

Rodney Grapes

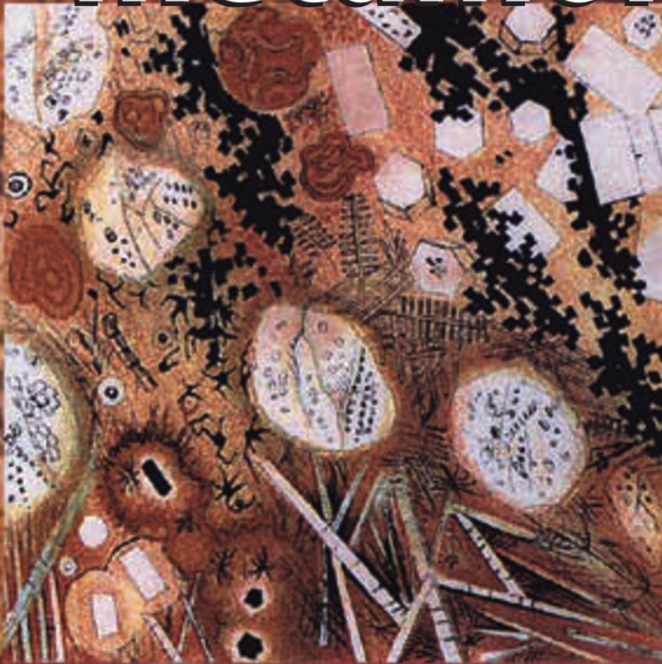
# Pyro- metamorphism



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With 192 Figures

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## Author

### Professor Dr. Rodney H. Grapes

Mineralogisch-Geochemisches Institut  
Albert-Ludwigs-Universität Freiburg  
Albertstr. 23 b  
79104 Freiburg  
Germany

*Now at:*

Department of Geosciences  
Sun Yat-sen (Zhongshan) University  
Guangzhou (Canton) 510275  
China

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## Preface

My interest in pyrometamorphosed rocks began in 1981–82 as a Humboldt Fellow at the Institute for Mineralogy, Ruhr University, Bochum, Germany, with Professor Werner Schreyer, where I began a study of basement xenoliths erupted from the Wehr Volcano, east Eifel. A comprehensive suite of xenoliths had already been obtained by Gerhard Wörner (now Professor of Geochemistry at Gottingen University) and I was fortunate to be able to select samples from his collection for further detailed study. The xenoliths, mainly mica schists, had all undergone various stages of reaction and fusion. Because the high temperature reaction products and textures were fine grained they were difficult to study petrographically and for me they presented an entirely new group of rocks that I had had almost no experience with. However, by extensive use of the backscattered electron image technique of the electron microprobe the “wonderful world” of mineral reaction/melting textures arrested in various stages of up-temperature transformation by quenching was revealed. Almost every image showed something new. I had entered the seemingly complex and at times contradictory realm of disequilibrium where metastable nucleation and crystal growth is the norm.

Pyrometamorphism is a type of thermal metamorphism involving very high temperatures often to the point of causing fusion in suitable lithologies at very low pressures. The high temperatures are provided by flow of mafic magma through conduits, by way of spontaneous combustion of coal, carbonaceous sediments, oil and gas, and through the action of lightning strikes. These conditions characterise the sanidinite facies of contact metamorphism. Although pyrometamorphic effects related to igneous activity are usually restricted to very narrow aureoles and xenoliths and to the point of impact in lightning strikes, pyrometamorphic rocks may be exposed over a surface area of hundreds to thousands of square kilometres in the case of combustion of gently dipping coal seams. In all these instances, temperature gradients are extreme, varying by several hundred degrees over a few metres or even centimetres. Relatively short periods of heating create an environment dominated by metastable melting and rapid mineral reaction rates driven by significant temperature overstepping of equilibrium conditions. This results in the formation of a large variety of high temperature minerals, many of which are metastable, are only found in pyrometamorphic rocks and are analogous to those crystallising from dry melts in laboratory quenching experiments at atmospheric pressure.

