Journal of Petrology, 2024, 65, egae120
https://doi.org/10.1093/petrology/egae120
ADVANCE ACCESS PUBLICATION DATE 8 NOVEMBER 2024
Letter

Major-Element Geochemistry and $Fe^{3+}/\Sigma Fe$ of Metabasites

JACOB B. FORSHAW[1,2,*], HUGO DOMINGUEZ[1], THORSTEN A. MARKMANN[1], RENÉE TAMBLYN[1], JÖRG HERMANN[1], NICOLAS RIEL[3] AND PIERRE LANARI[4,1]

[1]Institute of Geological Sciences, University of Bern, Baltzerstrasse 3, CH-3012 Bern, Switzerland
[2]Mineral Deposit Research Unit, Department of Earth, Ocean and Atmospheric Sciences, 2207 Main Mall, University of British Columbia, V6T 1Z4 Vancouver, Canada
[3]Institute of Geosciences, Johannes Gutenberg University, J.-J.-Becher-Weg, 21 D-55128 Mainz, Germany
[4]Institute of Earth Sciences, University of Lausanne, Géopolis, CH-1050 Lausanne, Switzerland

*Corresponding author. E-mail: jforshaw@eoas.ubc.ca

Metabasites (metamorphosed mafic rocks) are crucial for understanding metamorphic and tectonic processes. Their preservation in exhumed orogenic belts from throughout Earth's history and the diverse mineral assemblages they form under different pressure–temperature conditions make them valuable for studying metamorphic processes. This work compiles a database of 6186 major-element whole-rock analyses of metabasites from different metamorphic facies (low-grade, greenschist, blueschist, amphibolite, granulite, and eclogite). These are used to explore the range and variability in their composition and assess geochemical differences among metamorphic facies. To mitigate the impact of outliers, median values and median absolute deviations (MAD) are used as measures of central tendency and dispersion. Metabasites show decreased volatile content with increasing metamorphic grade and generally consistent major-element contents across facies, with subtle differences interpreted to result from sampling bias. The median worldwide metabasite is as follows (anhydrous, normalised values in wt %, ±MAD): SiO_2 = 51.36±3.40, TiO_2 = 1.33±0.82, Al_2O_3 = 15.47±1.97, FeO^{total} = 11.48±2.50, MnO 0.20±0.06, MgO = 6.83±2.25, CaO = 9.84±2.34, Na_2O = 2.82±1.05, K_2O = 0.50±0.61, and P_2O_5 = 0.18±0.16. The median $X_{Mg} = MgO/(MgO+FeO^{total})$ is 0.51±0.09. The median $Fe^{3+}/\Sigma Fe$ was measured by titration in 3153 samples and is 0.26±0.12, comparable to values in altered oceanic crust or arc basalts. Future research must carefully examine the distribution of Fe^{3+} amongst minerals in metabasites, allowing for a better evaluation of the median whole-rock $Fe^{3+}/\Sigma Fe$ and its potential susceptibility to analytical interferences.

Key words: Metabasites; Major-element geochemistry; $Fe^{3+}/\Sigma Fe$; Metamorphic facies; Whole-rock database

INTRODUCTION

Metabasites, a term introduced by the Finnish geologist V. Hackman (Sederholm, 1907), refer to metamorphosed mafic rocks such as basalt, dolerite, and gabbro (Miyashiro, 1973). Their mineral assemblages are sensitive to changing pressure–temperature (*P*–*T*) conditions, and since the pioneering work of Eskola (1920), they have served as the foundation for defining the metamorphic facies (Poldervaart, 1953; Fyfe *et al.*, 1958). Due to their widespread occurrence in nearly all tectonic-magmatic settings and sensitivity to metamorphic conditions, metabasites are crucial for understanding metamorphic processes.

Barth (1959) noted in his discussion of the geochemical composition of amphibolites – a type of metabasite – that '*among the metamorphic rocks, the amphibolites occupy a position rather similar to that of the basaltic-gabbroid rocks of the igneous suite*' but he emphasised that, unlike well-characterized basalts and gabbros, '*no corresponding characterisation has been made of amphibolites*.' Previous studies have produced average compositions for amphibolites ($n < 250$; e.g. Lapadu-Hargues, 1953; Poldervaart, 1955) and have examined compositional variations in metabasites from specific regions between metamorphic facies ($n < 200$, e.g. Carden, 1978; Clough & Field, 1980). However, no comprehensive analysis has been conducted on the major-element geochemistry of metabasites across different metamorphic facies on a global scale.

With an increasing degree of recrystallisation, mafic metamorphic rocks lose traces of their original mineralogy and texture, making it difficult to determine their protolith. This poses challenges in distinguishing whether metabasites were originally basalts or gabbros, and further complicates differentiating them from hydrothermally altered mafic rocks (e.g. spilites; Vallance, 1974), metasomatically altered rocks (Adams, 1909; Orville, 1969), basic tuffs (e.g. para-amphibolites; Evans & Leake, 1960; van de Kamp, 1968, 1970), greywackes (Rivalenti & Sighinolfi, 1969), or calc-silicate sediments (Walker *et al.*, 1959). Authors have used trace-element geochemical criteria to differentiate between the various volcanic rock protoliths (Winchester & Floyd, 1976; Floyd & Winchester, 1978) and decipher the igneous or sedimentary origin of the various types of amphibolite (Leake, 1964; Shaw & Kudoi, 1965). Consequently, understanding the geochemical composition of metabasites is essential for determining their origin.

Given the numerous processes that may alter their geochemistry, the term 'metabasite' encompasses various rock types with

RECEIVED SEPTEMBER 14, 2024; **REVISED** NOVEMBER 5, 2024; **ACCEPTED** NOVEMBER 6, 2024

significant compositional diversity, unlike basalts, which have a definitive compositional range (Middlemost, 1975). Even subtle variations in major-element geochemistry can affect phase equilibria, influencing the mineral assemblage and compositions formed during metamorphism (Hernández-Uribe *et al.*, 2020; Starr *et al.*, 2020b). Although several studies have generated phase diagrams for an average basalt composition to estimate representative *P–T* conditions for commonly occurring metabasic mineral assemblages and to compare these conditions across different metamorphic belts (e.g. Rebay *et al.*, 2010; Palin *et al.*, 2016; Wei & Duan, 2019), these diagrams are limited in their ability to account for the observed geochemical variability in metabasite compositions. This paper compiles published whole-rock analyses of metabasites across a range of metamorphic grades. Our goal is to document the range of chemical compositions of metabasites, establish a median composition, and assess compositional changes amongst the metamorphic facies. This work thus complements a study of similar scope on the major-element geochemistry of metapelites (Forshaw & Pattison, 2023b).

COMPILATION OF LITERATURE DATA

Although large databases of whole-rock data compiled from the literature are now available, they lack the comprehensive petrographic information that is required to assign metamorphic facies (e.g. Gard *et al.*, 2019). To address this issue, we compiled a whole-rock database from studies of metabasic rocks where authors detailed metamorphic facies or metamorphic mineral assemblages. Whole-rock measurements of metabasites were collected from papers and theses identified through targeted Google Scholar and ProQuest searches using combinations of the following keywords: whole-rock, bulk-rock, metabasite, metamorphism, basalt, prehnite-pumpellyite, greenschist, blueschist, amphibolite, granulite, and eclogite. In recent publications, data could often be copied directly from the PDF or online tables, whilst older data typically required the use of optical character recognition.

Only weight percent oxide values for individual rock samples analysed using bulk techniques such as wet chemistry, X-ray fluorescence, or Fusion Inductively Coupled Plasma Optical Emission Spectroscopy were included. The following major rock-forming components were analysed in all samples: SiO_2, TiO_2, Al_2O_3, FeO^{total}, MgO, and CaO. Over 98% of the samples included values for MnO, Na_2O, and K_2O, with the absence of these values typically due to concentrations falling below the detection limit of the analytical method. Where reported by the authors, determinations of P_2O_5, Fe_2O_3, H_2O^+, H_2O^-, CO_2, SO_3, and loss-on-ignition (LOI) have also been included. Fe_2O_3 was measured by titration, FeO was determined by difference, and volatiles were analysed by combustion (Gill, 1997). For separate determinations of volatiles, we combined H_2O^+ (structurally bound water), CO_2, and SO_3 together as an estimate for LOI (e.g. volatile content). We note that LOI and volatile content may not be equivalent, given the interference of ferrous-iron oxidation with LOI (Lechler & Desilets, 1987).

In this paper, we use the term metabasite in a broad sense to refer to a diverse range of metamorphosed mafic rocks, irrespective of their original protolith. Many papers and theses included whole-rock data from various metamorphosed rock types, including those that are not metabasites. Metamorphic rocks described as ultramafic, granitic, felsic, acidic, or sedimentary (e.g. banded iron formations, greywackes, Qz-bearing gneisses) were excluded based on descriptions, mineral assemblages, and chemical analyses. In high-grade, migmatitic rocks, samples described as melanosomes, leucosomes, or selvedges were excluded, whilst samples described as metatexites, diatexites, and migmatites, which incorporate a mixture of leucosome/melanosome/mesosome/palaeosome were included. Also included were samples described by metamorphic facies nomenclature, such as greenschists, blueschists, amphibolites, granulites, or eclogites, as well as those identified by their protolith, including metabasalt, metadolerite, metadiabase, metagabbro, meta-basaltic-andesite, and metamafite. Applying a compositional filter—e.g. restricting analyses to those that lie within the basalt field of the TAS diagram (Le Bas *et al.*, 1986)—might ensure more uniform compositions. However, this approach would undermine the aim of this paper, which is to examine the variety of what is generally termed metabasites in metamorphic petrology. We acknowledge that this may introduce outliers into our database, and we address this problem by examining median values and employing median absolute deviation (MAD) and kernel density estimate (KDE) analyses.

The resulting database contains 6186 analyses from 253 studies categorised into 217 localities (Table 1). The database exhibits a significant skew, with most metabasites originating from North America (40.5%) and Europe (29.4%), and a notable proportion from Asia (15.4%). In contrast, samples from Africa (4.7%), Antarctica (1.6%), Oceania (4.7%), and South America (3.7%) are under-represented (Table 1).

TREATMENT OF DATA

Metamorphic facies assignment

'*A metamorphic facies is a set of metamorphic mineral assemblages, repeatedly associated in space and time, such there is a constant and therefore predictable relation between mineral composition and chemical composition* (Turner, 1981).' Whilst many petrologists commonly link metamorphic facies with specific P–T ranges, it is crucial to note that facies are fundamentally characterized by their mineral assemblages rather than directly by *P–T* conditions, which are interpretative. It is possible, albeit rare, to observe multiple facies within the same outcrop, which can be attributed to differences in bulk composition, kinetic factors, or variable degrees of retrogression. These instances do not imply a simultaneous *P–T* environment but rather reflect complex histories, including both prograde and retrograde metamorphic events. Thus, in this paper, facies were classified based on some combination of the mineral assemblage and facies description given by the original authors rather than on the *P–T* conditions recorded (Fyfe & Turner, 1966; Ghent, 2020).

Six metamorphic facies were used: low-grade (LG), greenschist (Gs), blueschist (Bs), amphibolite (A), granulite (Gr), and eclogite (E). Although we attempted to classify samples into more specific subcategories (e.g. epidote amphibolite vs amphibolite), the reported mineral assemblages were, in many cases, too ambiguous to make precise distinctions. Unmetamorphosed basaltic rocks have not been included. The low-grade category encompasses the zeolite and prehnite-pumpellyite facies. The greenschist facies includes rocks containing some combination of chlorite, epidote, actinolite, and albite, whilst blueschist facies rocks are characterised by the presence of modally abundant Na-amphibole. Amphibolite facies rocks contain hornblende and Ca-bearing plagioclase, whilst eclogite facies rocks contain omphacite and garnet, with minimal Na-amphibole and retrograde plagioclase. Granulite facies rocks include those with orthopyroxene and clinopyroxene (i.e. low-moderate-*P*) as well as those with clinopyroxene, garnet, and Ti-rich amphibole

Table 1: Geographic locations with metabasic major-element whole-rock geochemistry

Country	#L	#WR	LG	Gs	A	Gr	Bs	E	References
WORLDWIDE	**217**	**6186**	**556**	**1105**	**2017**	**1069**	**360**	**614**	
AFRICA	**12**	**290**		**24**	**145**	**78**		**43**	
Botswana	1	24		24					(Kampunzu *et al.*, 1998)
Cameroon	1	10						10	(Bouyo *et al.*, 2019)
Egypt	1	8			8				(Abdel-Karim, 2003)
Kenya	1	12			12				(Miyake, 1984)
Nigeria	2	34			34				(Olade & Elueze, 1979; Olajide-Kayode *et al.*, 2023)
Sierra Leone	1	27				2		25	(Hills & Haggerty, 1989)
South Africa	2	98			59	39			(Geringer, 1979; Zelt, 1980; Clifford *et al.*, 1981; McStay, 1991; Raith & Meisel, 2001)
Tanzania	1	47			10	37			(Coolen, 1980)
Togo	2	30			22			8	(Agbossoumondé *et al.*, 2013, 2017)
ANTARCTICA	**6**	**101**		**7**	**35**	**36**		**6**	(Blight & Oliver, 1977; Storey & Meneilly, 1985; Vincenzo *et al.*, 1997; Rao *et al.*, 2000; Grosch, 2005; Suda *et al.*, 2008; Palmeri *et al.*, 2018; Kim *et al.*, 2019)
ASIA	**47**	**951**	**37**	**232**	**307**	**197**	**74**	**85**	
China	5	105		13	19	18		55	(Zhang *et al.*, 2006; Wang *et al.*, 2014; Huang *et al.*, 2018; Lü *et al.*, 2019; Liu *et al.*, 2021; Yan *et al.*, 2022)
India	12	159		68	54	30	7		(Subramaniam, 1959; Babu, 1970; Naqvi, 1971; Sen & Ray, 1971; Subbarao, 1971; Ramaswamy & Murty, 1973; Hazarika, 1985; Honegger *et al.*, 1989; Prakash, 1994; Walia, 1996; Faak *et al.*, 2012; Srivastava, 2012; Singh, 2022)
Indonesia	1	17							(Parkinson, 1996)
Iran	1	9			9				(Fatehi & Ahmadipour, 2018)
Japan	12	244	7	106	77	14	36	4	(Seki *et al.*, 1964; Kanisawa, 1969, 1971; Ernst *et al.*, 1970; Yûjirô, 1971; Sawada, 1973; Honma, 1974; Kutsukake, 1975; Tagiri & Onuki, 1976; Hoshino, 1979; Onuki & Ishimoto, 1980; Goto & Banno, 1990; Arakawa *et al.*, 2001)
Nepal	1	4						4	(Li *et al.*, 2019)
Oman	3	99	30	11	25		23	10	(El-Shazly *et al.*, 1994; Einaudi *et al.*, 2000; Ishikawa *et al.*, 2005)
Pakistan	1	84			33	49			(Jan & Kempe, 1973; Jan, 1977, 1988)
Papua New Guinea	1	30			22		8		(Worthing & Crawford, 1996)
Russia	4	95				86		9	(Glukhovskiy & Moralev, 1993; Molina *et al.*, 2002; Turkina & Nozhkin, 2014; Turkina, 2023)
Saudi Arabia	1	5			5				(Nasseef & Gass, 1977)
South Korea	3	45			45				(So & Kim, 1975; So, 1978; Lee & Cho, 2020)
Taiwan	1	43		31	12				(Yui *et al.*, 1990)
Vietnam	1	12		3	6			3	(Zhang *et al.*, 2013)
EUROPE	**54**	**1819**	**23**	**294**	**620**	**244**	**184**	**440**	
Austria	1	7						7	(Miladinova *et al.*, 2022)
Croatia	1	12			12				(Pamić *et al.*, 2002)
Czechia	2	44			37	7			(Janousek *et al.*, 2006; Ilnicki *et al.*, 2020)
Finland	2	36				36			(Paavola, 1984; Nehring *et al.*, 2010)
France	4	57		8	15		17	17	(Carpenter, 1976; Triboulet, 1980; Piboule & Briand, 1985; Korh *et al.*, 2009; Pujol-Solà *et al.*, 2022)
Germany	2	79		9	28			42	(Okrusch *et al.*, 1989; Schüssler *et al.*, 1989; Massonne & Czambor, 2007)
Greece	7	435	3	55	15		131	223	(Katagas & Sapountzis, 1977; Katagas & Panagos, 1979; Schliestedt, 1986; Schliestedt & Matthews, 1987; Barr, 1989; Ganor *et al.*, 1996; Liati & Seidel, 1996; Grandy, 2000; Robson, 2000; Marschall, 2005; Bulle *et al.*, 2010; Hamelin *et al.*, 2018; Skelton *et al.*, 2019; Gyomlai *et al.*, 2021)
Ireland	2	45			45				(Ryan *et al.*, 1983; Leake, 2016)

(Continued)

