a0.

Read, H.H., 1948. Granites and Granites. Origin of Granite. Geological Society of America, pp. 1–19.

Read, H.H., 1957. The Granite Controversy. Thomas murby.

Reade, T.M., 1889. XXVI. A consideration of the effects of contraction during the cooling of intrusive masses of granite and the cause of their solid continuity. Lond. Edinburgh Dublin Philos. Mag. J. Sci. 27, 233–237. https://doi.org/10.1080/14786448908628343.

Reiners, P.W., Brandon, M.T., 2006. Using thermochronology to understand orogenic erosion. Annu. Rev. Earth Planet. Sci. 34, 419–466. https://doi.org/10.1146/annurev.earth.34.031405.125202.

Reynolds, D.L., 1943. The South-Western end of the Newry Igneous complex. A contribution towards the petrogenesis of the granodiorites. Q. J. Geol. Soc. 99, 205–246. https://doi.org/10.1144/GSL.JGS.1943.099.01-04.13.

Reynolds, D.I., 1947. On the relationship between "fronts" of regional metamorphism and "fronts" of granitization. Geol. Mag. 84, 106–109.

Reynolds, D.L., 1958. Granite: some tectonic, petrological, and physico-chemical aspects. Geol. Mag. 95, 378–396. https://doi.org/10.1017/S0016756800062956.

Ribeiro, B.V., Lagoeiro, L., Faleiros, F.M., Hunter, N.J.R., Queiroga, G., Raveggi, M., Cawood, P.A., Finch, M., Campanha, G.A.C., 2020. Strain localization and fluid-assisted deformation in apatite and its influence on trace elements and U–Pb systematics. Earth Planet. Sci. Lett. 545, 116421. https://doi.org/10.1016/j.epsl.2020.116421.

Ringwood, A.E., 1974. The petrological evolution of island arc systems: twenty-seventh William Smith Lecture. J. Geol. Soc. Lond. 130, 183–204. https://doi.org/10.1144/gsjgs.130.3.0183.

Romano, M., Cifelli, R.L., Vai, G.B., 2016. The first geological map: an Italian legacy. Ital. J. Geosci. 135. https://doi.org/10.3301/IJG.2015.23.

Rosen, B.R., 1982. Darwin, coral reefs, and global geology. BioScience 32, 519–525. https://doi.org/10.2307/1308903.

Rosenberg, C.L., Handy, M.R., 2005. Experimental deformation of partially melted granite revisited: implications for the continental crust. J. Metamorph. Geol. 23, 19–28. https://doi.org/10.1111/j.1525-1314.2005.00555.x.

Rosenbusch, H., 1873. Mikroskopische Physiographie der Mineralien und Gesteine: ein Hülfsbuch bei mikroskopischen Gesteinsstudien. Schweizerbart.

Rosenbusch, H., 1877a. Mikroskopische Physiographie der Massigen Gesteine. E. Schweizerbart'sche Verlagshandlung.

Rosenbusch, H., 1877b. Die Steiger Schiefer und ihre Kontaktzone an den Granititen von Barr-Andlau und Hohwald. Abh. Geol. Spez. E. L. 1877, B. 1, 2.

Rosenbusch, H., 1896. Mikroskopische Physiographie der Mineralien und Gesteine: Massige Gesteine. E. Schweizerbart'sche Verlagshandlung.

Rosenbusch, H., 1910. Elemente der gesteinslehre. E. Schweizerbart'sche-verlagsbuchhandlung.

Rosenbusch, H., Iddings, J.P., 1888. Microscopical physiography of the rock-making minerals. Am. Nat. 22, 1097–1098. https://doi.org/10.1086/274834.

Rossetter, T., 2018. Realism on the rocks: novel success and James Hutton's theory of the earth. Stud. Hist. Philos. Sci. Part A 67, 1–13. https://doi.org/10.1016/j.shpsa.2017.10.005.

Rossi, P., Chevremont, P., 1987. Classification des associations magmatiques granitoïdes. Application à la cartographie des granitoïdes dans le cadre de la carte géologique à 1/50000 de France, pp. 14–18.

Rubin, A.E., Cooper, K.M., Till, C.B., Kent, A.J.R., Costa, F., Bose, M., Gravley, D., Deering, C., Cole, J., 2017. Rapid cooling and cold storage in a silicic magma reservoir recorded in individual crystals. Science 356, 1154–1156. https://doi.org/10.1126/science.aam8720.

Rudwick, M.J.S., 1962. Hutton and Werner compared: George Greenough's Geological Tour of Scotland in 1805. Br. J. Hist. Sci. 1, 117–135.