Compared with other types of metamorphic rocks, pyrometamorphic rocks are rare and volumetrically insignificant. This is probably the main reason why pyrometamorphism and sanidinite facies mineral assemblages have received scant attention in many

modern petrology text books despite the fact that there is a considerable literature on the subject dating back to 1873 when the first buchite was described and named. In recent years, a number of papers have appeared in international Earth Science journals detailing field relations, microtextures, mineralogy and geochemistry of pyrometamorphic rocks and related phenomena and so it seemed to me that there was a timely need for a review/synthesis of the subject. This book is the result. It is not a textbook but essentially a compilation of available data relating to some 76 terrestrial occurrences of igneous, combustion and lightning strike pyrometamorphism of quartzofeldspathic, calc-silicate, evaporite and mafic rock/sediment compositions. Examples of anthropogenic pyrometamorphism such as brick manufacture, slag production, waste incineration, drilling and ritual burning are also given for comparison. The last chapter deals with aspects of high temperature disequilibrium reactions and melting of some common silicate minerals. My hope is that the book will stimulate further research into these fascinating rocks to help explain the many unanswered questions relating to processes and products of metamorphism under very high temperature/low pressure conditions.

*Freiburg, September 2005*

*Rodney Grapes*

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## Acknowledgements

I am indebted to Professor Kurt Bucher for discussion and comments on aspects of pyrometamorphism and who kindly put the resources, infrastructure and secretarial services of Christine Höher and Karin Eckmann of the Mineralogisch-Geochemisches Institut (Freiburg University) at my disposal and thus made the project possible. Emeritus Professor Wolfhard Wimmenauer kindly shared his extensive knowledge on fulgurites. Dr. Hiltrud Müller-Sigmund is thanked for her expertise in German to English translation and guidance in using the Institute's electron microprobe, and I'm grateful to Melanie Katt for producing superb polished sections. A special thanks to the Institute Librarian, Susanne Schuble, who promptly and uncomplainingly obtained the many references I requested, especially from the basement archive where everything old and forgotten is kept. Erica Lutz is thanked for her drafting assistance until I became familiar with the CANVAS drawing programme.

I am particularly appreciative for the information on pyrometamorphic rock occurrences in Russia and the Central Asia Republics, much of it, text and photographs, unpublished, that was kindly supplied by Dr. Ella Sokol, a leading researcher in combustion metamorphism at the Institute of Mineralogy and Petrography of the Russian Academy of Sciences, Novosibirsk.

Finally, I would like to thank my wife, Agnes, for support in all sorts of ways and above all, for keeping me at it.



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## Introduction

*Pyrometamorphism*, from the Greek *pyr/pyro* = fire, *meta* = change; *morph* = shape or form, is a term first used by Brauns (1912a,b) to describe high temperature changes which take place at the immediate contacts of magma and country rock with or without interchanges of material. The term was applied to schist xenoliths in trachyte and phonolite magma of the Eifel area, Germany, that had undergone melting and elemental exchange (e.g. Na<sub>2</sub>O) with the magma to form rocks consisting mainly of alkali feldspar (sanidine, anorthoclase), cordierite, spinel, corundum, biotite, sillimanite and (relic) almandine garnet ± andalusite. Brauns (1912a,b) considered the essential indicators of pyrometamorphism to be the presence of glass with the implication that temperatures were high enough to induce melting, pyrogenic minerals (i.e. crystallised from an anhydrous melt), replacement of hydrous minerals by anhydrous ones, the preservation of crystal habits of reacted minerals and of rock textures.

Tyrrell (1926) defined pyrometamorphism as pertaining to the “effects of the highest degree of heat possible *without actual fusion*” [authors italics] and considered that the term could be usefully extended to “all products of the action of very high magmatic temperatures, whether aided or not by the chemical action of magmatic substances”. He regarded pyrometamorphic effects as “... conterminous with, and hardly distinguishable from, those due to assimilation and hybridization”. Tyrrell’s definition thus fails to include the presence of glass or fused rocks (buchites, see below) that are amongst the most typical products of pyrometamorphism.

A further term, *caustic* (= *corrosion*) *metamorphism* was introduced by Milch (1922) to describe the indurating, burning and fritting effects produced in country rocks by lavas and minor intrusions. It was replaced by Tyrrell (1926) with what he felt to be the more appropriate *optalic metamorphism* (Greek *optaleos* = baked [as bricks]) to describe such effects: “... optalic effects are produced by evanescent hot contacts at which heat is rapidly dissipated. The elimination of water and other volatile constituents, the bleaching of carbonaceous rocks by the burning off of carbon, the reddening of iron-bearing rocks by the oxidation of iron, induration, peripheral fusion of grains (fritting); in short, analogous kinds of alteration to those produced artificially in brick and coarse earthenware manufacture, are the most notable effects of this phase of metamorphism. Argillaceous rocks are often indurated with the production of an excessively hard material called *hornstone*, *lydian-stone*, or *porcellanite*. Some *hornstones* and *novaculite* are due to this action on siliceous clays and shales. The coking of coal seams by igneous intrusions, and the columnar structures induced both in coals and in some sandstones, are also to be regarded as the effects of optalic metamorphism”. The term is now ob-

soleite and the effects of combustion of coal and other organic matter, can be included under pyrometamorphism.