Table 1: Continued

Country	#L	#WR	LG	Gs	A	Gr	Bs	E	References
Italy	9	194	10	18	28	44	30	62	(Hoffmann, 1970; Capedri *et al.*, 1977; Reinsch, 1979; Pognante *et al.*, 1982; Messiga *et al.*, 1983; Cortesogno *et al.*, 1984; Sills & Tarney, 1984; Mazzucchelli & Siena, 1986; Conti *et al.*, 1988; Bea & Montero, 1999; Giacomini *et al.*, 2005; Starr *et al.*, 2020a; Weber *et al.*, 2022)
Norway	5	275			134	125		15	(Heier, 1962; Misra & Griffin, 1972; Clough, 1977; Dekker, 1978; Clough & Field, 1980; Krogh, 1980)
Poland	2	21			21				(Puziewicz, 2006; Ilnicki *et al.*, 2013)
Russia	3	65		2	28	11		24	(Khodorevskaya, 2012; Rass *et al.*, 2014; Terentiev & Santosh, 2017)
Scotland	4	233		151	66	16			(Wilson & Leake, 1972; Graham, 1973, 1976; Skelton, 1992; Smith & Phillips, 2002; Feisel *et al.*, 2018)
Spain	6	149			122	5		19	(Bard, 1969, 1970; Suen, 1978; van der Wegen, 1978; Bard & Moine, 1979; Castro *et al.*, 1996; Molina & Montero, 2003; Lorda *et al.*, 2014; Villaseca *et al.*, 2015; Pujol-Solà *et al.*, 2022)
Switzerland	4	134		34	69			31	(Wenk *et al.*, 1974; Puschnig, 2000; Widmer, 2001; Decrausaz *et al.*, 2021)
Wales	1	33	10	17			6		(Nataraj, 1967; Bevins *et al.*, 1991)
N. AMERICA	**71**	**2504**	**393**	**496**	**680**	**441**	**93**	**4**	
Canada	32	1516	262	410	376	110	3		(Baragar, 1960, 1969; Jennings, 1969; Preto, 1970; Fletcher, 1971; Mummery, 1972; de Wit & Strong, 1975; Hall-Beyer, 1976; Kuniyoshi & Liou, 1976; Coish, 1977a, 1977b; Ghent *et al.*, 1977; Stamatelopoulou-Seymour & MacLean, 1977; Fryer & Jenner, 1978; Baragar *et al.*, 1979; Hynes, 1980; Jenner & Fryer, 1980; Jolly, 1980; Dostal *et al.*, 1983; Ouellet, 1988; Sevigny, 1988; Brons, 1989; Pattison, 1991; Sawyer, 1991; Laflèche *et al.*, 1992; Owen, 1993; Plint & Gordon, 1997; Hozjan, 1999; Zwanzig & Bailes, 2010; Gilbert, 2011; Syme & Whalen, 2012; Syme, 2014; Jørgensen, 2017; Starr, 2017; Jørgensen *et al.*, 2019; Starr & Pattison, 2019b; Geen, 2021; Lazzarotto *et al.*, 2023)
Greenland	8	243	8	6	109	120			(Preston, 1969; Glassley & Sørensen, 1980; Mengel, 1983; Schiøtte, 1988; Messiga *et al.*, 1990; Bevins *et al.*, 1991; Haynes, 1998; Polat *et al.*, 2003)
Mexico	1	27				27			(Culí *et al.*, 2023)
Panama	1	7			7				(Tournon *et al.*, 1989)
USA	29	711	123	80	188	184	90	4	(Buddington, 1952; Wilcox & Poldervaart, 1958; Engel & Engel, 1962; Coleman & Lee, 1963; Ernst *et al.*, 1970; Jolly, 1970; Jolly & Smith, 1972; Maxey, 1972; Ghent & Coleman, 1973; Jen, 1975; Bohman, 1976; Clark, 1976; Aleinikoff, 1977; Carden, 1978; Perfit *et al.*, 1980; Dungan *et al.*, 1983; Jayko, 1984; Weakliem, 1984; Davis & Plafker, 1985; Hollocher, 1985; Stoddard, 1985; Thurston, 1985; Schumacher, 1988; Alibert *et al.*, 1991; Harper, 1995; Walker & Murphy, 1995; Chocyk-Jaminski, 1998; Liogys & Jenkins, 2000; Chocyk-Jaminski & Dietsch, 2002; Brady *et al.*, 2004; Bruand *et al.*, 2011; Becker *et al.*, 2023)
OCEANIA	**16**	**292**	**70**	**21**	**103**	**66**	**6**	**8**	
Australia	12	230	50		96	66			(Binns, 1964; Bradley, 1972; Wilson, 1976; Stephenson, 1977, 1980; Stephenson & Hensel, 1982; McNaughton & Wilson, 1983; Nash, 1984; Sivell, 1986, 1988; Crawford & Keays, 1987; Sivell & Foden, 1988)
New Caledonia	1	21			7		6	8	(Spandler *et al.*, 2004)
New Zealand	3	41	20	21					(Cooper & Lovering, 1970; Sivell, 1984; Houghton, 1985)

(Continued)

Table 1: Continued

Country	#L	#WR	LG	Gs	A	Gr	Bs	E	References
S. AMERICA	**11**	**229**	**33**	**31**	**127**	**7**	**3**	**28**	
Brazil	5	132	6		119	7			(Gomes *et al.*, 1964; Kuyumjian, 1989; de Oliveira *et al.*, 1993; Bicalho *et al.*, 2019; Capistrano *et al.*, 2021)
Chile	1	9	9						(Levi, 1969)
Colombia	3	40	18	16	3			3	(Spadea *et al.*, 1987; Spadea & Espinosa, 1996; García-Ramírez *et al.*, 2017)
Ecuador	1	11					3	8	(John *et al.*, 2010)
Venezuela	1	37		15	5			17	(Mottana *et al.*, 1985)

Note: #L—number of localities, #WR—number of whole-rock analyses, LG—Low-grade facies, Gs—Greenschist facies, A—Amphibolite facies, Gr—Granulite facies, Bs—Blueschist facies, E—Eclogite facies

(i.e. higher-*P*; see Pattison, 2003). A total of 465 analyses (8%) could not be classified into specific metamorphic facies. This was either because they belong to a transitional category between two facies, or insufficient information was provided to make a clear classification. The distribution of analyses across metamorphic facies is as follows: 9.7% low-grade, 19.3% greenschist, 35.3% amphibolite, 18.7% granulite, 6.3% blueschist, and 10.7% eclogite (Table 1). A complete catalogue listing all analyses detailing sample names, metamorphic facies, literature references, and whole rock data can be found in Table S1.

Plotting and projections

Metabasite compositions, expressed in weight percent and normalized to 100% with all iron as FeO^{total}, were plotted on a TiO_2 versus Al_2O_3 diagram. This approach differentiates igneous basalts from cumulates which show lower TiO_2 contents and either higher Al_2O_3 due to plagioclase accumulation or lower Al_2O_3 due to pyroxene accumulation (Miller & Thöni, 1995). Additionally, metabasites were plotted on an *igneous* AFM diagram to distinguish between tholeiitic and calc-alkaline nature. This uses wt % analyses and the following formulae: Alkali's = $K+N=K_2O+Na_2O$, $F=FeO^{total}$, and $M = MgO$).

Metabasites exhibit considerable chemical variability within the 12-component system SiO_2–TiO_2–Al_2O_3–Fe_2O_3–FeO–MnO–MgO–CaO–Na_2O–K_2O–P_2O_5–H_2O system (Spear, 1993). Visualising geochemical differences on ternary diagrams requires selecting three components, necessitating the exclusion or combination of certain components and projection from specific phases. For initial analysis, all iron was assumed to be FeO (ferrous). MnO was omitted. Whole rock analyses were then reduced to the eight-component (SiO_2–Al_2O_3–FeO^{total}–MgO–CaO–Na_2O–K_2O–H_2O) system using projections from apatite and ilmenite to remove P_2O_5 and TiO_2, respectively. The ilmenite projection is probably not valid at higher pressures where Ti may also or instead reside in rutile. Many metabasites lack quartz, making projection from quartz less rigorous when compared to metapelites, but we assume its presence for uniformity of treatment. Additionally, we project through H_2O, assuming H_2O saturated conditions, even though this assumption may not be valid in the eclogite and granulite facies (see Spear, 1993 for a discussion of both projections).

Metamorphic ternary diagrams utilise mol % values. To plot analyses in an ACN diagram, we ignore FeO^{total}, MgO, and K_2O and use the following formulae: $A = AlO_{3/2}$, C=CaO, and $N=NaO_{1/2}$ (after Spear, 1993). Whole-rock analyses are plotted in the ACFM tetrahedron using the following formulae: $A' = AlO_{3/2}-NaO_{1/2}-KO_{1/2}$, C=CaO, $F=FeO^{total}$, and M = MgO. The A' component here is calculated as in Forshaw *et al.* (2019), whereby the formula of Eskola (1920) is used, but with the A' coordinate expanded as in Spear (1993). Plotting the classical ACF diagram of Eskola (1920) requires Fe^{total} and Mg to be lumped together as a single component ($F+M = FeO^{total}+MgO$). One major shortcoming of this lumping is obscuring variation in $X_{Mg} = MgO/(Fe^{total}+MgO)$. Therefore, we plot a *metamorphic* AFM diagram in which $A^{0.5} = Al_2O_3$ (note the difference between A, A', and $A^{0.5}$); this requires additional projection from an average plagioclase composition (An_{33}) and idealised epidote (Laird, 1980; Spear, 1993). Whilst epidote and plagioclase projections are only valid for upper greenschist and lower amphibolite facies rocks, all whole-rock compositions were projected the same way to allow comparison. We emphasize that the ternary diagrams presented here are designed only to show compositional variability; none of them can rigorously assess the phase relations of metabasites due to the excessive number of important components (Spear, 1993).

Statistical analysis

As in Forshaw & Pattison (2023b), we use median values as measures of central tendency as these are least susceptible to outliers (Rock, 1988). Histograms of each element illustrate the distribution of all analyses and verify that the median values are close to the mode (see Supplemental Material). As measures of dispersion, we use median absolute deviations (MAD), kernel density estimates (KDE), and letter-value plots. MADs are provided alongside median values in Table 2. Two-dimensional KDEs are used to show the spread between variables on ternary diagrams in Fig. 1. Letter-value plots are used to depict the spread in each element for each metamorphic facies (Fig. 2). Letter-value plots extend traditional box-and-whisker plots by showing multiple quantiles beyond the median, quartiles, and whiskers, offering a detailed depiction of data distribution at various levels of granularity (Hofmann *et al.*, 2017). These were chosen over KDEs for this visualisation because they are less susceptible to bandwidth choice.

Compositional data are inherently multivariate, have a constant sum, and are thus constrained by the closure problem (Chayes, 1960). Compositional biplots were constructed to examine relationships in the components' covariance and distribution of the components themselves (Aitchison & Greenacre, 2002). No consistent patterns were found among the elements between different metamorphic facies (see Supplemental Material). Since interpreting log-ratio values and their associated biplots can be challenging (Rock, 1989), we use wt % oxides in our facies comparison (Forshaw & Pattison, 2023b).

Table 2: Median metabasite compositions

Facies		SiO_2	TiO_2	Al_2O_3	FeO^{total}	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	X_{Mg}	$Fe^{3+}/\Sigma Fe$	X^*_{Mg}
		(wt %)											(calculated from mol %)		
World-wide	MED	51.36	1.33	15.47	11.48	0.20	6.83	9.84	2.82	0.50	0.18		0.51	0.26	0.58
	MAD	3.40	0.82	1.97	2.50	0.06	2.25	2.34	1.05	0.61	0.16		0.09	0.12	0.10
	n	6186	6186	6186	6186	6068	6186	6186	6166	6158	5698		6186	3153	3153
All-MORB Mean		50.69	1.69	14.76	10.48	0.18	7.61	11.44	2.80	0.16	0.18		0.56		
AOC Composite		50.29	1.74	12.31	12.61	0.23	6.35	13.31	2.35	0.63	0.17		0.47	0.51	0.65
Lower Cont Crust		48.60	1.40	18.10	10.44	0.18	6.87	10.11	2.85	1.22	0.23		0.54		
Continental THB		48.62	0.71	17.72	8.55	0.16	10.03	11.54	2.45	0.16	0.08		0.68		
Intra-oceanic THB		50.76	0.59	15.46	8.86	0.16	11.15	10.86	1.89	0.17	0.09		0.69		
Back-arc basin THB		49.86	1.11	16.30	8.41	0.16	9.92	11.34	2.56	0.21	0.13		0.68		
Continental CAB		50.67	1.32	16.29	8.25	0.14	9.03	9.34	3.32	1.23	0.42		0.66		
Intra-oceanic CAB		49.20	0.69	12.92	9.69	0.20	12.93	11.21	1.99	0.97	0.20		0.70		
Low-grade	MED	52.03	1.67	14.99	11.85	0.20	6.26	8.84	3.17	0.78	0.20	2.80	0.48	0.36	0.59
	MAD	2.84	0.68	1.60	2.34	0.05	2.03	2.50	0.94	0.77	0.10	1.04	0.09	0.14	0.11
	n	556	556	556	556	515	556	556	541	556	469	514	556	387	387
Greenschist	MED	51.97	1.20	15.65	10.94	0.18	7.00	9.47	3.01	0.38	0.18	3.12	0.52	0.24	0.60
	MAD	3.79	0.75	1.95	2.14	0.05	2.54	2.71	1.14	0.61	0.18	1.61	0.10	0.12	0.12
	n	1105	1105	1105	1105	1059	1105	1105	1103	1094	997	1009	1105	652	652
Amphibolite	MED	51.08	1.30	15.53	11.61	0.20	6.84	10.17	2.58	0.52	0.18	1.27	0.51	0.25	0.56
	MAD	3.23	0.83	1.96	2.30	0.05	2.08	2.09	0.83	0.56	0.15	0.81	0.09	0.11	0.10
	n	2017	2017	2017	2017	2009	2017	2017	2015	2013	1909	1627	2017	1138	1138
Granulite	MED	50.28	1.27	15.52	12.38	0.21	6.89	10.12	2.54	0.62	0.18	0.59	0.50	0.21	0.56
	MAD	3.40	0.68	2.10	2.76	0.06	2.32	1.90	0.93	0.51	0.18	0.54	0.09	0.09	0.08
	n	1069	1069	1069	1069	1063	1069	1069	1069	1069	945	783	1069	494	494
Blueschist	MED	51.84	1.71	15.79	11.22	0.19	6.33	8.52	3.65	0.56	0.20	2.70	0.50	0.36	0.61
	MAD	3.99	0.78	2.20	2.35	0.15	2.09	3.37	1.38	0.89	0.16	1.94	0.09	0.14	0.08
	n	360	360	360	360	354	360	360	360	358	340	323	360	228	228
Eclogite	MED	51.55	1.44	15.17	10.95	0.20	7.05	9.85	3.46	0.22	0.13	1.10	0.52	0.23	0.60
	MAD	3.24	1.48	2.15	3.19	0.06	2.46	2.24	1.54	0.62	0.24	0.71	0.11	0.13	0.11
	n	614	614	614	614	607	614	614	613	605	581	539	614	174	174

Note: Median wt % oxide values did not sum to 100%, so they were renormalised with all iron as FeO^{total} and volatiles (loss-on-ignition [LOI], H_2O^+, CO_2, and SO_3) removed. Median absolute deviations (MAD) for each wt % oxide were scaled by the same factor used for renormalisation of the median (e.g. if the median total was 98.4%, MAD values were scaled by 1.02 = 100/98.4). X_{Mg}, $Fe^{3+}/\Sigma Fe$, X^*_{Mg} are defined in the text. The MAD for these variables was calculated directly from X_{Mg}, $Fe^{3+}/\Sigma Fe$, and X^*_{Mg} without incorporating error propagation from MgO, FeO^{total}, FeO, or Fe_2O_3. Therefore, the MAD for these values represents the spread of the variables themselves, rather than the propagated uncertainty from variability in the MgO, FeO^{total}, FeO, or Fe_2O_3; ALL-MORB Mean (Gale *et al.*, 2013). AOC Site 801 Super Composite (Kelley *et al.*, 2003; Brounce *et al.*, 2019). Lower Cont Crust (mafic end-member 45–50% composition; Hacker *et al.*, 2015). Continental THB and CAB (Cascades), Intra-oceanic and back-arc basin THB (Izu-Bonin), Intra-oceanic CAB (Vanatu; Schmidt & Jagoutz, 2017). All literature compositions renormalised to 100%. Abbreviations: MED—median, MAD—median absolute deviation, *n*—number of analyses, MORB—Mid-ocean ridge basalt, AOC—Altered Oceanic Crust THB—Tholeiitic basalt, CAB—Calc-alkaline basalt.

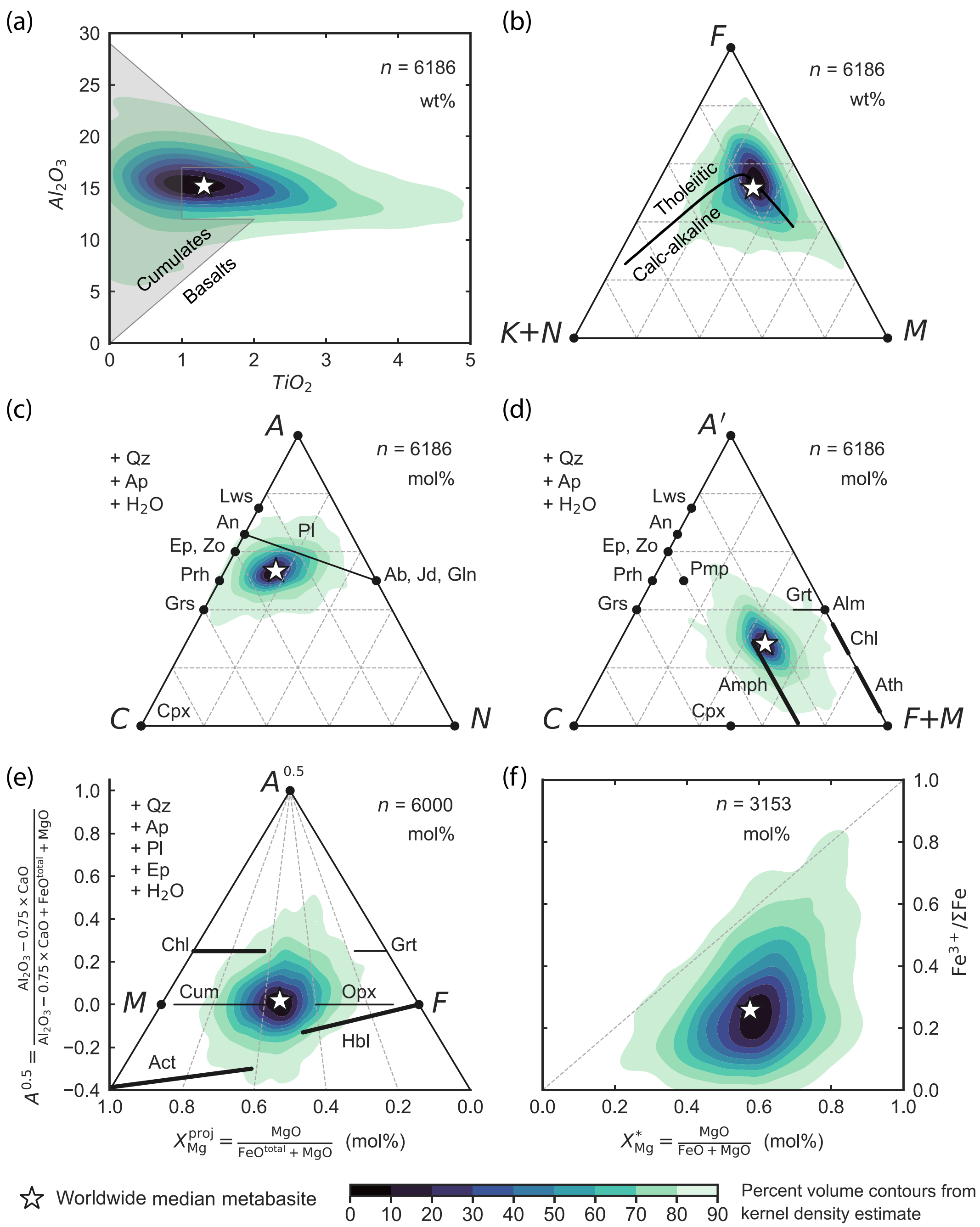

Figure 1. Distribution of metabasic whole-rock analyses. (a) Contoured KDE of Al_2O_3 versus TiO_2 (wt %). Cumulate and basalt delineation is as shown by Miller & Thöni (1995). (b) Contoured KDE of an igneous AFM (Alkali's K_2O+Na_2O, FeO^{total}, and MgO; wt %) diagram. Tholeiitic and calc-alkaline boundary after Rollinson & Pease (2021). (c/d) Contoured KDE of ACN and ACF diagrams after projection from apatite, ilmenite, quartz, and H_2O. (e) Contoured KDE of a metamorphic AFM diagram after projection from average plagioclase (An_{33}), epidote, apatite, ilmenite, quartz, and H_2O. (f) Contoured KDE of $Fe^{3+}/\Sigma Fe$ versus X^*_{Mg} for analyses where FeO was measured using titration. Median worldwide metabasite composition (star). Mineral abbreviations are after Warr (2021).