Rudwick, M.J.S., 1970. The strategy of Lyell's principles of geology. Isis 61, 5–33. https://doi.org/10.1086/350576.

Rudwick, M.J.S., 1998. Lyell and the principles of geology. Geol. Soc. Lond. Spec. Publ. 143, 1–15. https://doi.org/10.1144/GSL.SP.1998.143.01.02.

Rusak, A.A., Shchekina, T.I., Zinovyeva, N.G., Alferyeva, Y.O., Khvostikov, V.A., Gramenitskiy, E.N., Kotelnikov, A.R., 2021. The peculiarities of crystallization of lithium-containing granite melt with high water and fluorine contents in the temperature range of 800–400 °C and pressure of 1 Kbar (according to experimental data). Environ. Sci. Proc. 6, 9. https://doi.org/10.3390/iecms2021-09361.

Rushmer, T., 1996. Melt segregation in the lower crust: how have experiments helped us? Earth Environ. Sci. Trans. R. Soc. Edinb. 87, 73–83. https://doi.org/10.1017/S0263593300006490.

Russo, D., Fiannacca, P., Fazio, E., Cirrincione, R., Mamtani, M.A., 2022. From floor to roof of a batholith: geology and petrography of the north-eastern Serre Batholith (Calabria, southern Italy). J. Maps 0, 1–15. https://doi.org/10.1080/17445647.2022.2149358.

Salih, M.O., Rahman, E.M.A., 2021. Geology, geochemistry, and petrogenesis of Jebal Ruro A-type granite, Blue Nile State, Sudan: implications for origin of HFSE mineralization. Arab. J. Geosci. 14, 958. https://doi.org/10.1007/s12517-021-07283-0.