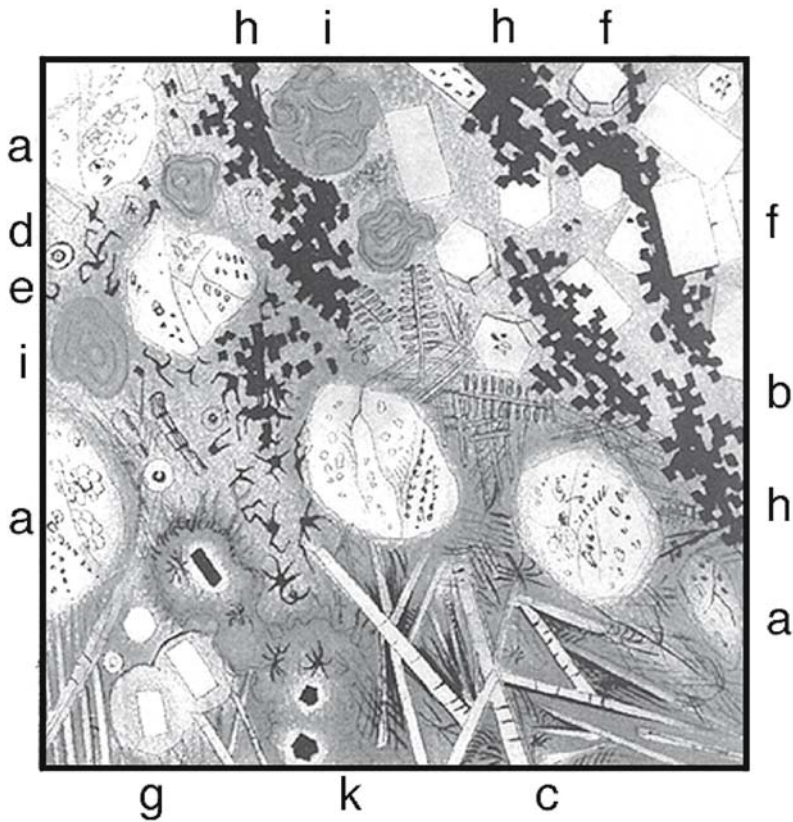
Pyrometamorphic rocks are thus extensively documented in relation to xenoliths in basic lavas and shallow intrusions, in narrow aureoles immediately adjacent basaltic necks and shallow intrusions, and as fragments in tuffs and volcanic breccias (Fyfe et al. 1959; Turner 1948, 1968). Most of the standard metamorphic petrology textbooks do not include the products of combustion of coal seams/organic-rich sediments, or lightning strikes, as pyrometamorphic products. The Subcommittee on the Systematics of Metamorphic Rocks (SCMR) of the International Union of Geological Sciences (IUGS) (Smulikowski et al. 1997) refers to these variants of contact metamorphism as *burning metamorphism* (although the term *combustion metamorphism* is also in use) and *lightning metamorphism*.

In contrast to the localised (contact) occurrence of pyrometamorphism associated with igneous rocks and particularly so in the case of lightning strikes, it is important to note that pyrometamorphic products of burning coal seams and carbonaceous sediments can be of regional extent, e.g. outcropping over an area of some 200 000 square kilometers in the western United States. However, the process involves steep temperature gradients to produce burnt to completely melted rocks over a restricted interval of anything from a few centimeters to a few meters at or near the Earth's surface.

## 1.1 Terms

There are a number of rock terms commonly used in association with the phenomenon of pyrometamorphism, e.g. buchite, porcellanite, sanidinite, emery, paralava, clinker, fulgurite, together with the more general terms, vitrified or fused and burnt rocks. These can be characterised, together with related and mostly outdated terms, as follows:

- *Buchite* – A partly to almost completely vitrified rock resulting from intense contact metamorphism. Pyrometamorphic xenoliths and contact aureole rocks described as altered (*verändert*) or glassy (*verglasst*) sandstone (buchites) associated with basaltic rocks were first described from a number of localities throughout Germany (e.g. Zirkel 1872, 1891; Mohl 1873, 1874; Lemberg 1883; Hussak 1883; Prohaska 1885; Rinne 1895). The term *buchite* appears to have been coined by Mohl (1873) presumably after the German geologist, Leopold von Buch (Tomkeieff 1940), to describe fused rock (*geglühte Sandstein*) in contact with basalt and replaced the term *basalt-jasper* (Fig. 1.1). Although initially applied to partially melted sandstone (Lemberg 1883; Morosevicz 1898; Bücking 1900; Harker 1904), *buchite* was later used to describe fused pelitic rocks (Flett 1911; Thomas 1922; Jugovics 1933). The rarely used term, *para-obsidian* describes a nearly holohyaline buchite containing a few microlites of phases such as mullite and tridymite.
- *Porcellanite* – A light coloured, very fine grained, completely recrystallised pyrometamorphosed clay, marl, shale or bauxitic lithomarge. Originally named from a naturally baked clay considered to be a variety of jasper (Werner 1789) which led to the adoption of the now obsolete term porcelain-jasper.



**Fig. 1.1.** Sketch of thin section of a tridymite-cordierite-clinopyroxene-spinel buchite from Otzberg, Germany (Fig. IV of Mohl 1873). This is the first rock to be termed *buchite*. The letters refer to: *a* = relic and cracked quartz overgrown by and with inclusions of tridymite; *b* = feathery-like/dendritic pyroxene (centre of diagram); *c* = needles of clinopyroxene; *d* = small vesicles with dark rims and centres; *e* = trichites of magnetite; *f* = rhombic and hexagonal crystals of cordierite (mistakenly identified as nepheline); *g* = glass surrounding cordierite; *h* = spinel; *i* = zoned pores filled with goethite; *k* = brown-coloured glass matrix

- **Sanidinite** – Sanidinite was proposed (Nose 1808) as a term for igneous rocks and segregations/inclusions therein consisting mainly of sanidine or anorthoclase (e.g. nosean sanidinite, hauyne sanidinite [*gleesite*], aegirine-augite sanidinite [*parafenite*], scapolite sanidinite [*hüttenbergite*]). The term is now mainly restricted to pyrometamorphic rocks (xenoliths) with a sanidine-syenite composition, but consisting of sanidine/anorthoclase, biotite, cordierite, orthopyroxene, sillimanite/mullite, spinel, corundum, ilmenite, Ti-magnetite (i.e. biotite sanidinite [*laachite*] of Brauns 1912a; Kalb 1935, 1936; Frechen 1947).
- **Emery** – A dark, hard, dense granular rock consisting mainly of corundum, spinel, magnetite and/or ilmenite-hematite (sometimes including pseudobrookite, mullite,

cordierite, sanidine) formed by high (near basaltic magma) temperature metamorphism of laterite (ferruginous bauxite), aluminous (pelitic) sediment, or as an aluminous residue (restite) resulting from removal of a “granitic” melt fraction from pelitic-psammitic rocks.

- *Paralava* – A name given to vesicular, aphanitic, fused shale and sandstone that resembles artificial slag or basalt in physical appearance, produced by the combustion of coal seams. Originally termed “para lavas” by Fermor (Hayden 1918) from observations in the Bokaro Coalfield, India, after previously regarding them as basaltic lava from their highly vesicular, ropy structure (Fermor 1914). The analogous term *parabasalt* has been adopted in Russian literature (e.g. Sharygin et al. 1999) to describe glassy and holocrystalline rocks that contain olivine, ortho/clinopyroxene, calcic plagioclase, Fe-Al spinels, ± leucite, resulting from melting by spontaneous combustion in waste heaps of the Chelyabinsk coal basin.
- *Clinker* – hard rock resembling burnt paving-brick (*klinkaerd*) used in Holland, that rings when struck with a hammer. Gresley (1883) defines clinker as coal altered by an igneous intrusion, but it is now applied to sedimentary rocks that have been baked and/or partially melted by the combustion of coal seams or bituminous sediments. In the United States, the term was first applied to hard red rocks overlying burnt coal seams in Eastern Montana by Prince Alexander Maximilian in 1833, because of their strong resemblance to the waste products of European brick kilns, and when struck, emitted a clear sound “like that of the best Dutch clinkers” (Sigsby 1966). Glassy clinkers (sometimes referred to as *scoria*) are effectively buchites.
- *Fulgurite* – (Latin *fulgur* = lightning). An irregular, glassy, often tabular or rod-like structure produced by the fusion of loose sediment, but also solid rock, by lightning.

## 1.2 Sanidinite Facies

As mentioned above, *sanidinite* is a term synonymous with pyrometamorphism and was first used by Brauns (1912a,b) to describe sanidine-rich xenoliths in volcanic rocks. The term was adopted by Eskola (1920; 1939, pp. 347–349) as his highest temperature, lowest pressure metamorphic facies (*sanidinite facies*) characterised by the occurrence of sanidine (typically with a high Na-content) and pigeonite (clinohypersthene). Compositions and notations of sanidinite facies minerals used throughout the text are listed in alphabetical order in Table 1.1.