COMPOSITIONAL VARIABILITY

Variation diagrams

On the igneous TiO_2 versus Al_2O_3 diagram, metabasic whole-rock analyses span the basalt-cumulate divide, displaying the widest variation in TiO_2 (Fig. 1a). On the *igneous* AFM diagram, the peak of the KDE intersects the boundary between calc-alkaline and tholeiitic rock series (Fig. 1b), with a greater proportion of analyses being tholeiitic. All analyses show a wide range in FeO^{total} and MgO (Fig. 1b). On the ACN diagram, metabasic whole-rock analyses form an ellipse, showing the greatest spread in Ca and Na, with relatively less variation in Al (Fig. 1c). The 50% VPC-KDE (volume per cent contour of the kernel density estimate) covers A = 0.48–0.60, C = 0.20–0.41, and N = 0.06–0.24 (Fig. 1c). The greater variation in Na and Ca could be attributed to spilitisation, which increases Na contents, and epidotisation, which increases Ca contents (Fig. 1c). On the ACF diagram, metabasic whole-rock analyses form an ellipse with the greatest spread in Al and Fe^{total}+Mg and relatively less variation in Ca (Fig. 1d). Fifty per

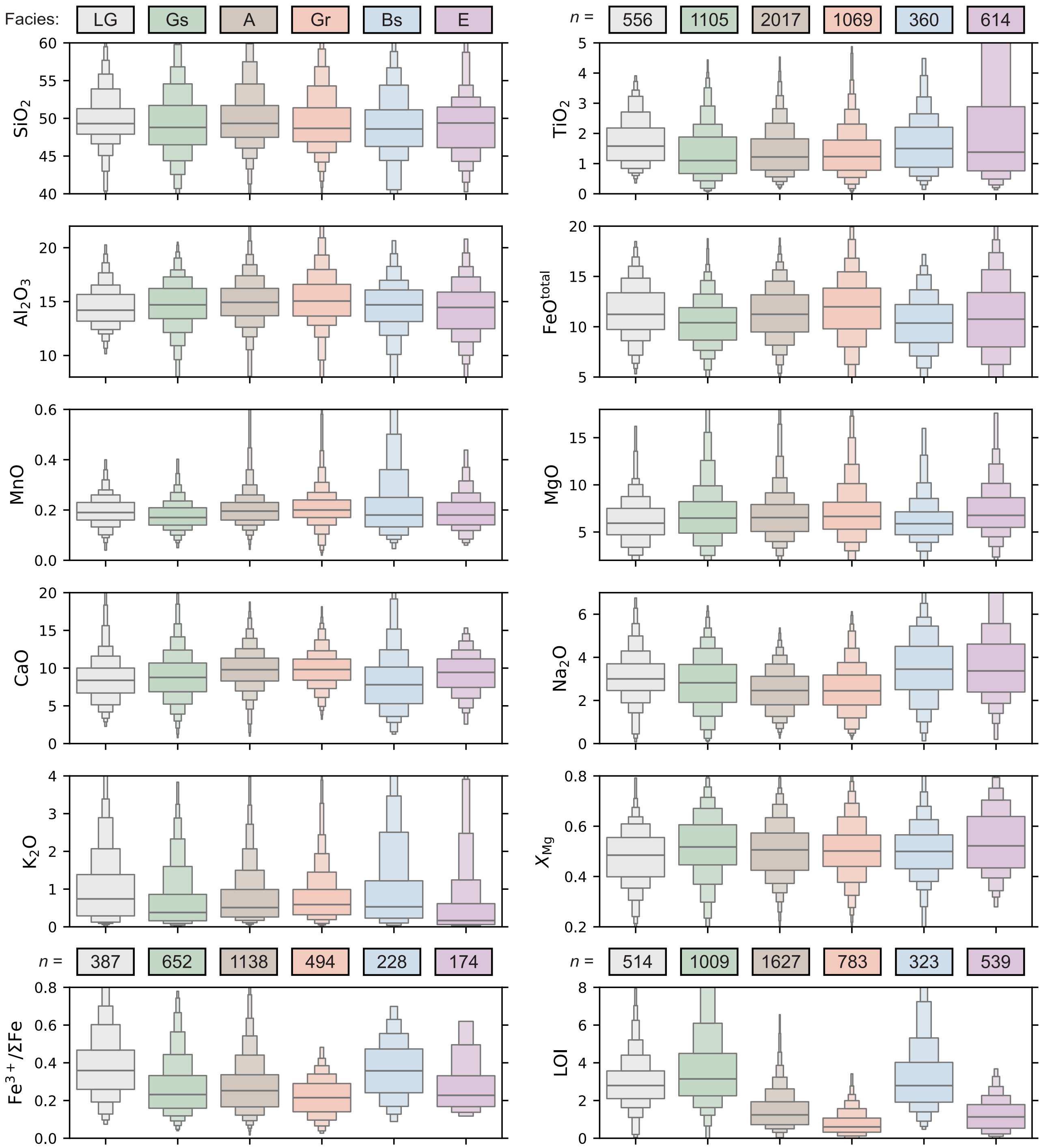

Figure 2. Letter-value plots depicting compositional ranges for each metamorphic facies. Data include elemental oxides and loss-on-ignition (LOI) in wt %, with $Fe^{3+}/\Sigma Fe$ and X_{Mg} calculated from mol %. The widest box shows the interquartile range (50% of the data) and the median value as a horizontal line. The second widest boxes (directly above and below the widest box) represent 25% of the data, the third widest boxes 12.5% of the data, and so forth. Metamorphic facies: Low-grade (LG), Greenschist (Gs), Amphibolite (A), Granulite (Gr), Blueschist (Bs), and Eclogite (E). The number of analyses in each category can be found in Table 2, with key differences between the number of analyses in elements or elemental ratios summarised in coloured boxes here.

cent of metabasites fall within the ranges $A' = 0.22–0.37$, $C = 0.18–0.30$, and $F+M = 0.37–0.56$, as indicated by the 50% VPC-KDE (Fig. 1d). Of the 6186 analyses, 186 plotted at anomalously low or high $A^{0.5}$ values (>1.0 or < 0.4) after projection from average plagioclase and epidote, which are not shown in Fig. 1e. On the metamorphic AFM diagram, metabasic whole-rock analyses show similar variations in Al, Fe^{total}, and Mg, with the 50% VPC-KDE covering $A^{0.5} = -0.13–0.17$ and X_{Mg}^{proj}=0.34–0.64 (Fig. 1e).

$Fe^{3+}/\Sigma Fe$

3153 analyses in the database had FeO measured by titration, permitting an estimate of the whole-rock $Fe^{3+}/\Sigma Fe$ and in turn $X^*_{Mg}=Mg/(Fe^{2+}+Mg)$. We note that $Fe^{3+}/\Sigma Fe$ is defined using molar quantities and is equivalent to the following variables used to describe the oxidation state of metamorphic rocks: $X_{Fe^{3+}} = Fe^{3+}/(Fe^{2+}+Fe^{3+}) = 2xFe_2O_3/(2xFe_2O_3+FeO)$ = Oxidation Ratio/100 (Chinner, 1960; Diener & Powell, 2010; Forshaw & Pattison, 2023a).

The 50% VPC-KDE covers a wide range of $Fe^{3+}/\Sigma Fe = 0.08–0.43$ and X^*_{Mg}=0.42–0.72 (Fig. 1f). The median worldwide metabasite has $Fe^{3+}/\Sigma Fe = 0.26 \pm 0.12$ and X^*_{Mg}=0.56±0.10, compared to X_{Mg} = 0.51±0.09 for all 6186 samples assuming all iron is FeO (Table 2).

Metamorphic facies

Fig. 2 shows compositional ranges for each metamorphic facies. A decrease in volatile content with increasing metamorphic grade is well-documented in metamorphic rocks (Fyfe *et al.*, 1978). Mafic rocks are predominantly anhydrous when crystallised and become variably hydrated at low temperatures before undergoing metamorphism. The extent of pre-metamorphic alteration in the protolith influences LOI content, accounting for the wide range of LOI values observed in rocks from lower-temperature facies (Fig. 2). The median and distribution of LOI are comparable for low-grade, greenschist, and blueschist facies rocks, all of which exhibit higher LOI than the other facies. A progressive decrease is observed from the greenschist to amphibolite and then granulite facies, similar to the trend found in pelitic rocks (Forshaw & Pattison, 2023b). Median LOI contents for blueschist and eclogite facies metabasites in this study (Bs = 2.7 and E = 1.1) are lower than the average LOI contents of lawsonite-bearing blueschists and eclogites (Lws-Bs = ~5.0 and Lws-E = ~3.0; Whitney *et al.*, 2020). Median $Fe^{3+}/\Sigma Fe$ is higher in the low-grade and blueschist facies, but comparable across the other facies (Fig. 2). A similar trend in median $Fe^{3+}/\Sigma Fe$ was found for the pelites, in which $Fe^{3+}/\Sigma Fe$ decreased from diagenetic shales up to the biotite zone in pelites (roughly greenschist facies in metabasites) and remained constant in higher grade zones (Forshaw & Pattison, 2023b). To evaluate variations in other major elements between facies, analyses were normalised to 100% on a volatile-free basis, with iron as FeO^{total}.

Median values and distribution patterns show no significant variation as a function of metamorphic facies for several major elements, including SiO_2, Al_2O_3, MnO, MgO, and K_2O (Fig. 2). Median TiO_2 is relatively higher in low-grade and blueschist facies rocks, and TiO_2 shows greater variability in eclogite facies samples. Median Na_2O is elevated in blueschist and eclogite facies rocks, whilst median CaO is lower in blueschist facies samples. Median FeO^{total} is slightly higher for the granulite facies than other metamorphic facies. The elevated Na_2O and lower CaO contents suggest increased spilitisation in blueschist facies rocks compared to other metamorphic facies (Vallance, 1974). This likely reflects sampling bias, where geologists tend to collect and analyse blueschist facies rocks rich in Na-amphiboles, which are prevalent in metaspilites. The greater variation in TiO_2 contents for eclogite facies rocks reflects the many Ti-rich, Fe–Ti gabbro samples included from Robson (2000); Fe–Ti gabbros and basalts typically contain zircon and, therefore, may be oversampled. Additionally, granulite facies metabasites show increased FeO^{total}, possibly due to the preferential analysis of garnet-bearing samples, an Fe^{2+}-rich mineral useful for thermobarometry.

DISCUSSION

Our comparison revealed only subtle compositional differences between metamorphic facies, apart from LOI and $Fe^{3+}/\Sigma Fe$. Therefore, we calculated a worldwide median metabasite with volatiles removed and all iron as FeO^{total} (Table 2; Fig. 1). This median gives equal weight to all analyses, which biases it towards amphibolite and granulite facies rocks, the most abundant in the database. Table 2 compares the worldwide median metabasite, and median metabasites for each metamorphic facies, with several mean and representative mafic igneous compositions from the literature. Literature compositions are within one MAD of the worldwide median metabasite for most elements. Notable exceptions include the low Al_2O_3 of altered oceanic crust and intra-oceanic calc-alkaline basalts, high K_2O of mafic lower continental crust and continental calc-alkaline basalts, and high X_{Mg} (i.e. low FeO and high MgO) of continental arc, intra-oceanic arc, and back-arc basin basalts (Table 2). Future work may benefit from compiling trace-element data where available to further distinguish compositional trends in metabasites across tectonic settings, though this would require careful consideration of data quality and analytical consistency given the variability in techniques over recent decades.

Iron, as the most abundant element with a variable valence state, plays a crucial role in controlling the redox budget of global rock cycles and the fluid-buffering capacity of rocks during metamorphism (Evans, 2006, 2012). Most of the literature compositions in Table 2 do not include measurements of $Fe^{3+}/\Sigma Fe$. Bézos *et al.* (2021) highlighted that '*the accurate and precise determination of the iron oxidation state ratio of MORB glasses has been a matter of controversy for the last three decades. None of the wet chemical methods used in the literature to measure this ratio converge toward a consensus value. The same difficulties have been observed for the most recent data obtained by XANES spectroscopy.*' Bézos *et al.* (2021) found that colorimetric measurements tend to overestimate ferrous iron in sulfide-bearing samples. By recalculating $Fe^{3+}/\Sigma Fe$ for 49 MORB glasses, they determined an average of 0.10 ± 0.02, which aligns with corrected colorimetric data (0.07±0.03, n = 78, Christie *et al.*, 1986), previous titration results (0.12±0.02, n = 104, Bézos & Humler, 2005), and some XANES measurements (0.10±0.02, n = 42, Berry *et al.*, 2018), but not others (0.16±0.01, n = 103, Cottrell & Kelley, 2011; 0.14±0.01, n = 103, Zhang *et al.*, 2018). Discrepancies are attributed to differences in the XANES spectra calibration, particularly the use of Mössbauer spectroscopy, which is subject to ongoing debate regarding acquisition conditions and data interpretation (Berry & O'Neill, 2021; Bézos *et al.*, 2021).

Given that most metabasites in the database likely did not develop at mid-ocean ridges, and that they have been variably hydrated and hydrothermally altered, it is important to compare them to basalts other than MORB. Rutter (2015), based on over 3000 titrations of variably altered ODP samples, estimated the average $Fe^{3+}/\Sigma Fe$ of young and old ocean crust to be 0.21 ± 0.04 and 0.23 ± 0.04, respectively. Brounce *et al.* (2019) determined by colorimetry a considerably higher average $Fe^{3+}/\Sigma Fe$ of 0.51 for altered oceanic crust at ODP site 801 (Table 2). These differences are likely due to Rutter's (2015) inclusion of both fresh and a range of altered samples, whilst Brounce *et al.* (2019) focused explicitly on altered oceanic crust. Using μ-XANES, several studies have shown that the $Fe^{3+}/\Sigma Fe$ of olivine-hosted melt inclusions representative of arc basalt magmas are more oxidised than MORB (reported $Fe^{3+}/\Sigma Fe$ values are not given here due to their sensitivity to the choice of XANES spectra calibration; Kelley & Cottrell, 2012; Gaborieau *et al.*, 2020; Cottrell *et al.*, 2021).

The observed median $Fe^{3+}/\Sigma Fe$ in our database is greater than that of MORB glass, lower than that of altered oceanic crust, and similar to that of arc basalts and the average of variably altered young and old ocean crust. However, the reliability of titration $Fe^{3+}/\Sigma Fe$ analyses, which make up the majority of our database, is also questionable due to several potential interferences (Flanagan, 1986; Potts, 1992). These include oxidation during modern surface weathering, the introduction of 'tramp' iron from steel crushing equipment, the oxidation of Fe^{2+}-bearing

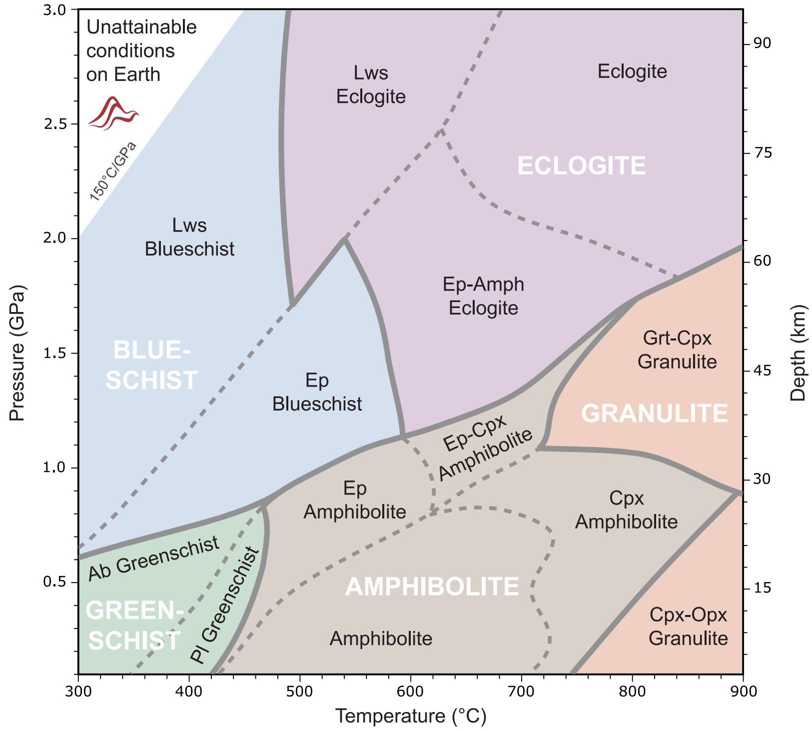

Figure 3. Predicted distribution of the metamorphic facies and their constituent subfacies as a function of pressure and temperature for the worldwide median metabasite ($Fe^{3+}/\Sigma Fe = 0.26$). Fields were delineated using the Gibbs-free energy minimiser MAGEMin (Riel *et al.*, 2022), an internally consistent thermodynamic dataset (Holland & Powell, 2011) and solution models (Green *et al.*, 2016). See Supplemental Material for further details.

minerals during grinding, the reduction of Fe^{3+} during solution if S^{2-} is present in soluble sulphide minerals, and the incomplete dissolution of Fe^{2+}-bearing porphyroblasts (Stokes, 1901; Mauzelius, 1907; Hillebrand, 1908; Schafer, 1966; Ritchie, 1968; Fitton & Gill, 1970; French & Adams, 1972; Atkin, 1977; Reay, 1981; Whipple *et al.*, 1984; O'Neill *et al.*, 1993; Saikkonen & Rautiainen, 1993; Canil *et al.*, 1994). The impact of each of these interferences, and consequently whether $Fe^{3+}/\Sigma Fe$ is overestimated or underestimated, largely depends on specific sample characteristics, processing procedures, and analytical methods.