Sandiford, M., Martin, N., Zhou, S., Fraser, G., 1991. Mechanical consequences of granite emplacement during high-*T*, low-*P* metamorphism and the origin of "anticlockwise"*PT* paths. Earth Planet. Sci. Lett. 107, 164–172. https://doi.org/10.1016/0012-821X(91)90052-J.
Savage, D., Cave, M.R., Milodowski, A.E., George, I., 1987. Hydrothermal alteration of granite by meteoric fluid: an example from the Carnmenellis Granite, United Kingdom. Contrib. Mineral. Petrol. 96, 391–405. https://doi.org/10.1007/BF00371257.
Scheerer, T., 1862. Die Gneuse des Sächsischen Erzgebirges und verwandte Gesteine, nach ihrer chemischen Constitution und geologischen Bedeutung:(Besonderer Abdruck ad Zeitschrift der Deutschen geolog. Gesellschaft. Bd. XIV p. 23.). Starcke.
Schiller, D., Finger, F., 2019. Application of Ti-in-zircon thermometry to granite studies: problems and possible solutions. Contrib. Mineral. Petrol. 174, 51. https://doi.org/10.1007/s00410-019-1585-3.
Schmid, R., Fettes, D., Harte, B., Davis, E., Desmons, J., Meyer-Marsilius, H.-J., Siivola, J., 2004. A systematic nomenclature for metamorphic rocks: How to name a metamorphic rock. In: Recommendations by the IUGS Subcommission on the Systematics of Metamorphic Rocks.
Schoene, B., Bowring, S.A., 2007. Determining accurate temperature–time paths from U–Pb thermochronology: An example from the Kaapvaal craton, southern Africa. Geochim. Cosmochim. Acta 71, 165–185. https://doi.org/10.1016/j.gca.2006.08.029.
Schorn, S., 2022. Self-induced incipient 'eclogitization' of metagranitoids at closed-system conditions. J. Metamorph. Geol. 40, 1271–1290. https://doi.org/10.1111/jmg.12665.
Schwarz, E.J., 1991. Magnetic expressions of intrusions including magnetic aureoles. Tectonophysics 192, 191–200. https://doi.org/10.1016/0040-1951(91)90256-R.
Scott, R.H., 1861. On the granite-rocks of donegal and the minerals associated therewith. Geologist 4, 537. https://doi.org/10.1017/S1359465600003610.
Scrope, G.P., 1825. Considerations on Volcanos, the Probable Causes of their Phenomena, the Laws which Determine their March, the Disposition of their Products, and their Connexion with the Present State and Past History of the Globe: Leading to the Establishment of a New Theory of the Earth. Phillips.
Secchi, F., Naitza, S., Oggiano, G., Cuccuru, S., Puccini, A., Conte, A.M., Giovanardi, T., Mazzucchelli, M., 2021. Geology of late-Variscan Sàrrabus pluton (South-Eastern Sardinia, Italy). J. Maps 17, 591–605. https://doi.org/10.1080/17445647.2021.1982032.
Secord, J.A., 1991. The discovery of a vocation: Darwin's early geology. Br. J. Hist. Sci. 24, 133–157. https://doi.org/10.1017/S0007087400027059.
Seddon, G., 1973. Abraham Gottlob Werner: history and folk-history. J. Geol. Soc. Aust. 20, 381–395. https://doi.org/10.1080/00167617308728824.
Sederholm, J.J., 1891. Studien über archäische Eruptivgesteine aus dem südwestlichen Finnland. Tschermaks Mineral. Petrogr. Mitt. 12, 97–142. https://doi.org/10.1007/BF03010466.
Sederholm, J.J., 1897. Über Eine Archäische Sedimentformation Im Südwestlichen Finland und Ihre Bedeutung Für Die Erklärung Der Entstehungsweise Des Grundgebirges.[With 4 Plates and a Map.].
Sederholm, J.J., 1907. Om granit och gneis: deras uppkomst, uppträdande och utbredning inom urberget i Fennoscandia. Bull. Comm. Géol. Fin. 23, 110p.
Sederholm, J.J., 1911. Om de tekniska egenskaperna hos finska graniter. Geologiska kommissionen 38.
Sederholm, J.J., 1926. On migmatites and associated pre-Cambrian rocks of southwestern Finland. Part II. The region around Barösundsfjärd W of Helsingfors and neighbouring areas. Bull. Comm. Géol. Fin. 77, 143 p.
Sederholm, J.J., 1967. Selected Works: Granites and Migmatites. Oliver and Boyd, Edinburgh. (Includes appreciation by P. Eskola).
Sedova, I.S., Glebovitskii, V.A., Samorukova, L.M., 2013. Geochemical types of granitization. Dokl. Earth Sci. 448, 248–253. https://doi.org/10.1134/S1028334X13020220.
Shand, S.J., 1948. Eruptive rocks: their genesis, composition, classification, and their relation to ore deposits, with a chapter on meteorites. J. Geol. 56, 593. https://doi.org/10.1086/625564.
Shandini, Y., Tadjou, J.M., 2012. Interpreting gravity anomalies in South Cameroon, Central Africa. Earth Sci. Res. J. 16, 5–9.
Shao, S., Ranjith, P.G., Wasantha, P.L.P., Chen, B.K., 2015. Experimental and numerical studies on the mechanical behaviour of Australian Strathbogie granite at high temperatures: an application to geothermal energy. Geothermics 54, 96–108. https://doi.org/10.1016/j.geothermics.2014.11.005.
Sharpe, D., 1852. XX. On the arrangement of the foliation and cleavage of the rocks of the north of Scotland. Philos. Trans. R. Soc. Lond. 142, 445–461. https://doi.org/10.1098/rstl.1852.0021.
Shchekina, T.I., Rusak, A.A., Alferyeva, Ya O., Gramenitskiy, E.N., Kotelnikov, A.R., Zinovieva, N.G., Bychkov, A. Yu, Bychkova, Ya V., Khvostikov, V.A., 2020. REE, Y, Sc, and Li partition between aluminosilicate and aluminofluoride melts, depending on pressure and water content in the model granite system. Geochem. Int. 58, 391–407. https://doi.org/10.1134/S0016702920040102.
Siebel, W., Reitter, E., Wenzel, T., Blaha, U., 2005. Sr isotope systematics of K-feldspars in plutonic rocks revealed by the Rb–Sr microdrilling technique. Chem. Geol. 222, 183–199. https://doi.org/10.1016/j.chemgeo.2005.06.012.
Singh, H.K., Sinha, S.K., Alam, M.A., Chandrasekharam, D., 2020. Tracing the evolution of thermal springs in the Hazaribagh area of Eastern Peninsular India through hydrogeochemical and isotopic analyses. Geothermics 85, 101817. https://doi.org/10.1016/j.geothermics.2020.101817.
Slack, J.F., Beck, F.M., Bradley, D.C., Felch, M.M., Marvinney, R.G., Whittaker, A.T.H., 2022. Potential for critical mineral deposits in Maine, USA. Atl. Geosci. 58, 155–191. https://doi.org/10.4138/atlgeo.2022.007.