In contact aureoles of shallow basaltic intrusions, in sediments overlying burnt coal seams and in combusted carbonaceous sediments, sanidinite facies rocks represent the end product of a continuous spectrum of contact metamorphism that occurs over very short distances ranging from centimeters to tens of meters. The effects of high temperature and chemical disequilibrium caused by incomplete reaction due to rapid heating and cooling that are indicated by pyrometamorphic mineral assemblages, their compositions, crystal habit, textures, and preservation of glass, are typically quite distinctive and do not fit well into other facies of contact metamorphism.

At low pressures (< 2 kb), differentiation of sanidinite facies from pyroxene hornfels facies rocks can be characterised by the absence of andalusite and pyralspite garnet

in quartzo-feldspathic rocks (Chapter 3) and grossular in calc-silicate rocks. In silica-poor calcareous rocks, Turner and Verhoogen (1960) propose that the formation of monticellite from diopside and forsterite marks the transition from pyroxene hornfels to sanidinite facies (Chapter 4). In mafic and ultramafic rocks the distinction from pyroxene hornfels assemblages is difficult. Both may contain olivine, clinopyroxene, orthopyroxene, spinel, and exhibit a hornfelsic texture, so that the distinction, although not particularly relevant, might depend on recognition of diagnostic mineral assemblages in intercalated metasedimentary rocks (Chapter 5).

Although melting, disordered feldspars, and pigeonite may be stable under granulite facies conditions, they recrystallise, invert and/or unmix during slow cooling (Miyashiro 1973), and it is rapid cooling rates as evidenced by finer grain size and a low pressure geological setting that should also be used to distinguish sanidinite facies from granulite facies rocks. A case in point is the emery rocks of the Cortland Complex, USA, that contain a “sanidinite facies” assemblage of sillimanite, spinel, corundum and Ti-Fe oxides (emeries) and represent extreme metamorphism of quartz-poor rocks involving partial melting and melt extraction, as evidenced by networks of quartzo-feldspathic veins. Local silicification reactions in the proximity of these veins has led to the formation of sapphirine, pyrope-rich garnet, Al-orthopyroxene and cordierite with increasing silica activity. While thermobarometry indicates formation temperatures at  $\sim 1000$  °C, a pressure of  $\sim 7.5$  kb puts these rocks well within the granulite facies field (Tracy and McLellan 1985).

Occurrences of sanidinite facies rocks are typically insignificant compared with other facies of metamorphism. They clearly contain unusual and unique mineral compositions and exhibit features of paragenesis that indicate a merging with igneous rocks. Mineral assemblages developed from fusion of pelitic, psammitic and marl compositions in particular are closely analogous to the products of crystallisation of *dry* melts in laboratory quenching experiments at atmospheric pressure (Turner 1948).

As stated above, sanidine often with a considerable Na-component is a key mineral of Eskola's definition of sanidinite facies and reflects the continuous solid solution between K- and Na-feldspars at temperatures  $> 650$  °C. The problem with the term is that many sanidinite facies rocks, e.g. calc-silicate, basic and ultrabasic lithologies, with K-absent, Al-Si-poor compositions, and even many buchites derived from fusion of quartzofeldspathic rocks, do not contain sanidine. In buchites, the K-feldspar component commonly remains dissolved in the melt (glass). In the case of “non-igneous” sanidinite (as xenoliths), sanidine/anorthoclase form when the melt “modified” by Na-exchange with surrounding magma (especially trachyte or phonolite) crystallises during high temperature annealing to enclose typical sanidinite facies minerals such as Ti-rich biotite, mullite-sillimanite, spinel, corundum, ilmenite, etc.

Nevertheless, despite the above-mentioned problems, the “sanidinite facies” as a facies of contact metamorphism is still in widespread use and is retained as one of the ten recommended main metamorphic facies by Smulikowski et al. (1997). Based on *T-P* estimates of pyrometamorphosed rock occurrences described later, the sanidinite facies stability field is shown in Fig. 1.2. The upper pressure limit is somewhat arbitrary, although it can be significantly higher than the  $\sim 0.6$  kb suggested by Turner and Verhoogen (1960; Fig. 79), and available data indicates lithostatic = vapour pressure conditions of  $< 3$  kb. While maximum temperature conditions resulting from *igneous ac-*