If the median $Fe^{3+}/\Sigma Fe$ of 0.26±0.12 determined here is not an analytical artefact, there must be a modally abundant and commonly occurring mineral with moderate to high Fe^{total} and moderate to high $Fe^{3+}/\Sigma Fe$ in each facies. In the low-grade and blueschist facies, pumpellyite, chlorite, epidote, and Na-amphiboles are possible candidates (Borg, 1956; Makanjuola & Howie, 1972; Zen, 1974). In the greenschist and amphibolite facies, epidote, actinolite, and hornblende are abundant and may contain substantial Fe^{3+} (Tilley, 1938; Buddington, 1952; Engel & Engel, 1962; Bard, 1970; Cooper, 1972; Wenk *et al.*, 1974; Starr & Pattison, 2019a). In the eclogite facies, omphacite is the only mineral with moderate $Fe^{3+}/\Sigma Fe$, but it has low to moderate Fe^{total} (Alderman, 1936; Switzer, 1945; Coleman *et al.*, 1965; Binns, 1967; Walters *et al.*, 2020). In the granulite facies, hornblende, if present, is modally minor, whilst orthopyroxene, clinopyroxene, and garnet only contain small amounts of Fe^{3+} (Binns, 1962, 1965a, 1965b; Engel *et al.*, 1964; Davidson, 1968, 1971; Ray & Sen, 1970; Sen & Ray, 1971; Jen & Kretz, 1981; Forshaw *et al.*, 2019). This uncertainty regarding which minerals host Fe^{3+} and the quantity present in each highlights the need for further study of the distribution of iron in metabasic minerals and rocks across all metamorphic facies. A similar disparity between $Fe^{3+}/\Sigma Fe$ from titration and that obtained by combining mineral modes with their estimated $Fe^{3+}/\Sigma Fe$ exists in metapelites (Forshaw & Pattison, 2023a, 2023b), suggesting that this is a universal problem. Insights may come from new in-situ synchrotron analyses (e.g. Dyar *et al.*, 2002; Masci *et al.*, 2019; Aulbach *et al.*, 2022; Marras *et al.*, 2024) or compilations of older wet chemical data (e.g. Forshaw & Pattison, 2021; Dubacq & Forshaw, 2024).

Fe^{3+} plays a critical role in the phase equilibria of metabasites, with many previous studies exploring this topic in detail (Diener & Powell, 2010; Rebay *et al.*, 2010; Palin *et al.*, 2016). Therefore, we do not extensively discuss this here; instead, we calculated equilibrium assemblage diagrams for the worldwide median metabasite using $Fe^{3+}/\Sigma Fe = 0$ and $Fe^{3+}/\Sigma Fe = 0.26$, providing a reference point for the predicted phase equilibria of this composition (Fig. S4–7). Figure 3 shows the predicted distribution of the metamorphic facies and their constituent subfacies as a function of pressure and temperature for the worldwide median metabasite ($Fe^{3+}/\Sigma Fe = 0.26$).

CONCLUSIONS

Major-element metabasite compositions vary due to differences in igneous crystallisation conditions, the extent of hydrothermal or metasomatic alteration, and whether they originate from mafic igneous rocks or certain calcareous sediments. This study compiled a database of 6186 major-element whole-rock analyses of metabasites from different metamorphic facies. It complements an earlier study of similar aims and scope concerned with metapelites (Forshaw & Pattison, 2023b). SiO_2, Al_2O_3, MnO, MgO, and K_2O show no significant variation as a function of metamorphic facies. Small variations in TiO_2, FeO, CaO, and Na_2O amongst facies are interpreted to represent sampling bias. Titration measurements indicate that Fe^{3+} is a significant component of the total Fe in metabasites. Further work is needed to ascertain the distribution of Fe^{3+} amongst minerals in metabasic rocks and whether the median $Fe^{3+}/\Sigma Fe$ of 0.26±0.12 is reliable or affected by analytical interferences. Changes in the proportions of major elements, particularly $Fe^{3+}/\Sigma Fe$, affect calculated phase equilibria significantly and, consequently, estimates of *P*–*T* conditions.

CONFLICTS OF INTEREST/COMPETING INTERESTS

Not applicable.

AVAILABILITY OF DATA AND MATERIAL

Not applicable.

CODE AVAILABILITY

Not applicable.

SUPPLEMENTARY DATA

Supplementary data are available at *Journal of Petrology* online.

ACKNOWLEDGEMENTS

We appreciate the efforts of the petrologists who performed the whole rock chemical analyses used in this study, particularly those who determined $Fe^{3+}/\Sigma Fe$ through titration. We are grateful to D. Pattison for valuable discussions on $Fe^{3+}/\Sigma Fe$ in metamorphic rocks and for his insightful comments on the manuscript that enhanced its clarity. We also thank E. Green and R. Powell for stimulating discussions surrounding the $Fe^{3+}/\Sigma Fe$ of metamorphic minerals and how current phase equilibrium models deal with Fe^{3+}. D. Hernández Uribe and two anonymous reviewers are thanked for their constructive comments. R. Gieré and G. Zellmer are thanked for their efficient editorial handling.

FUNDING

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant 850530).

REFERENCES

Abdel-Karim, A.-A. M. (2003). Mineralogy, geochemistry and petrogenetic implications of amphibolites from Wadi El-Seih area, central West Sinai, Egypt. *Egyptian Journal of Geology* **47**, 25–39.

Adams, F. D. (1909). On the origin of the amphibolites of the Laurentian area of Canada. *Journal of Geology* **17**, 1–18. https://doi.org/10.1086/621582.

Agbossoumondé, Y., Ménot, R.-P. & Nude, P. M. (2013). Geochemistry and Sm–Nd isotopic composition of the Agou igneous complex (AIC) from the pan-African orogen in southern Togo, West Africa: geotectonic implications. *Journal of African Earth Sciences* **82**, 88–99. https://doi.org/10.1016/j.jafrearsci.2013.02.007.

Agbossoumondé, Y., Ménot, R.-P. & de Araujo, C. E. G. (2017). Major, trace elements and Sr-Nd isotopic characteristics of high-pressure and associated metabasites from the Pan-African suture zone of southern Togo, West Africa. *Journal of Environment and Earth Science* **7**, 17–31.

Aitchison, J. & Greenacre, M. (2002). Biplots of compositional data. *Journal of the Royal Statistical Society Series C: Applied Statistics* **51**, 375–392. https://doi.org/10.1111/1467-9876.00275.

Alderman, A. R. (1936). Eclogites in the neighbourhood of Glenelg, Inverness-shire. *The Quarterly Journal of the Geological Society of London* **92**, 488–530. https://doi.org/10.1144/GSL.JGS.1935.091.01-04.24.

Aleinikoff, J. N. (1977). Petrochemistry and tectonic origin of the Ammonoosuc Volcanics, New Hampshire–Vermont. *GSA Bulletin* **88**, 1546–1552. https://doi.org/10.1130/0016-7606(1977)88<1546:patoot>2.0.co;2.

Alibert, C., Martin, P. & Lapierre, H. (1991). The origin of geochemical variations in a late permian volcanic arc, eastern Klamath Mountains, California. *Journal of Volcanology and Geothermal Research* **46**, 299–322. https://doi.org/10.1016/0377-0273(91)90090-m.

Arakawa, Y., Kouta, T. & Kanda, Y. (2001). Geochemical characteristics of amphibolites in the Oki metamorphic rocks, Oki-Dogo Island, southwestern Japan: mixed occurrence of amphibolites with different geochemical affinity. *Journal of Mineralogical and Petrological Sciences* **96**, 175–187. https://doi.org/10.2465/jmps.96.175.

Atkin, B. P. (1977) *A mineralogical and chemical study of the paragenesis of opaque minerals in the Donegal granites and their aureole rocks*. Eire: University of Liverpool, Liverpool, United Kingdom.

Aulbach, S., Woodland, A. B., Stagno, V., Korsakov, A. V., Mikhailenko, D. & Golovin, A. (2022). Fe^{3+} distribution and $Fe^{3+}/\Sigma Fe$-oxygen fugacity variations in kimberlite-borne eclogite xenoliths, with comments on clinopyroxene-garnet oxy-thermobarometry. *Journal of Petrology* **63**, egac076. https://doi.org/10.1093/petrology/egac076.

Babu, V. R. R. M. (1970). Petrology of metamorphic rocks of almandine-amphibolite facies in Saidapuram–Podalakuru area, Nellore district, Andhra Pradesh, India. *Tschermaks Mineralogische Und Petrographische Mitteilungen* **14**, 171–194. https://doi.org/10.1007/bf01089046.

Baragar, W. R. A. (1960). Petrology of basaltic rocks in part of the Labrador trough. *GSA Bulletin* **71**, 1589–1644. https://doi.org/10.1130/0016-7606(1960)71[1589:pobrip]2.0.co;2.

Baragar, W. R. A. (1969) *The Geochemistry of Coppermine River Basalts*. Ottawa: Geological Survey of Canada, Paper 69-44. https://doi.org/10.4095/106434.

Baragar, W. R. A., Plant, A. G., Pringle, G. J. & Schau, M. (1979). Diagenetic and postdiagenetic changes in the composition of an Archean pillow. *Canadian Journal of Earth Sciences* **16**, 2102–2121. https://doi.org/10.1139/e79-199.

Bard, J.-P. (1969) *Le métamorphisme régional progressif des Sierras D'Aracena en Andalousie Occidentale (Espagna). A place dans le segment Hercynien Sud-Ibérique*. Doctoral thesis, University of Montpellier, Montpellier, France.

Bard, J.-P. (1970). Composition of hornblendes formed during the hercynian progressive metamorphism of the Aracena metamorphic belt (SW Spain). *Contributions to Mineralogy and Petrology* **28**, 117–134. https://doi.org/10.1007/bf00404994.

Bard, J. P. & Moine, B. (1979). Acebuches amphibolites in the Aracena hercynian metamorphic belt (Southwest Spain): geochemical variations and basaltic affinities. *Lithos* **12**, 271–282. https://doi.org/10.1016/0024-4937(79)90018-5.

Barr, H. M. (1989) *Fluid-rock interactions during blueschist and greenschist metamorphism in the Aegean area of Greece*. Doctoral thesis. Edinburgh, United Kingdom: University of Edinburgh.

Barth, T. F. W. (1959). Principles of classification and norm calculations of metamorphic rocks. *The Journal of Geology* **67**, 135–152. https://doi.org/10.1086/626570.

Bea, F. & Montero, P. (1999). Behavior of accessory phases and redistribution of Zr, REE, Y, Th, and U during metamorphism and partial melting of metapelites in the lower crust: an example from the Kinzigite formation of Ivrea-Verbano, NW Italy. *Geochimica et Cosmochimica Acta* **63**, 1133–1153. https://doi.org/10.1016/s0016-7037(98)00292-0.

Becker, N.A., George, F.R., Guice, G.L., Crowley, J.L., Nelson, W.R., Browning-Hanson, J.F., Roy, S., and Viete, D.R. (2023) Subduction initiation recorded in the Dadeville Complex of Alabama and Georgia, southeastern United States. *Geosphere* **19**, 1729–1746. https://doi.org/10.1130/ges02643.1.

Berry, A. J., and O'Neill, H. St. C. (2021). Oxygen Content, Oxygen Fugacity, the Oxidation State of Iron, and Mid-Ocean Ridge Basalts. In Moretti, R. and Neuville D. R. eds., *Magma Redox Geochemistry. Geophysical Monograph Series*, American Geophysical Union and John Wiley and Sons, Inc. 155–163, https://doi.org/10.1002/9781119473206.ch8.

Berry, A. J., Stewart, G. A., O'Neill, H. St. C., Mallmann, G. & Mosselmans, J. F. W. (2018). A re-assessment of the oxidation state of iron in MORB glasses. *Earth and Planetary Science Letters* **483**, 114–123. https://doi.org/10.1016/j.epsl.2017.11.032.

Bevins, R. E., Robinson, D. & Rowbotham, G. (1991). Compositional variations in mafic phyllosilicates from regional low-grade metabasites and application of the chlorite geothermometer. *Journal of Metamorphic Geology* **9**, 711–721. https://doi.org/10.1111/j.1525-1314.1991.tb00560.x.

Bézos, A. & Humler, E. (2005). The $Fe^{3+}/\Sigma Fe$ ratios of MORB glasses and their implications for mantle melting. *Geochimica et Cosmochimica Acta* **69**, 711–725. https://doi.org/10.1016/j.gca.2004.07.026.

Bézos, A., Guivel, C., La, C., Fougeroux, T. & Humler, E. (2021). Unraveling the confusion over the iron oxidation state in MORB glasses. *Geochimica et Cosmochimica Acta* **293**, 28–39. https://doi.org/10.1016/j.gca.2020.10.004.

Bicalho, V., Remus, M. V. D., Rizzardo, R. & Dani, N. (2019). Geochemistry, metamorphic evolution and tectonic significance of metabasites from Caçapava do Sul, southern Brazil: Brazilian. *Journal of Geology* **49**, e20180039. https://doi.org/10.1590/2317-4889201920180039.

Binns, R. A. (1962). Metamorphic pyroxenes from the Broken Hill district, New South Wales. *Mineralogical Magazine and Journal of the Mineralogical Society* **33**, 320–338. https://doi.org/10.1180/minmag.1962.033.259.06.

Binns, R. A. (1964). Zones of progressive regional metamorphism in the Willyama Complex, Broken Hill District, New South Wales. *Journal of the Geological Society of Australia* **11**, 283–330. https://doi.org/10.1080/00167616408728577.

Binns, R. A. (1965a). Hornblendes from some basic hornfelses in the New England region, New South Wales. *Mineralogical Magazine and Journal of the Mineralogical Society* **34**, 52–65. https://doi.org/10.1180/minmag.1965.034.268.04.

Binns, R. A. (1965b). The mineralogy of metamorphosed basic rocks from the Willyama Complex, Broken Hill district, New South Wales. Part I. Hornblendes. *Mineralogical Magazine* **35**, 561–587. https://doi.org/10.1180/minmag.1965.035.272.01.

Binns, R. A. (1967). Barroisite-bearing Eclogite from Naustdal, Song og Fjordane, Norway. *Journal of Petrology* **8**, 349–371. https://doi.org/10.1093/petrology/8.3.349.

Blight, D. F. & Oliver, R. L. (1977). The metamorphic geology of the Windmill Islands, Antarctica: a preliminary account. *Journal of the Geological Society of Australia* **24**, 239–262. https://doi.org/10.1080/00167617708728986.

Bohman, R. P. (1976) *A Geochemical Study of the Portage Lake basalts in the Winona Quadrangle Houghton County, Michigan*. Masters thesis. Wayne State University, Detroit, Michigan, USA.

Borg, I. Y. (1956). Glaucophane schists and eclogites near Healdsburg, California. *GSA Bulletin* **67**, 1563–1584. https://doi.org/10.1130/0016-7606(1956)67[1563:gsaenh]2.0.co;2.

Bouyo, M. H., Penaye, J., Mouri, H. & Toteu, S. F. (2019). Eclogite facies metabasites from the Paleoproterozoic Nyong Group, SW Cameroon: mineralogical evidence and implications for a high-pressure metamorphism related to a subduction zone at the NW margin of the Archean Congo craton. *Journal of African Earth Sciences* **149**, 215–234. https://doi.org/10.1016/j.jafrearsci.2018.08.010.

Bradley, G. M. (1972) *The geochemistry of a medium pressure granulite terrain at Southern Eyre Peninsula, Australia*. Doctoral thesis. Australian National University, Canberra, Australia.

Brady, J.B., Mohlman, H.K., Harris, C., Carmichael, S.K., Jacob, L.J., and Chaparro, W.R. (2004). General geology and geochemistry of metamorphosed Proterozoic mafic dikes and sills, Tobacco Root Mountains, Montana *in* Brady, J.B., Burger, H.R., Cheney, J.T., and Harms, T.A. eds., *Precambrian Geology of the Tobacco Root Mountains, Montana*, Boulder, Colorado, Geological Society of America Special Paper 377, 89-104. https://doi.org/10.1130/0-8137-2377-9.89.

Brons, D. J. (1989) *Stratigraphy and metamorphism of mafic volcanic rocks near Arsenic Lake, Temagami, Ontario*. Masters thesis. Laurentian University, Sudbury, Ontario, Canada.

Brounce, M., Cottrell, E. & Kelley, K. A. (2019). The redox budget of the Mariana subduction zone. *Earth and Planetary Science Letters* **528**, 115859. https://doi.org/10.1016/j.epsl.2019.115859.

Bruand, E., Gasser, D., Bonnand, P. & Stuewe, K. (2011). The petrology and geochemistry of a metabasite belt along the southern margin of Alaska. *Lithos* **127**, 282–297. https://doi.org/10.1016/j.lithos.2011.07.026.

Buddington, A. F. (1952). Chemical petrology of some metamorphosed Adirondack gabbroic, syenitic and quartz syenitic rocks. *American Journal of Science* **Bowen volume**, 37–84.

Bulle, F., Bröcker, M., Gärtner, C. & Keasling, A. (2010). Geochemistry and geochronology of HP mélanges from Tinos and Andros, cycladic blueschist belt, Greece. *Lithos* **117**, 61–81. https://doi.org/10.1016/j.lithos.2010.02.004.

Canil, D., O'Neill, H. S. C., Pearson, D. G., Rudnick, R. L., McDonough, W. F. & Carswell, D. A. (1994). Ferric iron in peridotites and mantle oxidation states. *Earth and Planetary Science Letters* **123**, 205–220. https://doi.org/10.1016/0012-821x(94)90268-2.

Capedri, S., Garuti, G., Rivalenti, G., Rossi, A. & Sinigoi, S. (1977). The origin of the Ivrea-Verbano basic formation (Italian Western Alps)—whole rock geochemistry. *RENDICONTI Società Italiana di Mineralogia e Petrologia* **33**, 593–600.

Capistrano, G. G., Schmitt, R. S., Medeiros, S. R. & Vieira, T. A. T. (2021). Ediacaran ophiolite relics in the SE Brazilian coast: Field, geochemical and geochronological evidence from metabasites and paragneisses. *Journal of South American Earth Sciences* **105**, 103040. https://doi.org/10.1016/j.jsames.2020.103040.

Carden, J. R. (1978) *The comparative petrology of Blueschists and Greenschists in the Brooks Range and Kodiak-Seldovia Schist Belts*. Doctoral thesis. University of Alaska, Anchorage, Alaska, United States of America.

Carpenter, M. S. N. (1976) *Petrogenetic study of the glaucophane schists and associated rocks from the Ile De Groiz, Brittany, France*. Doctoral thesis. University of Oxford, Oxford, United Kingdom.