Smith, W., 1815. A Delineation of the Strata of England and Wales, with part of Scotland. John Cary. ed, London.
Song, Z.-T., Xu, X.-S., 2022. Petrogenesis of high-maficity S-type granites: Insight from the early Paleozoic Jinxi granite, South China. Lithos 412–413, 106597. https://doi.org/10.1016/j.lithos.2022.106597.
Sonnerat, P., 1782. Voyage aux Indes orientales et a` la Chine, fait par ordre du roi depuis 1774 jusqu'en 1781. 2 volumes. Paris: Sonnerat, Froullé, Nyon, Barrois.
Sorby, H.C., 1858. On the microscopical, structure of crystals, indicating the origin of minerals and rocks. Q. J. Geol. Soc. 14, 453–500. https://doi.org/10.1144/GSL.JGS.1858.014.01-02.44.
Sparrman, A., 1785. A Voyage to the Cape of Good Hope, towards the Antarctic Polar Circle, and Round the World; but Chiefly into the Country of the Hottentots and Caffres, from the Year 1772 to 1776. 2 volumes. White, Cash & Byrne, Dublin.
Stagpoole, V., Caratori Tontini, F., Barretto, J., Davy, B., Edbrooke, S., 2016. Inversion of magnetic and gravity data reveals subsurface igneous bodies in Northland, New Zealand. N. Z. J. Geol. Geophys. 59, 416–425. https://doi.org/10.1080/00288306.2016.1162178.
Stall, S., Yarmey, L., Cutcher-Gershenfeld, J., Hanson, B., Lehnert, K., Nosek, B., Parsons, M., Robinson, E., Wyborn, L., 2019. Make scientific data FAIR. Nature 570, 27–29. https://doi.org/10.1038/d41586-019-01720-7.
Stipp, M., Stünitz, H., Heilbronner, R., Schmid, S.M., 2002. Dynamic recrystallization of quartz: correlation between natural and experimental conditions. Geol. Soc. Lond. Spec. Publ. 200, 171–190. https://doi.org/10.1144/GSL.SP.2001.200.01.11.
Stone, P., 2020. Robert Jameson's transition from Neptunism to Plutonism as reflected in his lectures at Edinburgh University, 1820–33. Scott. J. Geol. 56, 85–99. https://doi.org/10.1144/sjg2019-031.
Streckeisen, A., 1974. Classification and nomenclature of plutonic rocks recommendations of the IUGS subcommission on the systematics of Igneous Rocks. Geol. Rundsch. 63, 773–786. https://doi.org/10.1007/BF01820841.
Stringham, B., 1953. Granitization and hydrothermal alteration at Bingham, Utah. GSA Bull. 64, 945–992. https://doi.org/10.1130/0016-7606(1953)64[945:GAHAAB]2.0.CO;2.
Strong, D., Turnbull, R., Haubrock, S., Mortimer, N., 2016. Petlab: New Zealand's national rock catalogue and geoanalytical database. N. Z. J. Geol. Geophys. 59, 475–481. https://doi.org/10.1080/00288306.2016.1157086.
Stumbea, D., 2003. Granitization Phenomena in the Gilau Mountains (Romania). A Geochemical Approach. Acta Mirieralogica-Petrographica, Abstract Series 1, Szeged, 1.
Sun, S.-S., Eadington, P.J., 1987. Oxygen isotope evidence for the mixing of magmatic and meteoric waters during tin mineralization in the Mole Granite, New South Wales, Australia. Econ. Geol. 82, 43–52. https://doi.org/10.2113/gsecongeo.82.1.43.
Tang, L., Wagner, T., Fusswinkel, T., Zhang, S.-T., Hu, X.-K., Schlegel, T.U., 2021. Fluid inclusion evidence for the magmatic-hydrothermal evolution of closely linked porphyry Au, porphyry Mo, and barren systems, East Qinling, China. GSA Bull. 134, 1529–1548. https://doi.org/10.1130/B36170.1.
Tatsumi, Y., 1986. Formation of the volcanic front in subduction zones. Geophys. Res. Lett. 13, 717–720. https://doi.org/10.1029/GL013i008p00717.
Tauson, L.V., Kozlov, V.D., 1973. Distribution functions and ratios of trace-element concentrations as estimators of the ore-bearing potential of granites. Geochem. Explor. 1972, 37–44.
Tavazzani, L., Peres, S., Sinigoi, S., Demarchi, G., Musumeci, G., 2017. Structure and petrography of the Valle Mosso pluton, Sesia Magmatic System, Southern Alps. J. Maps 13, 684–697. https://doi.org/10.1080/17445647.2017.1354787.
Teall, J.J.H., 1888. British Petrography with Special Reference to the Igneous Rocks. Dulao & Company.
Tex, E.D., 1990. Punctuated equilibria between rival concepts of granite genesis in the late 18th, 19th, and early 20th centuries. Geol. J. 25, 215–219. https://doi.org/10.1002/gj.3350250304.
Teyssier, C., Whitney, D.L., 2002. Gneiss domes and orogeny. Geology 30, 1139–1142. https://doi.org/10.1130/0091-7613(2002)030<1139:GDAO>2.0.CO;2.
Tichomirowa, M., Käßner, A., Sperner, B., Lapp, M., Leonhardt, D., Linnemann, U., Münker, C., Ovtcharova, M., Pfänder, J.A., Schaltegger, U., Sergeev, S., von Quadt, A., Whitehouse, M., 2019. Dating multiply overprinted granites: the effect of protracted magmatism and fluid flow on dating systems (zircon U-Pb: SHRIMP/SIMS, LA-ICP-MS, CA-ID-TIMS; and Rb–Sr, Ar–Ar) – Granites from the Western Erzgebirge (Bohemian Massif, Germany). Chem. Geol. 519, 11–38. https://doi.org/10.1016/j.chemgeo.2019.04.024.
Tischendorf, G., Förster, H.-J., 1992. Central European granitoids and their tectonic setting: Implications from a new discrimination diagram. Zentralblatt Für Geologie Und Paläontologie, Teil 1, 791–801.
Tomkeieff, S.I., 1939. The classification of igneous rocks: an historical approach. Geol. Mag. 76, 41–48. https://doi.org/10.1017/S0016756800070618.
Truche, L., Bourdelle, F., Salvi, S., Lefeuvre, N., Zug, A., Lloret, E., 2021. Hydrogen generation during hydrothermal alteration of peralkaline granite. Geochim. Cosmochim. Acta 308, 42–59. https://doi.org/10.1016/j.gca.2021.05.048.
Turner, H.W., 1899. The Granitic Rocks of the Sierra Nevada. J. Geol. 7, 141–162.
Turner, S., Ireland, T., Foden, J., Belousova, E., Wörner, G., Keeman, J., 2022. A comparison of granite genesis in the Adelaide Fold Belt and Glenelg River Complex using U-Pb, Hf and O isotopes in zircon. J. Petrol. egac102. https://doi.org/10.1093/petrology/egac102.
Tuttle, O.F., 1948. A new hydrothermal quenching apparatus. Am. J. Sci. 246, 628–635. https://doi.org/10.2475/ajs.246.10.628.
Tuttle, O.F., Bowen, N.L., 1958. Origin of Granite in the Light of Experimental Studies in the System NaAlSi3O8–KAlSi3O8–SiO2–H2O. https://doi.org/10.1130/MEM74.

Van Daele, J., Dewaele, S., Melcher, F., Onuk, P., Spikings, R., Glorie, S., Jepson, G., Muchez, P., 2020. Geochronology of metamorphism, deformation and fluid circulation: a comparison between Rb-Sr and Ar-Ar phyllosilicate and U-Pb apatite systematics in the Karagwe-Ankole Belt (Central Africa). Gondwana Res. 83, 279–297. https://doi.org/10.1016/j.gr.2020.02.008.
Van Hise, C.R., 1890. The Pre-Cambrian rocks of the black hills. GSA Bull. 1, 203–244. https://doi.org/10.1130/GSAB-1-203.
Velasco, J., 1844. Historia del reino de Quito en la America Meridional: La historia natural. Imprenta del Gobierno.
Vernon, R.H., 1986. K-feldspar megacrysts in granites — Phenocrysts, not porphyroblasts. Earth Sci. Rev. 23, 1–63. https://doi.org/10.1016/0012-8252(86)90003-6.
Vigneresse, J.L., 1990. Use and misuse of geophysical data to determine the shape at depth of granitic intrusions. Geol. J. 25, 249–260. https://doi.org/10.1002/gj.3350250308.
Vigneresse, J.L., 1995. Control of granite emplacement by regional deformation. Tectonophysics 249, 173–186. https://doi.org/10.1016/0040-1951(95)00004-7.
Vigneresse, J.L., 1999. Intrusion level of granitic massifs along the Hercynian belt: balancing the eroded crust. Tectonophysics 307, 277–295. https://doi.org/10.1016/S0040-1951(99)00104-3.
Vigneresse, J.L., 2004. A new paradigm for granite generation. Earth Environ. Sci. Trans. R. Soc. Edinb. 95, 11–22. https://doi.org/10.1017/S0263593300000882.
Vigneresse, J.L., Burg, J.P., 2000. Continuous vs. discontinuous melt segregation in migmatites: insights from a cellular automaton model. Terra Nova 12, 188–192. https://doi.org/10.1046/j.1365-3121.2000.00299.x.
Vigneresse, J.L., Clemens, J.D., 2000. Granitic magma ascent and emplacement: neither diapirism nor neutral buoyancy. Geol. Soc. Lond. Spec. Publ. 174, 1–19. https://doi.org/10.1144/GSL.SP.1999.174.01.01.
Vigneresse, J.L., Barbey, P., Cuney, M., 1996. Rheological transitions during partial melting and crystallization with application to felsic magma segregation and transfer. J. Petrol. 37, 1579–1600. https://doi.org/10.1093/petrology/37.6.1579.
Vila, E.B., 2016. Evolución histórica de la cartografía geológica en España, Desde Sus orígenes Hasta los Mapas de Verneuil Y Collomb (1864) Y Maestre (1865) (Doctoral dissertation,. Universidad Politécnica de Madrid.
Vine, F.J., Matthews, D.H., 1963. Magnetic anomalies over oceanic ridges. Nature 199, 947–949. https://doi.org/10.1038/199947a0.
Virgili, C., 2003. El Fin de los Mitos geológicos. Lyell Nivela, Madrid Sp, 320pp.
Virgili, C., 2007. Lyell and the Spanish geology. Geol. Acta 119–126. https://doi.org/10.1344/105.000000314.
Vogt, J.H.L., 1884. Studier over Slagger. PA Norstedt & söner.
Vogt, J.H.L., 1888. Einige Bemerkungen fiber die Zusammensetzung der kristallisierten Schlacken. Berg- Hiittenmginn. Z. 187, 167-172, 187-189, 197-199, 216-218.
Von Buch, L., 1845. On the form of granitic rocks, and the structure of granite. Q. J. Geol. Soc. 1, 126–128. https://doi.org/10.1144/GSL.JGS.1845.001.01.29.
von Bunsen, R., 1851. Über die Prozesse der vulkanischen Gesteinsbildungen Islands. Pogg. Ann. 83, 197–272.
von Bunsen, R., 1861. Über die Bildung des Granites. Z. Deut. Geol. Ges. 13, 61–63.
von Humboldt, A., 1822. Ensayo Politico Sobre el Reino de la Nueva-España. Rosa.
von Humboldt, A., 1825. Essai politique sur le royaume de la Nouvelle-Espagne, Deuxième éd. ed. Chez Antoine-Augustin Renouard, Paris. https://doi.org/10.5962/bhl.title.95434.
von Humboldt, A., 1841. Diagram of a cross-section of the earth's crust. In: From Heinrich Berghaus, Physikalischer Atlas (Gotha: J. Perthes, 1852).
Wagner, T., Fusswinkel, T., Wälle, M., Heinrich, C.A., 2016. Microanalysis of fluid inclusions in crustal hydrothermal systems using laser ablation methods. Elements 12, 323–328. https://doi.org/10.2113/gselements.12.5.323.