Castro, A., Fernandez, C., la Rosa, J. D. D., Moreno-Ventas, I. & Rogers, G. (1996). Significance of MORB-derived amphibolites from the Aracena Metamorphic Belt, Southwest Spain. *Journal of Petrology* **37**, 235–260. https://doi.org/10.1093/petrology/37.2.235.

Chayes, F. (1960). On correlation between variables of constant sum. *Journal of Geophysical Research* **65**, 4185–4193. https://doi.org/10.1029/jz065i012p04185.

Chinner, G. A. (1960). Pelitic gneisses with varying ferrous/ferric ratios from Glen Clova, Angus, Scotland. *Journal of Petrology* **1**, 178–217. https://doi.org/10.1093/petrology/1.1.178.

Chocyk-Jaminski, M. (1998) *Geochemistry and tectonic significance of meta-igneous rocks of the Gneiss Dome Belt, Southwestern New England Appalachians*. Doctoral thesis. University of Cincinnati, Cincinnati, Ohio, United States of America.

Chocyk-Jaminski, M. & Dietsch, C. (2002). Geochemistry and tectonic setting of metabasic rocks of the Gneiss Dome Belt, SW New England Appalachians. *Physics and Chemistry of the Earth, Parts A/B/C* **27**, 149–167. https://doi.org/10.1016/s1474-7065(01)00012-2.

Christie, D. M., Carmichael, I. S. E. & Langmuir, C. H. (1986). Oxidation states of mid-ocean ridge basalt glasses. *Earth and Planetary Science Letters* **79**, 397–411. https://doi.org/10.1016/0012-821x(86)90195-0.

Clark, M. D. (1976) *The geology and petrochemistry of the Precambrian metamorphic rocks of the Grand Canyon, Arizona*. Doctoral thesis. University of Leicester, Leicester, United Kingdom.

Clifford, T. N., Stumpfl, E. F., Burger, A. J., McCarthy, T. S. & Rex, D. C. (1981). Mineral-chemical and isotopic studies of Namaqualand granulites, South Africa: a grenville analogue. *Contributions to Mineralogy and Petrology* **77**, 225–250. https://doi.org/10.1007/bf00373538.

Clough, P. W. L. (1977) *The petrochemistry of metabasites from a precambrian amphibolite-granulite transition zone, South Norway*. University of Nottingham, Nottingham, United Kingdom.

Clough, P. W. L. & Field, D. (1980). Chemical variation in metabasites from a proterozoic amphibolite-granulite transition zone, South Norway. *Contributions to Mineralogy and Petrology* **73**, 277–286. https://doi.org/10.1007/bf00381446.

Coish, R. (1977a) *Igneous and metamorphic petrology of the mafic units of the Betts Cove and Blow-Me-Down ophiolites, Newfoundland*. Doctoral thesis. University of Western Ontario, London, Ontario, Canada.

Coish, R. A. (1977b). Ocean floor metamorphism in the Betts Cove ophiolite, Newfoundland. *Contributions to Mineralogy and Petrology* **60**, 255–270. https://doi.org/10.1007/bf01166800.

Coleman, R. G. & Lee, D. E. (1963). Glaucophane-bearing metamorphic rock types of the Cazadero Area, California. *Journal of Petrology* **4**, 260–301. https://doi.org/10.1093/petrology/4.2.260.

Coleman, R. G., Lee, D. E., Beatty, L. B. & Brannock, W. W. (1965). Eclogites and eclogites: their differences and similarities. *Geological Society of America Bulletin* **40**, 1965. https://doi.org/10.1130/0016-7606(1965)76[483:EAETDA]2.0.CO;2.

Conti, P., Pisa, A. D., Gattiglio, M., Meccheri, M. & Vietti, N. (1988). Nuovi dati sulle metabasiti di Valle del Giardino del basamento paleozoico apuano (Appennino settentrionale). *Atti della Società Toscana di Scienze Naturali, Memorie* **95**, 89–103.

Coolen, J. J. M. M. M. (1980) *Chemical petrology of the Furua granulite complex, southern Tanzania*. *Series 1*. GUA Papers of Geology, Geological Institute, Amsterdam, Netherlands.

Cooper, A. F. (1972). Progressive metamorphism of metabasic rocks from the Haast Schist Group of Southern New Zealand. *Journal of Petrology* **13**, 457–492. https://doi.org/10.1093/petrology/13.3.457.

Cooper, A. F. & Lovering, J. F. (1970). Greenschist amphiboles from Haast River, New Zealand. *Contributions to Mineralogy and Petrology* **27**, 11–24. https://doi.org/10.1007/BF00539538.

Cortesogno, L., Lucchetti, G. & Spadea, P. (1984). Pumpellyite in low-grade metamorphic rocks from Ligurian and Lucanian Apennines, Maritime Alps and Calabria (Italy). *Contributions to Mineralogy and Petrology* **85**, 14–24. https://doi.org/10.1007/bf00380217.

Cottrell, E. & Kelley, K. A. (2011). The oxidation state of Fe in MORB glasses and the oxygen fugacity of the upper mantle. *Earth and Planetary Science Letters* **305**, 270–282. https://doi.org/10.1016/j.epsl.2011.03.014.

Cottrell, E., Birner, S.K., Brounce, M., Davis, F.A., Waters, L.E., and Kelley, K.A. (2021). Oxygen Fugacity Across Tectonic Settings *in* Moretti, R. and Neuville D. R. eds., *Magma Redox Geochemistry: Geophysical Monograph Series*. American Geophysical Union and John Wiley and Sons, Inc. 33–61, https://doi.org/10.1002/9781119473206.ch3.

Crawford, A. J. & Keays, R. R. (1987). Petrogenesis of Victorian Cambrian tholeiites and implications for the origin of associated boninites. *Journal of Petrology* **28**, 1075–1109. https://doi.org/10.1093/petrology/28.6.1075.

Culí, L., Reche, J., Solé, J. & Ortega-Gutiérrez, F. (2023). Meso-Neoproterozoic basic-intermediate mafic granulites (metabasites) from the ∼1 Ga granulitic southwestern Oaxacan complex, Mexico, crustal evolution and phase equilibria modeling. *Lithos* **454**, 107239. https://doi.org/10.1016/j.lithos.2023.107239.

Davidson, L. R. (1968). Variation in ferrous iron-magnesium distribution coefficients of metamorphic pyroxenes from Quairading, Western Australia. *Contributions to Mineralogy and Petrology* **19**, 239–259. https://doi.org/10.1007/BF00508913.

Davidson, L. R. (1971) Metamorphic hornblendes from basic granulites of the Quairading district, Western Australia. *Neues Jahrbuch für Mineralogie - Monatschafte* **8**, 344–359.

Davis, A. & Plafker, G. (1985). Comparative geochemistry and petrology of Triassic basaltic rocks from the Taku Terrane on the Chilkat Peninsula and Wrangellia. *Canadian Journal of Earth Sciences* **22**, 183–194. https://doi.org/10.1139/e85-016.

Decrausaz, T., Müntener, O., Manzotti, P., Lafay, R. & Spandler, C. (2021). Fossil oceanic core complexes in the Alps. New field, geochemical and isotopic constraints from the Tethyan Aiguilles Rouges ophiolite (Val d'Hérens, Western Alps, Switzerland). *Swiss Journal of Geosciences* **114**, 3. https://doi.org/10.1186/s00015-020-00380-4.

Dekker, A. G. C. (1978) *Amphiboles and their host rocks in the high-grade metamorphic Precambrian of Rogaland/Vest-Agder, SW. Norway*. Doctoral thesis. Utrecht University, Utrecht, Netherlands.

Diener, J. F. A. & Powell, R. (2010). Influence of ferric iron on the stability of mineral assemblages. *Journal of Metamorphic Geology* **28**, 599–613. https://doi.org/10.1111/j.1525-1314.2010.00880.x.

Dostal, J., Baragar, W. R. A. & Dupuy, C. (1983). Geochemistry and petrogenesis of basaltic rocks from Coppermine River area, Northwest Territories. *Canadian Journal of Earth Sciences* **20**, 684–698. https://doi.org/10.1139/e83-062.

Dubacq, B. & Forshaw, J. B. (2024). The composition of metapelitic biotite, white mica, and chlorite: a review with implications for solid-solution models. *European Journal of Mineralogy* **36**, 657–685. https://doi.org/10.5194/ejm-36-657-2024.

Dungan, M. A., Vance, J. A. & Blanchard, D. P. (1983). Geochemistry of the Shuksan greenschists and blueschists, North Cascades, Washington: variably fractionated and altered metabasalts of oceanic affinity. *Contributions to Mineralogy and Petrology* **82**, 131–146. https://doi.org/10.1007/bf01166608.

Dyar, M. D., Gunter, M. E., Delany, J. S., Lanzarotti, A. A. & Sutton, S. R. (2002). Systematics in the structure and XANES spectra of pyroxenes, amphiboles, and micas as derived from oriented single crystals. *Canadian Mineralogist* **40**, 1375–1393. https://doi.org/10.2113/gscanmin.40.5.1375.

Einaudi, F., Pezard, P. A., Cochemé, J.-J., Coulon, C., Laverne, C. & Godard, M. (2000). Petrography, geochemistry and physical properties of a continuous extrusive section from the Sarami Massif, Semail ophiolite. *Marine Geophysical Researches* **21**, 387–408. https://doi.org/10.1023/a:1026752415989.

El-Shazly, A. K., Worthing, M. A., Jayawardane, J. J. & Varne, R. (1994). Geochemistry of metamorphosed mafic rocks from Saih Hatat: pre-obduction history of NE Oman. *Journal of the Geological Society* **151**, 999–1016. https://doi.org/10.1144/gsjgs.151.6.0999.

Engel, A. E. J. & Engel, C. G. (1962). Hornblendes formed during progressive metamorphism of amphibolites, northwest Adirondack mountains, New York. *Bulletin of the Geological Society of America* **73**, 1499–1514. https://doi.org/10.1130/0016-7606(1962)73[1499:hfdpmo]2.0.co;2.

Engel, A. E. J., Engel, C. G. & Havens, R. G. (1964). Mineralogy of amphibolite interlayers in the gneiss complex, Northwest Adirondack Mountains, New York. *The Journal of Geology* **72**, 131–156. https://doi.org/10.1086/626973.

Ernst, W. G., Seki, Y., Onuki, H., and Gilbert, M. C. (1970) Comparative Study of Low-Grade Metamorphism in the California Coast Ranges and the Outer Metamorphic Belt of Japan, *in* Donnay, J.D.H. and Nowacki, W. eds., *Comparative Study of Low-Grade Metamorphism in the California Coast Ranges and the Outer Metamorphic Belt of Japan: Geological Society of America Memoirs*, *Boulder, Colorado*. https://doi.org/10.1130/mem124.

Eskola, P. (1920). The mineral facies of rocks. *Norsk Geologisk Tidsskrift* **6**, 143–194.

Evans, K. A. (2006). Redox decoupling and redox budgets: conceptual tools for the study of earth systems. *Geology* **34**, 489–492. https://doi.org/10.1130/g22390.1.

Evans, K. A. (2012). The redox budget of subduction zones. *Earth-Science Reviews* **113**, 11–32. https://doi.org/10.1016/j.earscirev.2012.03.003.

Evans, B. W. & Leake, B. E. (1960). The composition and origin of the striped amphibolites of Connemara, Ireland. *Journal of Petrology* **1**, 337–363. https://doi.org/10.1093/petrology/1.1.337.

Faak, K., Chakraborty, S. & Dasgupta, S. (2012). Petrology and tectonic significance of metabasite slivers in the lesser and higher Himalayan domains of Sikkim, India. *Journal of Metamorphic Geology* **30**, 599–622. https://doi.org/10.1111/j.1525-1314.2012.00987.x.

Fatehi, H. & Ahmadipour, H. (2018). Geochemistry and petrogenesis of metabasites from the Gol-e-Gohar complex in southern Sanandaj-Sirjan metamorphic zone, south of Iran; evidences for crustal extension and magmatism at early Palaeozoic. *Geologica Acta* **16**, 293–319.

Feisel, Y., White, R. W., Palin, R. M. & Johnson, T. E. (2018). New constraints on granulite facies metamorphism and melt production in the Lewisian Complex, Northwest Scotland. *Journal of Metamorphic Geology* **36**, 799–819. https://doi.org/10.1111/jmg.12311.

Fitton, J. G. & Gill, R. C. O. (1970). The oxidation of ferrous iron in rocks during mechanical grinding. *Geochimica et Cosmochimica Acta* **34**, 518–524. https://doi.org/10.1016/0016-7037(70)90143-2.

Flanagan, F.J. (1986) *Reference samples in geology and geochemistry. U.S. G.P.O. Bulletin 1582 USGS Numbered Series*, *United States of America* https://doi.org/10.3133/b1582.

Fletcher, C. J. N. (1971). Local equilibrium in a two-pyroxene amphibolite. *Canadian Journal of Earth Sciences* **8**, 1065–1080. https://doi.org/10.1139/e71-093.

Floyd, P. A. & Winchester, J. A. (1978). Identification and discrimination of altered and metamorphosed volcanic rocks using immobile elements. *Chemical Geology* **21**, 291–306. https://doi.org/10.1016/0009-2541(78)90050-5.

Forshaw, J. B. & Pattison, D. R. M. (2021). Ferrous/ferric (Fe^{2+}/Fe^{3+}) partitioning among silicates in metapelites. *Contributions to Mineralogy and Petrology* **176**. https://doi.org/10.1007/s00410-021-01814-4.

Forshaw, J. B. & Pattison, D. R. M. (2023a). Bulk compositional influence on diverse metapelitic mineral assemblages in the Whetstone Lake area, Ontario. *Journal of Petrology* **64**, 1–29. https://doi.org/10.1093/petrology/egad071.

Forshaw, J. B. & Pattison, D. R. M. (2023b). Major-element geochemistry of pelites. *Geology* **51**, 39–43. https://doi.org/10.1130/g50542.1.

Forshaw, J. B., Waters, D. J., Pattison, D. R. M., Palin, R. M. & Gopon, P. (2019). A comparison of observed and thermodynamically predicted phase equilibria and mineral compositions in mafic granulites. *Journal of Metamorphic Geology* **37**, 153–179. https://doi.org/10.1111/jmg.12454.

French, W. J. & Adams, S. J. (1972). A rapid method for the extraction and determination of iron(II) in silicate rocks and minerals. *Analyst* **97**, 828–831. https://doi.org/10.1039/an9729700828.

Fryer, B. J. & Jenner, G. A. (1978). Geochemistry and origin of the Archean Prince Albert Group volcanics, western Melville Peninsula, Northwest Territories, Canada. *Geochimica et Cosmochimica Acta* **42**, 1645–1654. https://doi.org/10.1016/0016-7037(78)90253-3.

Fyfe, W. S. & Turner, F. J. (1966). Reappraisal of the metamorphic facies concept. *Contributions to Mineralogy and Petrology* **12**, 354–364. https://doi.org/10.1007/bf00616820.

Fyfe, W. S., Turner, F. J. & Verhoogen, J. (1958). Metamorphic reactions and metamorphic facies. *Geological Society of America* **73**. https://doi.org/10.1130/mem73.

Fyfe, W. S., Price, N. J. & Thompson, A. B. (1978) *Fluids in the earth's crust: their significance in metamorphic, tectonic, and chemical transport processes*. Elsevier Scientific Pub. Co. ; Distributions for the U.S. and Canada, Elsevier/North-Holland, Amsterdam, Netherlands.

Gaborieau, M., Laubier, M., Bolfan-Casanova, N., McCammon, C. A., Vantelon, D., Chumakov, A. I., Schiavi, F., Neuville, D. R. & Venugopal, S. (2020). Determination of $Fe^{3+}/\Sigma Fe$ of olivine-hosted melt inclusions using Mössbauer and XANES spectroscopy. *Chemical Geology* **547**, 119646. https://doi.org/10.1016/j.chemgeo.2020.119646.

Gale, A., Dalton, C. A., Langmuir, C. H., Su, Y. & Schilling, J. G. (2013). The mean composition of ocean ridge basalts. *Geochemistry, Geophysics, Geosystems* **14**, 489–518. https://doi.org/10.1029/2012gc004334.

Ganor, J., Matthews, A., Schliestedt, M. & Garfunkel, Z. (1996). Oxygen isotopic heterogeneities of metamorphic rocks: an original tectonostratigraphic signature, or an imprint of exotic fluids? A case study of Sifnos and Tinos islands (Greece). *European Journal of Mineralogy* **8**, 719–732. https://doi.org/10.1127/ejm/8/4/0719.

García-Ramírez, C. A., Ríos-Reyes, C. A., Castellanos-Alarcón, O. M. & Mantilla-Figueroa, L. C. (2017). Petrology, geochemistry and geochronology of the Arquía Complex's metabasites at the Pijao-Génova sector, Central Cordillera, Colombian Andes. *Boletín de Geología* **39**, 105–126. https://doi.org/10.18273/revbol.v39n1-2017005.

Gard, M., Hasterok, D. & Halpin, J. A. (2019). Global whole-rock geochemical database compilation. *Earth System Science Data* **11**, 1553–1566. https://doi.org/10.5194/essd-11-1553-2019.

Geen, A. C. (2021) *High temperature forearc metamorphism and consequences for sulfide stability in the Pacific Rim Terrane, British Columbia*. Masters thesis. University of Victoria, Victoria, British Columbia, Canada.

Geringer, G. J. (1979). The origin and tectonic setting of amphibolites in part of the Namaqua metamorphic belt, South Africa. *South African Journal of Geology* **82**, 287–303.

Ghent, E. (2020). Metamorphic facies: a review and some suggestions for changes. *The Canadian Mineralogist* **58**, 437–444. https://doi.org/10.3749/canmin.1900078.

Ghent, E. D. & Coleman, R. G. (1973). Eclogites from Southwestern Oregon. *Bulletin of the Geological Society of America* **84**, 2471–2488. https://doi.org/10.1130/0016-7606(1973)84<2471:efso>2.0.co;2.

Ghent, E. D., Nicholls, J., Stout, M. Z. & Rottenfusser, B. (1977). Clinopyroxene amphibolite boudins from Three Valley Gap, British Columbia. *The Canadian Mineralogist* **15**, 269–229.

Giacomini, F., Bomparola, R. M. & Ghezzo, C. (2005). Petrology and geochronology of metabasites with eclogite facies relics from NE Sardinia: constraints for the Palaeozoic evolution of Southern Europe. *Lithos* **82**, 221–248. https://doi.org/10.1016/j.lithos.2004.12.013.

Gilbert, H. P. (2011) *Geology and geochemistry of arc and ocean floor volcanic rocks in the northern Flin Flon Belt, Embury–Wabishkok–Naosap lakes area, Manitoba (parts of NTS 63K13, 14)*. Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, Geoscientific Report GR2011-1, 46 p. + DVD.

Gill, R. (1997). Modern analytical geochemistry, an introduction to quantitative chemical analysis techniques for earth, environmental and materials scientists. https://doi.org/10.4324/9781315844381.

Glassley, W. E. & Sørensen, K. (1980). Constant P_s-T amphibolite to granulite facies transition in Agto (West Greenland) metadolerites: implications and applications. *Journal of Petrology* **21**, 69–105. https://doi.org/10.1093/petrology/21.1.69.

Glukhovskiy, M. Z. & Moralev, V. M. (1993). Archean metabasites of the Sunnagin Dome, Aldan Shield: petrochemistry and origin. *International Geology Review* **35**, 739–757. https://doi.org/10.1080/00206819309465554.

Gomes, C. D. B., Santini, P. & Dutra, C. V. (1964). Petrochemistry of a precambrian amphibolite from the Jaragua area, Sao Paulo, Brazil. *Journal of Geology* **72**, 664–680. https://doi.org/10.1086/627022.

Goto, A. & Banno, S. (1990). Hydration of basic granulite to garnet-epidote amphibolite in the Sanbagawa metamorphic belt, Central Shikoku, Japan. *Chemical Geology* **v. 85**, 247–263. https://doi.org/10.1016/0009-2541(90)90003-p.

Graham, C. M. (1973) *Chemical petrology of metamorphosed basic rocks of the Dalradian series, with particular reference to the Knapdale area of Argyll*. Doctoral thesis. University of Edinburgh, Edinburgh, United Kingdom.

Graham, C. M. (1976). Petrochemistry and tectonic significance of Dalradian metabasaltic rocks of the SW. Scottish Highlands. *Journal of the Geological Society* **132**, 61–84. https://doi.org/10.1144/gsjgs.132.1.0061.

Grandy, A. (2000) Geochemistry of the metagabbros of Syros. In: *Thirteenth Keck Research Symposium*. Keck Geology Consortium.

Green, E. C. R., White, R. W., Diener, J. F. A., Powell, R., Holland, T. J. B. & Palin, R. M. (2016). Activity–composition relations for the calculation of partial melting equilibria in metabasic rocks. *Journal of Metamorphic Geology* **34**, 845–869. https://doi.org/10.1111/jmg.12211.

Grosch, E. G. (2005) *A metamorphic and geochemical study of mafic rocks across the Pencksökket-Jutulstraumen discontinuity, Western Dronning Maud Land, East Antarctica*. Masters thesis. University of Cape Town, Cape Town, South Africa.

Gyomlai, T., Agard, P., Marschall, H. R., Jolivet, L. & Gerdes, A. (2021). Metasomatism and deformation of block-in-matrix structures in Syros: the role of inheritance and fluid-rock interactions along the subduction interface. *Lithos* **386-387**, 105996. https://doi.org/10.1016/j.lithos.2021.105996.

Hacker, B. R., Kelemen, P. B. & Behn, M. D. (2015). Continental lower crust. *Annual Review of Earth and Planetary Sciences* **43**, 167–205. https://doi.org/10.1146/annurev-earth-050212-124117.

Hall-Beyer, M. C. (1976) *Chemical petrology of some Northern Saskatchewan granulites*. Masters thesis. University of Alberta, Edmonton, Alberta, Canada.

Hamelin, C., Brady, J. B., Cheney, J. T., Schumacher, J. C., Able, L. M. & Sperry, A. J. (2018). Pseudomorphs after Lawsonite from Syros, Greece. *Journal of Petrology* **59**, 2353–2384. https://doi.org/10.1093/petrology/egy099.

Harper, G.D. (1995). Pumpellyosite and prehnitite associated with epidosite in the Josephine ophiolite—Ca metasomatism during upwelling of hydrothermal fluids at a spreading axis *in* Schiffman P. and Day, H. W. eds., *Low-Grade Metamorphism of Mafic Rocks*. Boulder, Colorado, Geological Society of America Special Paper 296, 101–122, https://doi.org/10.1130/spe296-p101.

Haynes, J. E. (1998) *Processes of granulite formation*. West Greenland: University of Oxford, Oxford, United Kingdom.

Hazarika, L. K. (1985) *A study of Precambrian rocks of the Mairang area, Meghalaya*. Doctoral thesis. University of Gauhati, Guwahati, Assam, India.

Heier, K. S. (1962). The possible origins of amphibolites in an area of high metamorphic grade. *Norwegian Journal of Geology* **42**, 157–165.

Hernández-Uribe, D., Palin, R. M., Cone, K. A. & Cao, W. (2020). Petrological implications of seafloor hydrothermal alteration of subducted Mid-Ocean ridge basalt. *Journal of Petrology* **61**, egaa086. https://doi.org/10.1093/petrology/egaa086.

Hillebrand, W. F. (1908). The influence of fine grinding on the water and ferrous-iron content of minerals and rocks. *Journal of the American Chemical Society* **30**, 1120–1131. https://doi.org/10.1021/ja01949a010.

Hills, D. V. & Haggerty, S. E. (1989). Petrochemistry of eclogites from the Koidu Kimberlite Complex, Sierra Leone. *Contributions to Mineralogy and Petrology* **103**, 397–422. https://doi.org/10.1007/bf01041749.

Hoffmann, C. (1970). Die Glaukophangesteine, ihre stofflichen Äquivalente und Uniwandlungsprodukte in Nordcalabrien (Süditalien). *Contributions to Mineralogy and Petrology* **27**, 283–320. https://doi.org/10.1007/bf00389815.

Hofmann, H., Wickham, H. & Kafadar, K. (2017). Letter-value plots: boxplots for large data. *Journal of Computational and Graphical Statistics* **26**, 469–477. https://doi.org/10.1080/10618600.2017.1305277.

Holland, T. J. B. & Powell, R. (2011). An improved and extended internally consistent thermodynamic dataset for phases of petrological interest, involving a new equation of state for solids. *Journal of Metamorphic Geology* **29**, 333–383. https://doi.org/10.1111/j.1525-1314.2010.00923.x.

Hollocher, K. T. (1985) *Geochemistry of metamorphosed volcanic rocks in the Middle Ordovician Partridge Formation, and amphibole dehydration reactions in the high-grade metamorphic zones of Central Massachusetts*. Doctoral thesis. Amherst: University of Massachusetts, United States of America.

Honegger, K., Fort, P. L., Mascle, G. & Zimmermann, J.-L. (1989). The blueschists along the Indus Suture Zone in Ladakh, NW

Himalaya. *Journal of Metamorphic Geology* **7**, 57–72. https://doi.org/10.1111/j.1525-1314.1989.tb00575.x.

Honma, H. (1974). Major element chemistry of metamorphic and granitic rocks of the Yanai District in the Ryoke Belt. *The Journal of the Japanese Association of Mineralogists, Petrologists and Economic Geologists* **69**, 193–204. https://doi.org/10.2465/ganko1941.69.193.

Hoshino, M. (1979). Two-pyroxene amphibolites in Dogo, Oki Islands, Skimane-Ken, Japan. *The Journal of the Japanese Association of Mineralogists, Petrologists and Economic Geologists* **74**, 87–99. https://doi.org/10.2465/ganko1941.74.87.

Houghton, B. F. (1985). Petrology of the calcalkaline lavas of the Permian Takitimu Group, southern New Zealand. *New Zealand Journal of Geology and Geophysics* **28**, 649–665. https://doi.org/10.1080/00288306.1985.10422539.

Hozjan, D. J. (1999) *Blueschist metamorphism within the Bridge River-complex, Goldbridge, British Columbia*. Masters thesis. University of Calgary, Calgary, Alberta, Canada.

Huang, G., Brown, M., Guo, J., Piccoli, P. & Zhang, D. (2018). Challenges in constraining the P-T conditions of mafic granulites: an example from the northern trans-North China Orogen. *Journal of Metamorphic Geology* **36**, 739–768. https://doi.org/10.1111/jmg.12308.

Hynes, A. (1980). Carbonatization and mobility of Ti, Y, and Zr in Ascot Formation metabasalts, SE Quebec. *Contributions to Mineralogy and Petrology* **75**, 79–87. https://doi.org/10.1007/bf00371891.

Ilnicki, S., Szczepański, J. & Pin, C. (2013). From back-arc to rifted margin: geochemical and Nd isotopic records in Neoproterozoic?-Cambrian metabasites of the Bystrzyckie and Orlickie Mountains (Sudetes, SW Poland). *Gondwana Research* **23**, 1104–1121. https://doi.org/10.1016/j.gr.2012.06.017.

Ilnicki, S., Szczepański, J. & Pin, C. (2020). Tholeiitic- and boninite-series metabasites of the Nové Město Unit and northern part of the Zábřeh Unit (Orlica–Śnieżnik Dome, Bohemian Massif): petrogenesis and tectonic significance. *International Journal of Earth Sciences* **109**, 1247–1271. https://doi.org/10.1007/s00531-020-01845-5.

Ishikawa, T., Fujisawa, S., Nagaishi, K. & Masuda, T. (2005). Trace element characteristics of the fluid liberated from amphibolite-facies slab : inference from the metamorphic sole beneath the Oman ophiolite and implication for boninite genesis. *Earth and Planetary Science Letters* **240**, 355–377. https://doi.org/10.1016/j.epsl.2005.09.049.

Jan, M. Q. (1977) *The Mineralogy, Geochemistry, and Petrology of Swat Kohistan, NW Pakistan*. Doctoral thesis. University of London, King's College, London, United Kingdom.

Jan, M. Q. (1988). Geochemistry of amphibolites from the southern part of the Kohistan arc, N. Pakistan. *Mineralogical Magazine* **52**, 147–159. https://doi.org/10.1180/minmag.1988.052.365.02.

Jan, M. Q. & Kempe, D. R. C. (1973). The petrology of the basic and intermediate rocks of upper Swat, Pakistan. *Geological Magazine* **110**, 285–300. https://doi.org/10.1017/s0016756800036116.

Janousek, V., Gerdes, A., Vrána, S., Finger, F., Erban, V., Friedl, G. & And Braithwaite, C. J. R. (2006). Low-pressure Granulites of the Lišov Massif, Southern Bohemia: Viséan Metamorphism of Late Devonian plutonic arc rocks. *Journal of Petrology* **47**, 705–744. https://doi.org/10.1093/petrology/egi091.

Jayko, A. S. (1984) *Deformation and metamorphism of the Eastern Franciscan Belt, Northern California*. Doctoral thesis. Santa Cruz: University of California, California, United States of America.

Jen, L.-S. (1975) *Spatial distribution of crystals and phase equilibria in charnockitic granulites from the Adirondack Mountains, New York*. Doctoral thesis. University of Ottawa, Ottawa, Ontario, Canada.

Jen, L. S. & Kretz, R. (1981). Mineral chemistry of some mafic granulites from the Adirondack Region. *Canadian Mineralogist* **19**, 479–491.

Jenner, G. A. & Fryer, B. J. (1980). Geochemistry of the upper Snooks Arm Group basalts, Burlington Peninsula, Newfoundland: evidence against formation in an island arc. *Canadian Journal of Earth Sciences* **17**, 888–900. https://doi.org/10.1139/e80-087.

Jennings, D. S. (1969) *Origin and Metamorphism of Part of the Hermon Group Near Bancroft, Ontario*. Doctoral thesis. McMaster University, Hamilton, Ontario, Canada.

John, T., Scherer, E. E., Schenk, V., Herms, P., Halama, R. & Garbe-Schönberg, D. (2010). Subducted seamounts in an eclogite-facies ophiolite sequence: the Andean Raspas complex, SW Ecuador. *Contributions to Mineralogy and Petrology* **159**, 265–284. https://doi.org/10.1007/s00410-009-0427-0.

Jolly, W. T. (1970). Zeolite and prehnite-pumpellyite facies in south Central Puerto Rico. *Contributions to Mineralogy and Petrology* **27**, 204–224. https://doi.org/10.1007/bf00385778.

Jolly, W. T. (1980). Development and degradation of Archean Lavas, Abitibi Area, Canada, in light of major element geochemistry. *Journal of Petrology* **21**, 323–363. https://doi.org/10.1093/petrology/21.2.323.

Jolly, W. T. & Smith, R. E. (1972). Degradation and metamorphic differentiation of the Keweenawan Tholeiitic Lavas of Northern Michigan, U.S.A. *Journal of Petrology* **13**, 273–309. https://doi.org/10.1093/petrology/13.2.273.

Jørgensen, T. R. C. (2017) *Evolution of the Sudbury Igneous Complex Southern Metamorphic Aureole and controls on Anatexis*. Doctoral thesis. Laurentian University, Sudbury, Ontario, Canada.

Jørgensen, T. R. C., Tinkham, D. K. & Lesher, C. M. (2019). Low-P and high-T metamorphism of basalts: insights from the Sudbury impact melt sheet aureole and thermodynamic modelling. *Journal of Metamorphic Geology* **37**, 271–313. https://doi.org/10.1111/jmg.12460.

van de Kamp, P. C. (1968). Geochemistry and origin of metasediments in the HaliburtonMadoc area, southeastern Ontario. *Canadian Journal of Earth Sciences* **5**, 1337–1372. https://doi.org/10.1139/e68-134.

van de Kamp, P. C. (1970). The Green Beds of the Scottish Dalradian Series: geochemistry, origin, and metamorphism of mafic sediments. *The Journal of Geology* **78**, 281–303. https://doi.org/10.1086/627518.

Kampunzu, A. B., Akanyang, P., Mapeo, R. B. M., Modie, B. N. & Wendorff, M. (1998). Geochemistry and tectonic significance of the Mesoproterozoic Kgwebe metavolcanic rocks in Northwest Botswana: implications for the evolution of the Kibaran Namaqua-Natal Belt. *Geological Magazine* **135**, 669–683. https://doi.org/10.1017/s001675689800123x.

Kanisawa, S. (1969). Garnet-amphibolites at Yokokawa in the Abukuma metamorphic belt, Japan. *Contributions to Mineralogy and Petrology* **20**, 164–176. https://doi.org/10.1007/bf00399629.

Kanisawa, S. (1971). Basic and intermediate volcanic rocks from the Paleozoic formations in the Southern Kitakami Mountainland, Japan. *The Journal of the Japanese Association of Mineralogists, Petrologists and Economic Geologists* **65**, 247–264. https://doi.org/10.2465/ganko1941.65.247.

Katagas, C. & Panagos, A. G. (1979). Pumpellyite-actinolite and greenschist facies metamorphism in lesvos island (Greece). *Tschermaks Mineralogische Und Petrographische Mitteilungen* **26**, 235–254. https://doi.org/10.1007/bf01089839.

Katagas, C. & Sapountzis, E. (1977). Petrochemistry of low and medium grade mafic metamorphic rocks from Leros Island, Greece. *Tschermaks Mineralogische Und Petrographische Mitteilungen* **24**, 39–55. https://doi.org/10.1007/bf01081744.

Kelley, K. A. & Cottrell, E. (2012). The influence of magmatic differentiation on the oxidation state of Fe in a basaltic arc magma. *Earth and Planetary Science Letters* **329-330**, 109–121. https://doi.org/10.1016/j.epsl.2012.02.010.

Kelley, K. A., Plank, T., Ludden, J. & Staudigel, H. (2003). Composition of altered oceanic crust at ODP sites 801 and 1149. *Geochemistry, Geophysics, Geosystems* **4**. https://doi.org/10.1029/2002gc000435.

Khodorevskaya, L. I. (2012). Granulite facies metamorphism and metasomatism in the gabbro-anorthosites of the Kolvitsa massif, Kola Peninsula. *Geochemistry International* **50**, 272–288. https://doi.org/10.1134/s0016702912010041.

Kim, T., Kim, Y., Cho, M. & Lee, J. I. (2019). P–T evolution and episodic zircon growth in barroisite eclogites of the Lanterman range, northern Victoria Land, Antarctica. *Journal of Metamorphic Geology* **37**, 509–537. https://doi.org/10.1111/jmg.12474.

Korh, A. E., Schmidt, S. T., Ulianov, A. & Potel, S. (2009). Trace element partitioning in HP–LT metamorphic assemblages during subduction-related metamorphism, ile de Groix, France: a detailed LA-ICPMS study. *Journal of Petrology* **50**, 1107–1148. https://doi.org/10.1093/petrology/egp034.

Krogh, E. J. (1980). Geochemistry and petrology of glaucophane-bearing eclogites and associated rocks from Sunnfjord, Western Norway. *Lithos* **13**, 355–380. https://doi.org/10.1016/0024-4937(80)90054-7.

Kuniyoshi, S. & Liou, J. G. (1976). Burial metamorphism of the Karmutsen volcanic rocks, northeastern Vancouver Island, British Columbia. *American Journal of Science* **276**, 1096–1119. https://doi.org/10.2475/ajs.276.9.1096.

Kutsukake, T. (1975). Metabasites in the Ryôke zone of the Toyonemura area, Aichi prefecture, Japan. *The Journal of the Japanese Association of Mineralogists, Petrologists and Economic Geologists* **70**, 177–193. https://doi.org/10.2465/ganko1941.70.177.

Kuyumjian, R. M. (1989) *The geochemistry and tectonic significance of amphibolites from the Chapada sequence, Central Brazil*. Doctoral thesis. University of London, King's College, London, United Kingdom.

Laflèche, M. R., Dupuy, C. & Dostal, J. (1992). Tholeiitic volcanic rocks of the late Archean Blake River Group, southern Abitibi greenstone belt: origin and geodynamic implications. *Canadian Journal of Earth Sciences* **29**, 1448–1458. https://doi.org/10.1139/e92-116.

Laird, J. (1980). Phase equilibria in mafic schist from Vermont. *Journal of Petrology* **21**, 1–37. https://doi.org/10.1093/petrology/21.1.1-a.

Lapadu-Hargues, P. (1953). Sur la composition chimique moyenne des amphibolites. *Bulletin de la Société Géologique de France* **S6-III**, 153–173. https://doi.org/10.2113/gssgfbull.s6-iii.1-3.153.

Lazzarotto, M., Pattison, D. R. M., Gagné, S. & Couëslan, C. G. (2023) *Metamorphic map of the Flin Flon domain, west-central Manitoba (parts of NTS 63J, K, N, O)*. Manitoba Geological Survey, Winnipeg, Geoscientific Paper GP2023–1.