Walker, J.D., Bowers, T.D., Black, R.A., Glazner, A.F., Lang Farmer, G., Carlson, R.W., 2006. A geochemical database for western North American volcanic and intrusive rocks (NAVDAT). In: Sinha, A.K. (Ed.), Geoinformatics: Data to Knowledge. Geological Society of America, p. 0. https://doi.org/10.1130/2006.2397(05.
Walton, M., 1960. Granite problems: the exploration of physical and chemical processes leads to a reorientation of our thinking. Science 131, 635–645. https://doi.org/10.1126/science.131.3401.635.
Wang, W., Zhao, J., Cheng, Q., 2011. Analysis and integration of geo-information to identify granitic intrusions as exploration targets in southeastern Yunnan District, China. Comput. Geosci. 37, 1946–1957. https://doi.org/10.1016/j.cageo.2011.06.023.
Wang, X.-S., Williams-Jones, A.E., Hu, R.-Z., Shang, L.-B., Bi, X.-W., 2021. The role of fluorine in granite-related hydrothermal tungsten ore genesis: results of experiments and modeling. Geochim. Cosmochim. Acta 292, 170–187. https://doi.org/10.1016/j.gca.2020.09.032.
Wang, C., Alard, O., Lai, Y.-J., Foley, S.F., Liu, Y., Munnikhuis, J., Wang, Y., 2022a. Advances in in-situ Rb-Sr dating using LA-ICP-MS/MS: applications to igneous rocks of all ages and to the identification of unrecognized metamorphic events. Chem. Geol. 610, 121073. https://doi.org/10.1016/j.chemgeo.2022.121073.
Wang, D., Wang, X.-L., Cai, Y., Li, J.-Y., Du, D.-H., Shu, X.-J., 2022b. Exploring the Sn–W metallogenic potential of Late Jurassic Ganfang-Guyangzhai granite suite, South China: zircon and apatite geochemistry. Ore Geol. Rev. 144, 104863. https://doi.org/10.1016/j.oregeorev.2022.104863.
Wark, D.A., Watson, E.B., 2006. TitaniQ: a titanium-in-quartz geothermometer. Contrib. Mineral. Petrol. 152, 743–754. https://doi.org/10.1007/s00410-006-0132-1.
Watts, D.R., Harris, N.B.W., 2005. The 2002 NASA GLENN SOARS Working Group§#, 2005. Mapping granite and gneiss in domes along the North Himalayan antiform with ASTER SWIR band ratios. GSA Bull. 117, 879–886. https://doi.org/10.1130/B25592.1.
Wedepohl, K.H., 1969. Handbook of Geochemistry. Springer, Berlin, Heidelberg.
Wedepohl, K.H., 1995. The composition of the continental crust. Geochim. Cosmochim. Acta 59, 1217–1232. https://doi.org/10.1016/0016-7037(95)00038-2.
Wegener, A., 1912. Die Entstehung der Kontinente. Geol. Rundsch. 3, 276–292. https://doi.org/10.1007/BF02202896.
Weinberg, R.F., 1992. Internal circulation in a buoyant two-fluid Newtonian sphere: implications for composed magmatic diapirs. Earth Planet. Sci. Lett. 110, 77–94. https://doi.org/10.1016/0012-821X(92)90040-3.
Weinberg, R.F., 1996. Ascent mechanism of felsic magmas: news and views. Earth Environ. Sci. Trans. R. Soc. Edinb. 87, 95–103. https://doi.org/10.1017/S0263593300006519.
Weinberg, R.F., 1999. Mesoscale pervasive felsic magma migration: alternatives to dyking. Lithos 46, 393–410. https://doi.org/10.1016/S0024-4937(98)00075-9.
Weinberg, R.F., Podladchikov, Y., 1994. Diapiric ascent of magmas through power law crust and mantle. J. Geophys. Res. Solid Earth 99, 9543–9559. https://doi.org/10.1029/93JB03461.
Weisheit, A., Bons, P.D., Elburg, M.A., 2013. Long-lived crustal-scale fluid flow: the hydrothermal mega-breccia of Hidden Valley, Mt. Painter Inlier, South Australia. Int. J. Earth Sci. 102, 1219–1236. https://doi.org/10.1007/s00531-013-0875-7.
Wenzel, F., Sandmeier, K.-J., Wälde, W., 1987. Properties of the lower crust from modeling refraction and reflection data. J. Geophys. Res. Solid Earth 92, 11575–11583. https://doi.org/10.1029/JB092iB11p11575.
Werner, A.G., 1787. Kurze Klassifikation und Beschreibung der verschiedenen Gebirgsarten. Walther.
White, A.J.R., Chappell, B.W., 1977. Ultrametamorphism and granitoid genesis. Tectonophysics 43, 7–22. https://doi.org/10.1016/0040-1951(77)90003-8.