Le Bas, M., Le Maitre, R., Streckeisen, A., Zanettin, B. & IUGS Subcommission on the Systematics of Igneous Rocks (1986). A chemical classification of volcanic rocks based on the total alkali-silica diagram. *Journal of Petrology* **27**, 745–750. https://doi.org/10.1093/petrology/27.3.745.

Leake, B. E. (1964). The chemical distinction between ortho- and Para-amphibolites. *Journal of Petrology* **5**, 238–254. https://doi.org/10.1093/petrology/5.2.238.

Leake, B. E. (2016). The metabasites and garnet amphibolites of Glencolumbkille, Co. Donegal and the early mafic intrusions into the Dalradian rocks of Donegal, Connemara and Scotland. *Irish Journal of Earth Sciences* **34**, 27. https://doi.org/10.3318/ijes.2016.34.27.

Lechler, P. J. & Desilets, M. O. (1987). A review of the use of loss on ignition as a measurement of total volatiles in whole-rock analysis. *Chemical Geology* **63**, 341–344. https://doi.org/10.1016/0009-2541(87)90171-9.

Lee, Y. & Cho, M. (2020). Fluid-present partial melting of Paleoproterozoic Okbang amphibolite in the Yeongnam Massif, Korea. *Lithosphere* **2020**. https://doi.org/10.2113/2020/8854615.

Levi, B. (1969). Burial metamorphism of a cretaceous volcanic sequence west from Santiago, Chile. *Contributions to Mineralogy and Petrology* **24**, 30–49. https://doi.org/10.1007/bf00398751.

Li, Q., Zhang, L., Fu, B., Bader, T. & Yu, H. (2019). Petrology and zircon U–Pb dating of well-preserved eclogites from the Thongmön area in central Himalaya and their tectonic implications. *Journal of Metamorphic Geology* **37**, 203–226. https://doi.org/10.1111/jmg.12457.

Liati, A. & Seidel, E. (1996). Metamorphic evolution and geochemistry of kyanite eclogites in central Rhodope, northern Greece. *Contributions to Mineralogy and Petrology* **123**, 293–307. https://doi.org/10.1007/s004100050157.

Liogys, V. A. & Jenkins, D. M. (2000). Hornblende geothermometry of amphibolite layers of the Popple Hill gneiss, north-west Adirondack lowlands, New York, USA. *Journal of Metamorphic Geology* **18**, 513–530. https://doi.org/10.1046/j.1525-1314.2000.00271.x.

Liu, X., Chen, Y., Wang, W., Xia, M., Hu, J., Li, Y., Hu, D. & Song, B. (2021). Carboniferous eclogite and garnet–omphacite granulite from northeastern Hainan Island, South China: implications for the evolution of the eastern Palaeo-Tethys. *Journal of Metamorphic Geology* **39**, 101–132. https://doi.org/10.1111/jmg.12563.

Lorda, M. E. S., Sarrionandia, F., Ábalos, B., Carrracedo, M., Eguíluz, L. & Ibarguchi, J. I. G. (2014). Geochemistry and paleotectonic setting of Ediacaran metabasites from the Ossa-Morena Zone (SW Iberia). *International Journal of Earth Sciences* **103**, 1263–1286. https://doi.org/10.1007/s00531-013-0937-x.

Lü, Z., Zhang, L., Yue, J. & Li, X. (2019). Ultrahigh-pressure and high-P lawsonite eclogites in Muzhaerte, Chinese western Tianshan. *Journal of Metamorphic Geology* **37**, 717–743. https://doi.org/10.1111/jmg.12482.

Makanjuola, A. A. & Howie, R. A. (1972). The mineralogy of the glaucophane schists and associated rocks from Île de Groix, Brittany, France. *Contributions to Mineralogy and Petrology* **35**, 83–118. https://doi.org/10.1007/bf00370922.

Marras, G., Mikhailenko, D., McCammon, C. A., Agasheva, E. & Stagno, V. (2024). Ferric iron in eclogitic garnet and clinopyroxene from the V. Grib kimberlite pipe (NW Russia): evidence of a highly oxidized subducted slab. *Journal of Petrology* **65**, egae054. https://doi.org/10.1093/petrology/egae054.

Marschall, H. R. (2005) *Lithium, Beryllium and Boron in High-Pressure Metamorphic Rocks from Syros (Greece)*. Doctoral thesis. Heidelberg University, Heidelberg, Germany.

Masci, L., Dubacq, B., Verlaguet, A., Chopin, C., Andrade, V. D. & Herviou, C. (2019). A XANES and EPMA study of Fe^{3+} in chlorite: importance of oxychlorite and implications for cation site distribution and thermobarometry. *American Mineralogist* **104**, 403–417. https://doi.org/10.2138/am-2019-6766.

Massonne, H. J. & Czambor, A. (2007). Geochemical signatures of Variscan eclogites from the Saxonian Erzgebirge, Central Europe. *Chemie der Erde* **67**, 69–83. https://doi.org/10.1016/j.chemer.2006.07.001.

Mauzelius, R. (1907). On the determination of ferrous iron in rock analysis. *Geologiska Föreningen i Stockholm Förhandlingar* **29**, 388–388. https://doi.org/10.1080/11035890609445559.

Maxey, L. R. (1972) *Metamorphism and origin of Precambrian amphibolites of the New Jersey Highlands*. Doctoral thesis. Rutgers University, New Jersey, United States of America.

Mazzucchelli, M. & Siena, F. (1986). Geotectonic significance of the metabasites of the Kinzigitic Series, Ivrea-Verbano Zone (Western Italian Alps). *Tschermaks Mineralogische Und Petrographische Mitteilungen* **35**, 99–116. https://doi.org/10.1007/bf01140842.

McNaughton, N. J. & Wilson, A. F. (1983). The geochemical and oxygen-isotope affinities of Proterozoic mafic granulites from the Einasleigh Metamorphics, northern Queensland. *Precambrian Research* **v. 21**, 21–37. https://doi.org/10.1016/0301-9268(83)90003-7.

McStay, J. (1991) *Granulite-facies metamorphism, fluid buffering and partial melting in the Buffels River area of the Namaqualand Metamorphic Complex, South Africa*. University of Cape Town, Cape Town, South Africa.

Mengel, F. C. (1983). Chemistry of coexisting mafic minerals in granulite facies amphibolites from West Greenland: clues to conditions of metamorphism. *Neues Jahrbuch für Mineralogie - Abhandlungen* **147**, 315–340.

Messiga, B., Piccardo, G. B. & Ernst, W. G. (1983). High-pressure Eo-Alpine parageneses developed in magnesian metagabbros, Gruppo di Voltri, Western Liguria, Italy. *Contributions to Mineralogy and Petrology* **83**, 1–15. https://doi.org/10.1007/bf00373074.

Messiga, B., Tribuzio, R. & Vannucci, R. (1990). Mafic and ultramafic pods with eclogitic relics from the Proterozoic Nagssugtoqidian mobile belt of East Greenland. *Lithos* **25**, 101–118. https://doi.org/10.1016/0024-4937(90)90009-p.

Middlemost, E. A. K. (1975). The basalt clan. *Earth-Science Reviews* **11**, 337–364. https://doi.org/10.1016/0012-8252(75)90039-2.

Miladinova, I., Froitzheim, N., Nagel, T. J., Janák, M., Fonseca, R. O. C., Sprung, P. & Münker, C. (2022). Constraining the process of intracontinental subduction in the Austroalpine Nappes: implications from petrology and Lu-Hf geochronology of eclogites. *Journal of Metamorphic Geology* **40**, 423–456. https://doi.org/10.1111/jmg.12634.

Miller, C. & Thöni, M. (1995). Origin of eclogites from the Austroalpine Ötztal basement (Tirol, Austria): geochemistry and Sm-Nd vs. Rb-Sr isotope systematics. *Chemical Geology* **122**, 199–225. https://doi.org/10.1016/0009-2541(95)00033-i.

Misra, S. N. & Griffin, W. L. (1972). Geochemistry and metamorphism of dolerite dikes from Austvågøy in Lofoten. *Norwegian Journal of Geology* **52**, 409–425.

Miyake, A. (1984). Phase equilibria in the hornblende-bearing basic gneisses of the Uvete area, Central Kenya. *Journal of Metamorphic Geology* **2**, 165–177. https://doi.org/10.1111/j.1525-1314.1984.tb00294.x.

Miyashiro, A. (1973) *Metamorphism and Metamorphic Belts*. Dordrecht, London: Springer, 492 p., https://doi.org/10.1007/978-94-011-6836-6

Molina, J. F. & Montero, P. (2003). The behaviour of trace elements in high-P mineral assemblages:a LA-ICP-MS study of mafic rocks from theNevado-Filábride complex (SE Spain). *Schweizerische Mineralogische und Petrographische Mitteilungen* **83**, 97–109. https://doi.org/10.5169/seals-63138.

Molina, J. F., Austrheim, H., Glodny, J. & Rusin, A. (2002). The eclogites of the Marun–Keu complex, polar Urals (Russia): fluid control on reaction kinetics and metasomatism during high P metamorphism. *Lithos* **61**, 55–78. https://doi.org/10.1016/s0024-4937(02)00070-1.

Mottana, A., Bocchio, R., Liborio, G., Morten, L. & Maresch, W. V. (1985). The eclogite-bearing metabasaltic sequence of Isla margarita, Venezuela: a geochemical study. *Chemical Geology* **50**, 351–368. https://doi.org/10.1016/0009-2541(85)90128-7.

Mummery, R. C. (1972) *Coronite amphibolites from the Whitestone area, Parry Sound*. Doctoral thesis. McMaster University, Hamilton, Ontario, Canada.

Naqvi, S. M. (1971). The petrochemistry and significance of jogimardi traps, chitaldrug schist belt, Mysore. *Bulletin Volcanologique* **35**, 1069–1093. https://doi.org/10.1007/bf02596866.

Nash, P. W. (1984) *Structural, metamorphic and geochemical distinctions of low and high terrains. Fox Mountain area, north west Queensland*. Bachelors thesis. University of Adelaide, Adelaide, South Australia, Australia.

Nasseef, A. O. & Gass, I. G. (1977). Granitic and metamorphic rocks of the Taif area, western Saudi Arabia. *GSA Bulletin* **88**, 1721–1730. https://doi.org/10.1130/0016-7606(1977)88<1721:gamrot>2.0.co;2.

Nataraj, T. S. (1967) *Glaucophanic metamorphism in Anglesey*. Doctoral thesis. University of Leeds, Leeds, United Kingdom.

Nehring, F., Foley, S. F. & Hölttä, P. (2010). Trace element partitioning in the granulite facies. *Contributions to Mineralogy and Petrology* **159**, 493–519. https://doi.org/10.1007/s00410-009-0437-y.

O'Neill, H. St. C., Rubie, D.C., Canil, D., Geiger, C. A., Ross, C. R., Seifert, F., and Woodland, A. B. (1993) Ferric Iron in the Upper Mantle and In Transition Zone Assemblages: Implications for Relative Oxygen Fugacities in the Mantle, *in* E. Takahashi, R. Jeanloz, D. Rubie eds., *Evolution of the Earth and Planets. Geophysical Monograph*. American Geophysical Union and John Wiley and Sons, Inc. **74**, 73–88, https://doi.org/10.1029/gm074p0073.

Okrusch, M., Seidel, E., Schüssler, U. & Richter, P. (1989) Geochemical Characteristics of Metabasites in Different Tectonic Units of the Northeast Bavarian Crystalline Basemen. *In* Emmermann, R., Wohlenberg, J. eds., *The German Continental Deep Drilling Program (KTB)*. *Exploration of the Deep Continental Crust*. Berlin, Heidelberg: Springer, 67–79. https://doi.org/10.1007/978-3-642-74588-1_5

Olade, M. A. & Elueze, A. A. (1979). Petrochemistry of the Ilesha amphibolites and Precambrian crustal evolution in the Pan-African domain of SW Nigeria. *Precambrian Research* **8**, 303–318. https://doi.org/10.1016/0301-9268(79)90033-0.

Olajide-Kayode, J. O., Olisa, O. G., Okunlola, O. A. & Olatunji, A. S. (2023). Petrology and amphibole-plagioclase chemistry of amphibolites in the Ilesa area, Southwestern Nigeria. *Journal of African Earth Sciences* **199**, 104844. https://doi.org/10.1016/j.jafrearsci.2023.104844.

de Oliveira, M. A. F., Alves, F. R. & Kihara, Y. (1993). Mafic granulites and amphibolites of the São José do Rio Pardo-Caconde high grade terrain. *Geochimica Brasiliensis* **7**.

Onuki, H. & Ishimoto, N. (1980). Garnet-clinopyroxene amphibolites from the Yawataham District in the Sanbagawa Belt—a preliminary note on the Kawamai Mass. *The Journal of the Japanese Association of Mineralogists, Petrologists and Economic Geologists* **75**, 209–215. https://doi.org/10.2465/ganko1941.75.special2_209.

Orville, P. M. (1969). A model for metamorphic differentiation origin of thin-layered amphibolites. *American Journal of Science* **267**, 64–86. https://doi.org/10.2475/ajs.267.1.64.

Ouellet, E. (1988) *Evolution tectono-métamorphique de la continuité lithologique des roches vertes du Supérieur dans la zone orogénique de la Province du Grenville*. Masters thesis. Université du Québec à Chicoutimi, Chitcoutimi, Québec, Canada. https://doi.org/10.1522/1445881.

Owen, J. V. (1993). Syn-metamorphic element transfer across lithological boundaries in the Port-aux–Basques gneiss complex, Newfoundland. *Lithos* **29**, 217–233. https://doi.org/10.1016/0024-4937(93)90018-8.

Paavola, J. (1984). On the Archean high-grade metamorphic rocks in the Varpaisjärvi area, Central Finland. *Geological Survey of Finland, Bulletin* **327**.

Palin, R. M., White, R. W., Green, E. C. R., Diener, J. F. A., Powell, R. & Holland, T. J. B. (2016). High-grade metamorphism and partial melting of basic and intermediate rocks. *Journal of Metamorphic Geology* **34**, 871–892. https://doi.org/10.1111/jmg.12212.

Palmeri, R., Godard, G., Vincenzo, G. D., Sandroni, S. & Talarico, F. M. (2018). High-pressure granulite-facies metamorphism in central Dronning Maud land (East Antarctica): implications for Gondwana assembly. *Lithos* **300-301**, 361–377. https://doi.org/10.1016/j.lithos.2017.12.014.

Pamić, J., Balen, D. & Tibljaš, D. (2002). Petrology and geochemistry of orthoamphibolites from the Variscan metamorphic sequences of the south Tisia in Croatia—an overview with geodynamic implications. *International Journal of Earth Sciences* **91**, 787–798. https://doi.org/10.1007/s00531-002-0258-y.

Parkinson, C. D. (1996). The origin and significance of metamorphosed tectonic blocks in mélanges: evidence from Sulawesi, Indonesia. *Terra Nova* **8**, 312–323. https://doi.org/10.1111/j.1365-3121.1996.tb00564.x.

Pattison, D. R. M. (1991). Infiltration-driven dehydration and anatexis in granulite facies metagabbro, Grenville Province, Ontario, Canada. *Journal of Metamorphic Geology* **9**, 315–332. https://doi.org/10.1111/j.1525-1314.1991.tb00526.x.

Pattison, D. R. M. (2003). Petrogenetic significance of orthopyroxene-free garnet + clinopyroxene + plagioclase +/− quartz-bearing metabasites with respect to the amphibolite and granulite facies. *Journal of Metamorphic Geology* **21**, 21–34. https://doi.org/10.1046/j.1525-1314.2003.00415.x.

Perfit, M. R., Heezen, B. C., Rawson, M. & Donnelly, T. W. (1980). Chemistry, origin and tectonic significance of metamorphic rocks from the Puerto Rico Trench. *Marine Geology* **34**, 125–156. https://doi.org/10.1016/0025-3227(80)90069-9.

Piboule, M. & Briand, B. (1985). Geochemistry of eclogites and associated rocks of the southeastern area of the French Massif Central: origin of the protoliths. *Chemical Geology* **50**, 189–199. https://doi.org/10.1016/0009-2541(85)90120-2.

Plint, H. E. & Gordon, T. M. (1997). The Slide Mountain terrane and the structural evolution of the Finlayson Lake Fault Zone, southeastern Yukon. *Canadian Journal of Earth Sciences* **34**, 105–126. https://doi.org/10.1139/e17-009.

Pognante, U., Lombardo, B. & Venturelli, G. (1982). Petrology and geochemistry of Fe–Ti gabbros and plagiogranites from the Western Alps ophiolites. *Schweizerische Mineralogische und Petrographische Mitteilungen* **62**, 457–472. https://doi.org/10.5169/seals-47981.

Polat, A., Hofmann, A. W., Münker, C., Regelous, M. & Appel, P. W. U. (2003). Contrasting geochemical patterns in the 3.7–3.8 Ga pillow basalt cores and rims, Isua greenstone belt, Southwest Greenland: implications for postmagmatic alteration processes. *Geochimica et Cosmochimica Acta* **67**, 441–457. https://doi.org/10.1016/s0016-7037(02)01094-3.

Poldervaart, A. (1953). Metamorphism of basaltic rocks: a review. *GSA Bulletin* **64**, 259–274. https://doi.org/10.1130/0016-7606(1953)64[259:mobrar]2.0.co;2.

Poldervaart, A. (1955) Chemistry of the Earth's Crust, *in* Poldervaart, A. eds., *Crust of the Earth. A Symposium*, Boulder, Colorado, Geological Society of America Special Paper 62, 119–144, https://doi.org/10.1130/spe62-p119.

Potts, P.J. (1992) *A Handbook of Silicate Rock Analysis*: Springer New York, NY, 622 p., https://doi.org/10.1007/978-1-4615-3270-5.

Prakash, D. (1994). Garnetiferous basic granulites from the area north Doddabetta, Nilgiri District Tamil Nadu. *Bulletin of the Indian Geologists' Association* **27**, 129–141.

Preston, R. M. F. (1969) *The petrology and structure of the north eastern Neriaarea, south-west Greenland*. Doctoral thesis. Durham University, Durham, United Kingdom.

Preto, V. A. G. (1970). Amphibolites from the Grand Forks Quadrangle of British Columbia, Canada. *GSA Bulletin* **81**, 763–782. https://doi.org/10.1130/0016-7606(1970)81[763:aftgfq]2.0.co;2.

Pujol-Solà, N., Casas, J. M., Proenza, J. A., Blanco-Quintero, I. F., Druguet, E., Liesa, M., Román-Alpiste, M. J. & Álvaro, J. J. (2022). Cadomian metabasites of the Eastern Pyrenees revisited. *Geologica Acta* **20**, 1–IV. https://doi.org/10.1344/geologicaacta2022.20.13.