Wilkinson, M.D., Dumontier, M., Aalbersberg, Ij J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L.B., Bourne, P.E., Bouwman, J., Brookes, A.J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C.T., Finkers, R., Gonzalez-Beltran, A., Gray, A.J.G., Groth, P., Goble, C., Grethe, J.S., Heringa, J., 't Hoen, P.A.C., Hooft, R., Kuhn, T., Kok, R., Kok, J., Lusher, S.J., Martone, M.E., Mons, A., Packer, A.L., Persson, B., Rocca-Serra, P., Roos, M., van Schaik, R., Sansone, S.-A., Schultes, E., Sengstag, T., Slater, T., Strawn, G., Swertz, M.A., Thompson, M., van der Lei, J., van Mulligen, E., Velterop, J., Waagmeester, A., Wittenburg, P., Wolstencroft, K., Zhao, J., Mons, B., 2016. The FAIR Guiding Principles for scientific data management and stewardship. Sci. Data 3, 160018. https://doi.org/10.1038/sdata.2016.18.
Wilson, J.T., 1965. A new class of faults and their bearing on continental drift. Nature 207, 343–347. https://doi.org/10.1038/207343a0.
Wilson, R.C.L., 1975. Atlantic opening and Mesozoic continental margin basins of Iberia. Earth Planet. Sci. Lett. 25, 33–43. https://doi.org/10.1016/0012-821X(75)90207-1.
Winkler, H.G.F., von Platen, H., 1961. Experimentelle Gesteinsmetamorphose—IV: bildung anatektischer Schmelzen aus metamorphisierten Grauwacken. Geochim. Cosmochim. Acta 24, 48–69. https://doi.org/10.1016/0016-7037(61)90007-2.
Wolf, T., 1892. Geografía Y geología del Ecuador.
Wolf, K.L., Troll, W., Kuhn, D., von Engelhardt, W., 1989. Goethe. Die Schriften zur Naturwissenschaft. Verlag Hermann Böhlaus Nachfolger Weimar, Weimar.
Wool, D., 2001. Charles Lyell –"the father of geology"– as a forerunner of modern ecology. Oikos 94, 385–391. https://doi.org/10.1034/j.1600-0706.2001.940301.x.
Xie, F., Lang, X., Tang, J., Ma, D., Zou, B., 2019. Late Cretaceous magmatic activity in the southern Lhasa terrane: insights from the Dazhuqu hornblende gabbro and the Xietongmen granite porphyry. Int. Geol. Rev. 61, 1642–1665. https://doi.org/10.1080/00206814.2018.1531273.
Yang, C., 1982. The genetic types of the granitoids in South China. In: Geology of Granites and their Metallogenetic Relations, Proc. Nanjing Symp. Science Press, pp. 253–276.
Yang, F., Wu, G., Chen, G., Li, S., Li, Y., Zhang, T., Chen, Y., 2024. Petrogenesis and implications for tin mineralization of the Beidashan granitic pluton, southern Great Xing'an Range, NE China: constraints from whole-rock and accessory mineral geochemistry. J. Asian Earth Sci. 259, 105883. https://doi.org/10.1016/j.jseaes.2023.105883.
Yin, A., 2004. Gneiss domes and gneiss dome systems. In: Whitney, D.L., Teyssier, C., Siddoway, C.S. (Eds.), Gneiss Domes in Orogeny. Geological Society of America, p. 0. https://doi.org/10.1130/0–8137–2380-9.1.
Young, D., 1999. The rise of the theory of differentiation in igneous petrology (part 2 of 2). Earth Sci. Hist. 18, 295–320. https://doi.org/10.17704/eshi.18.2.b5567lq151334j45.
Young, D.A., 2018. Mind over Magma: The Story of Igneous Petrology, Mind over Magma. Princeton University Press. https://doi.org/10.1515/9780691187723.
Zack, T., Hogmalm, K.J., 2016. Laser ablation Rb/Sr dating by online chemical separation of Rb and Sr in an oxygen-filled reaction cell. Chem. Geol. 437, 120–133. https://doi.org/10.1016/j.chemgeo.2016.05.027.
Žák, J., Holub, F.V., Kachlík, V., 2006. Magmatic stoping as an important emplacement mechanism of Variscan plutons: evidence from roof pendants in the Central Bohemian Plutonic Complex (Bohemian Massif). Int. J. Earth Sci. 95, 771–789. https://doi.org/10.1007/s00531-006-0076-8.
Zametzer, A., Kirkland, C.L., Hartnady, M.I.H., Barham, M., Champion, D.C., Bodorkos, S., Smithies, R.H., Johnson, S.P., 2022. Applications of Pb isotopes in granite K-feldspar and Pb evolution in the Yilgarn Craton. Geochim. Cosmochim. Acta 320, 279–303. https://doi.org/10.1016/j.gca.2021.11.029.
Zhang, Y., Robinson, J., Schaubs, P.M., 2011. Numerical modelling of structural controls on fluid flow and mineralization. Geosci. Front. 2, 449–461. https://doi.org/10.1016/j.gsf.2011.05.011.
Zhang, Y., Wong, L.N.Y., Chan, K.K., 2019. An extended grain-based model accounting for microstructures in rock deformation. J. Geophys. Res. Solid Earth 124, 125–148. https://doi.org/10.1029/2018JB016165.

Zhang, L., Chen, Z., Wang, F., White, N.C., Zhou, T., 2021. Release of uranium from uraninite in granites through alteration: implications for the source of granite-related uranium ores. Econ. Geol. 116, 1115–1139. https://doi.org/10.5382/econgeo.4822.

Zheng, H., Luo, J., Zhang, Y., Feng, J., Zeng, Y., Wang, M., 2021. Geological characteristics and distribution of granite geothermal reservoir in Southeast Coastal areas in China. Front. Earth Sci. 9.

Zhuang, L., Zang, A., 2021. Laboratory hydraulic fracturing experiments on crystalline rock for geothermal purposes. Earth Sci. Rev. 216, 103580. https://doi.org/10.1016/j.earscirev.2021.103580.

Zirkel, F., 1866. Lehrbuch der Petrographie. A. Marcus.

Zirkel, F., 1873. Die Mikroskopische Beschaffenheit der Mineralien und Gesteine. W. Engelmann.

Zirner, A.L.K., Marks, M.A.W., Wenzel, T., Jacob, D.E., Markl, G., 2015. Rare earth elements in apatite as a monitor of magmatic and metasomatic processes: the Ilímaussaq complex, South Greenland. Lithos 228–229, 12–22. https://doi.org/10.1016/j.lithos.2015.04.013.