Puschnig, A. R. (2000). The oceanic Forno unit (Rhetic Alps): field relations, geochemistry and paleogeographic setting. *Eclogae Geologicae Helvetiae* **93**(2).

Puziewicz, J. (2006). The retrograde metamorphism in the Niedźwiedź Amphibolite Massif (SW Poland): from incipient melting to pumpellyite crystallization. *Neues Jahrbuch für Mineralogie - Abhandlungen* **183**, 1–11. https://doi.org/10.1127/0077-7757/2006/0056.

Raith, J. G. & Meisel, T. (2001). Metabasites along the amphibolite-granulite facies transition in the Okiep Copper District, South Africa. *South African Journal of Geology* **104**, 77–100. https://doi.org/10.2113/104.1.77.

Ramaswamy, A. & Murty, M. S. (1973). The charnockite series of Amaravathi, Gunter District, Andhra Pradesh, South India. *Geological Magazine* **110**, 171–184. https://doi.org/10.1017/s0016756800047919.

Rao, D. R., Rashid, S. A. & Panthulu, G. V. C. (2000). Origin of Mg-Metatholeiites of the Schirmacher region, East Antarctica: constraints from trace elements and Nd-Sr isotopic systematics. *Gondwana Research* **3**, 91–104. https://doi.org/10.1016/s1342-937x(05)70060-5.

Rass, I. T., Aranovich, L. Y., Korpechkov, D. I. & Kozlovskii, V. M. (2014). Geochemistry of metamorphic processes in mafic rocks of the Krasnaya Guba area, Belomorian Mobile Belt. *Geochemistry International* **52**, 670–686. https://doi.org/10.1134/s0016702914060068.

Ray, S. & Sen, S. K. (1970). Partitioning of major exchangeable cations among orthopyroxene, calcic pyroxene and hornblende in basic Granulites from Madras. *Neues Jahrbuch für Mineralogie - Abhandlungen* **114**, 61–88.

Reay, A. (1981). The effect of disc mill grinding on some rock-forming minerals. *Mineralogical Magazine* **44**, 179–182. https://doi.org/10.1180/minmag.1981.044.334.10.

Rebay, G., Powell, R. & Diener, J. F. A. (2010). Calculated phase equilibria for a morb composition in a P-T range, 450-650 °C and 18-28 kbar: the stability of eclogite. *Journal of Metamorphic Geology* **28**, 635–645. https://doi.org/10.1111/j.1525-1314.2010.00882.x.

Reinsch, D. (1979). Glaucophanites and eclogites from Val Chiusella, Sesia-Lanzo zone (Italian Alps). *Contributions to Mineralogy and Petrology* **70**, 257–266. https://doi.org/10.1007/bf00375355.

Riel, N., Kaus, B. J. P., Green, E. C. R. & Berlie, N. (2022). MAGEMin, an efficient Gibbs energy minimizer: application to igneous systems. *Geochemistry, Geophysics, Geosystems* **23**. https://doi.org/10.1029/2022gc010427.

Ritchie, J. A. (1968). Effect of metallic iron from grinding on ferrous iron determinations. *Geochimica et Cosmochimica Acta* **32**, 1363–1366. https://doi.org/10.1016/0016-7037(68)90036-7.

Rivalenti, G. & Sighinolfi, G. P. (1969). Geochemical study of graywackes as a possible starting material of para-amphibolites.

Contributions to Mineralogy and Petrology **23**, 173–188. https://doi.org/10.1007/bf00371531.
Robson, R. M. L. (2000) *High grade blueschist metamorphism in a Serpentine Melange, Syros, Greece*. Doctoral thesis. University of Edinburgh, Edinburgh, United Kingdom.
Rock, N. M. S. (1988). Summary statistics in geochemistry: a study of the performance of robust estimates. *Mathematical Geology* **20**, 243–275. https://doi.org/10.1007/bf00890256.
Rock, N. M. S. (1989). Letter to the editor: reply to Aitchison. *Mathematical Geology* **21**, 791–793. https://doi.org/10.1080/07434618712331274349.
Rollinson, H.R., and Pease, V. (2021) *Using Geochemical Data. To Understand Geological Processes*, Cambridge: Cambridge University Press. https://doi.org/10.1017/9781108777834.
Rutter, J. (2015) *Characterising low temperature alteration and oxidation of the upper oceanic crust*. Doctoral thesis. University of Southampton, Southampton, United Kindgom.
Ryan, P. D., Max, M. D. & Kelly, T. (1983). The petrochemistry of the basic volcanic rocks of the South Connemara Group (Ordovician), western Ireland. *Geological Magazine* **120**, 141–152. https://doi.org/10.1017/s0016756800025292.
Saikkonen, R. J. & Rautiainen, I. A. (1993). Determination of ferrous iron in rock and mineral samples by three volumetric methods. *Bulletin - Geological Society of Finland* **65**, 59–64. https://doi.org/10.17741/bgsf/65.1.005.
Sawada, K. (1973). Geochemistry of geosynclinal greenstones of the Chichibu and Sambagawa Belts in Central Shikoku. *The Journal of the Geological Society of Japan* **79**, 651–668. https://doi.org/10.5575/geosoc.79.651.
Sawyer, E. W. (1991). Disequilibrium melting and the rate of melt-residuum separation during Migmatization of mafic rocks from the Grenville Front, Quebec. *Journal of Petrology* **32**, 701–738. https://doi.org/10.1093/petrology/32.4.701.
Schafer, H. N. S. (1966). The determination of iron(II) oxide in silicate and refractory materials. Part I. A review. *The Analyst*. https://doi.org/10.1039/AN9669100755.
Schiøtte, L. (1988). Field occurrence and petrology of deformed metabasite bodies in the Rinkian mobile belt, Umanak district, West Greenland. *Rapport Grønlands Geologiske Undersøgelse* **141**, 1–36. https://doi.org/10.34194/rapggu.v141.8053.
Schliestedt, M. (1986). Eclogite-Blueschist relationships as evidenced by mineral equilibria in the high-pressure metabasic rocks of Sifnos (Cycladic Islands), Greece. *Journal of Petrology* **27**, 1437–1459. https://doi.org/10.1093/petrology/27.6.1437.
Schliestedt, M. & Matthews, A. (1987). Transformation of blueschist to greenschist facies rocks as a consequence of fluid infiltration, Sifnos (Cyclades), Greece. *Contributions to Mineralogy and Petrology* **97**, 237–250. https://doi.org/10.1007/bf00371243.
Schmidt, M. W. & Jagoutz, O. (2017). The global systematics of primitive arc melts. *Geochemistry, Geophysics, Geosystems* **18**, 2817–2854. https://doi.org/10.1002/2016gc006699.
Schumacher, J. C. (1988). Stratigraphy and geochemistry of the Ammonoosuc Volcanics, Central Massachusetts and southwestern New Hampshire. *American Journal of Science* **288**, 619–663. https://doi.org/10.2475/ajs.288.6.619.
Schüssler, U., Richter, P. & Okrusch, M. (1989). Metabasites from the KTB Oberpfalz target area, Bavaria—geochemical characteristics and examples of mobile behaviour of “immobile” elements. *Tectonophysics* **157**, 135–148. https://doi.org/10.1016/0040-1951(89)90347-8.
Sederholm, J. J. (1907). Om granit och geis. *Bulletin de la commission Géologique de Finlande* **23**, 1–110.
Seki, Y., Oba, T., Mori, R. & Kuriyagawa, S. (1964). Sanbagawa metamorphism in the central part of Kii Peninsula. *The Journal of the Japanese Association of Mineralogists, Petrologists and Economic Geologists* **52**, 73–89. https://doi.org/10.2465/ganko1941.52.73.
Sen, S. K. & Ray, S. (1971). Hornblende-pyroxene granulites versus pyroxene granulites: a study from the type charnockite area. *Neues Jahrbuch für Mineralogie - Abhandlungen* **115**, 291–314.
Sevigny, J. H. (1988) *Geochemistry and petrology of amphibolites, granites, and metasedimentary rocks, Monashee Mountains, southeastern Canadian Cordillera*. Doctoral thesis. University of Calgary, Calgary, Alberta, Canada.
Shaw, D. M. & Kudoi, A. M. (1965). A test of the discriminant function in the amphibolite problem. *Mineralogical Magazine and Journal of the Mineralogical Society* **34**, 423–435. https://doi.org/10.1180/minmag.1965.034.268.38.
Sills, J. D. & Tarney, J. (1984). Petrogenesis and tectonic significance of amphibolites interlayered with metasedimentary gneisses in the Ivrea Zone. *Southern Alps, northwest Italy: Tectonophysics* **107**, 187–206. https://doi.org/10.1016/0040-1951(84)90251-8.
Singh, M. R. (2022). Geochemistry of metabasites from the western Singhbhum Craton,eastern India: implications for subduction-zone tectonics and mantle-wedge metasomatism. *Geologica Acta* **20**, 17–15. https://doi.org/10.1344/GeologicaActa2022.20.11.
Sivell, W. J. (1984). Low-grade metamorphism of the brook street Volcanics, D’Urville Island, New Zealand. *New Zealand Journal of Geology and Geophysics* **27**, 167–190. https://doi.org/10.1080/00288306.1984.10422525.
Sivell, W. J. (1986). A basaltic-ferrobasaltic granulite association, Oonagalabi gneiss complex, Central Australia: magmatic variation in an early Proterozoic rift. *Contributions to Mineralogy and Petrology* **93**, 381–394. https://doi.org/10.1007/bf00389396.
Sivell, W. J. (1988). Geochemistry of metatholeiites from the harts range, Central Australia: implications for mantle source heterogeneity in a Proterozoic mobile belt. *Precambrian Research* **40-41**, 261–275. https://doi.org/10.1016/0301-9268(88)90071-x.
Sivell, W. J. & Foden, J. D. (1988). Amphibolites from the Entia Gneiss Complex, Eastern Arunta inlier: geochemical evidence for a proterozoic transition from extensional to compressional tectonics. *Precambrian Research* **38**, 235–255. https://doi.org/10.1016/0301-9268(88)90004-6.
Skelton, A. D. L. (1992) *Petrological, geochemical and field studies of fluid infiltration during regional metamorphism of the Dalradian of the SW Scottish Highlands*. Doctoral thesis. University of Edinburgh, Edinburgh, United Kingdom.
Skelton, A., Peillod, A., Glodny, J., Klonowska, I., Månbro, C., Lodin, K. & Ring, U. (2019). Preservation of high-P rocks coupled to rock composition and the absence of metamorphic fluids. *Journal of Metamorphic Geology* **37**, 359–381. https://doi.org/10.1111/jmg.12466.
Smith, C. G. & Phillips, E. R. (2002). Cummingtonite in the Dalradian of NE Scotland. *Mineralogical Magazine* **66**, 337–352. https://doi.org/10.1180/0026461026620031.
So, C.-S. (1978). Geochemistry and origin of amphibolite and magnetite from the Yangyang iron deposit in the Gyeonggi metamorphic complex, Republic of Korea. *Mineralium Deposita* **13**, 105–117. https://doi.org/10.1007/bf00202910.
So, C.-S. & Kim, S.-M. (1975). The chemistry and origin of amphibolitic rocks in the Sobaegsan Metamorphic Belt and the Ogbang and Sangdong tungsten mine areas, Korea. *Economic and Environmental Geology* **8**, 164.
Spadea, P. & Espinosa, A. (1996). Petrology and chemistry of late cretaceous volcanic rocks from the southernmost

segment of the Western Cordillera of Colombia (South America). *Journal of South American Earth Sciences* **9**, 79–90. https://doi.org/10.1016/0895-9811(96)00029-6.

Spadea, P., Delaloye, M., Espinosa, A., Orrego, A. & Wagner, J. J. (1987). Ophiolite complex from La Tetilla, Southwestern Colombia, South America. *The Journal of Geology* **95**, 377–395. https://doi.org/10.1086/629136.

Spandler, C., Hermann, J., Arculus, R. & Mavrogenes, J. (2004). Geochemical heterogeneity and element mobility in deeply subducted oceanic crust; insights from high-pressure mafic rocks from New Caledonia. *Chemical Geology* **206**, 21–42. https://doi.org/10.1016/j.chemgeo.2004.01.006.

Spear, F. S. (1993) *Metamorphic phase equilibria and pressure-temperature-time paths*. Washington, DC: Mineralogical Society of America.

Srivastava, R. K. (2012). Petrological and geochemical studies of paleoproterozoic mafic dykes from the Chitrangi region, Mahakoshal Supracrustal Belt, Central Indian Tectonic Zone: Petrogenetic and tectonic significance. *Journal of the Geological Society of India* **80**, 369–381. https://doi.org/10.1007/s12594-012-0155-3.

Stamatelopoulou-Seymour, K. & MacLean, W. H. (1977). The geochemistry of possible metavolcanic rocks and their relationship to mineralization at Montauban-Les-Mines, Quebec. *Canadian Journal of Earth Sciences* **14**, 2440–2452. https://doi.org/10.1139/e77-212.

Starr, P. G. (2017) *Sub-Greenschist To Lower Amphibolite Facies Metamorphism Of Basalts: Examples From Flin Flon, Manitoba And Rossland, British Columbia*. University of Calgary, Calgary, Alberta, Canada.

Starr, P. G. & Pattison, D. R. M. (2019a). Equilibrium and disequilibrium processes across the greenschist–amphibolite transition zone in metabasites. *Contributions to Mineralogy and Petrology* **174**, 18. https://doi.org/10.1007/s00410-019-1553-y.

Starr, P. G. & Pattison, D. R. M. (2019b). Metamorphic devolatilization of basalts across the greenschist-amphibolite facies transition zone: insights from isograd mapping, petrography and thermodynamic modelling. *Lithos* **342-343**, 295–314. https://doi.org/10.1016/j.lithos.2019.05.020.

Starr, P. G., Broadwell, K. S., Dragovic, B., Scambelluri, M., Haws, A. A., Caddick, M. J., Smye, A. J. & Baxter, E. F. (2020a). The subduction and exhumation history of the Voltri Ophiolite, Italy: evaluating exhumation mechanisms for high-pressure metamorphic massifs. *Lithos* **376-377**, 105767. https://doi.org/10.1016/j.lithos.2020.105767.

Starr, P. G., Pattison, D. R. M. & Ames, D. E. (2020b). Mineral assemblages and phase equilibria of metabasites from the prehnite–pumpellyite to amphibolite facies, with the Flin Flon Greenstone Belt (Manitoba) as a type example. *Journal of Metamorphic Geology* **38**, 71–102. https://doi.org/10.1111/jmg.12513.

Stephenson, N. C. N. (1977). Coexisting hornblendes and biotites from Precambrian gneisses of the south coast of Western Australia. *Lithos* **10**, 9–27. https://doi.org/10.1016/0024-4937(77)90027-5.

Stephenson, N. C. N. (1980). Precambrian amphibolites and basic granulites of the south coast of Western Australia. *Journal of the Geological Society of Australia* **27**, 91–104. https://doi.org/10.1080/00167618008729123.

Stephenson, N. C. N. & Hensel, H. D. (1982). Amphibolites and related rocks from the Wongwibinda metamorphic complex, northern N.S.W., Australia. *Lithos* **15**, 59–75. https://doi.org/10.1016/s0024-4937(82)80006-6.

Stoddard, E. F. (1985). Zoned plagioclase and the breakdown of hornblende in pyroxene amphibolites. *The Canadian Mineralogist* **23**, 195–204.

Stokes, H. N. (1901) *On pyrite and marcasite*, Vol. 186. Govt. Print. Off. Bulletin, Washington, United States of America. p.50. https://doi.org/10.3133/b186.

Storey, B. C. & Meneilly, A. W. (1985). Petrogenesis of metamorphic rocks within a subduction-accretion terrane, Signy Island, South Orkney Islands. *Journal of Metamorphic Geology* **3**, 21–42. https://doi.org/10.1111/j.1525-1314.1985.tb00303.x.

Subbarao, K. V. (1971). The origin of the Kunavaram amphibolites, Khammam District, Andhra Pradesh, India. *Geological Magazine* **108**, 131–136. https://doi.org/10.1017/s0016756800051153.

Subramaniam, A. P. (1959). Charnockites of the type area near Madras; a reinterpretation. *American Journal of Science* **257**, 321–353. https://doi.org/10.2475/ajs.257.5.321.

Suda, Y., Kawano, Y., Yaxley, G., Korenaga, H. & Hiroi, Y. (2008). Magmatic evolution and tectonic setting of metabasites from Lützow–Holm Complex, East Antarctica. *Geological Society Special Publication* **308**, 211–233. https://doi.org/10.1144/sp308.11.

Suen, C.-Y. J. (1978) *Geochemistry of peridotites and associated mafic rocks, Ronda ultramafic complex, Spain*. Doctoral thesis. Massachusetts Institute of Technology, Cambridge, Massachusetts, United States of America.

Switzer, G. S. (1945). Eclogite from the California glaucophane schists. *American Journal of Science* **243**, 1–8. https://doi.org/10.2475/ajs.243.1.1.

Syme, E. C. (2014) Geology of the Athapapuskow Lake area, western Flin Flon belt, Manitoba (part of NTS 63K12). *Manitoba Innovation, Energy and Mines*, Manitoba Geological Survey, Winnipeg, Geoscientific Report GR2014-1, 210 p., 1 DVD.

Syme, E. C. & Whalen, J. B. (2012) Geology of the Elbow Lake area, central Flin Flon Belt, Manitoba (part of NTS 63K15W). *Manitoba Innovation, Energy and Mines*, Manitoba Geological Survey, Winnipeg, Geo-scientific Report GR2012-1, 100 p., 1 DVD.

Tagiri, M. & Onuki, H. (1976). Subcalcic hornblendes in the epidote amphibolites of the Yamagami metamorphic complex in the northern Abukuma Plateau. *The Journal of the Japanese Association of Mineralogists, Petrologists and Economic Geologists* **71**, 229–237. https://doi.org/10.2465/ganko1941.71.229.

Terentiev, R. A. & Santosh, M. (2017). Clinopyroxenites (diopsidites) and metabasites from the East Sarmatian Orogen, East European craton. *Geological Journal* **52**, 745–767. https://doi.org/10.1002/gj.2837.

Thurston, S. P. (1985). Structure, petrology, and metamorphic history of the Nome Group blueschist terrane, Salmon Lake area, Seward Peninsula, Alaska. *GSA Bulletin* **96**, 600–617. https://doi.org/10.1130/0016-7606(1985)96<600:spamho>2.0.co;2.

Tilley, C. E. (1938). The status of hornblende in low grade metamorphic zones of green schists. *Geological Magazine* **75**, 497–511. https://doi.org/10.1017/s0016756800091950.

Tournon, J., Triboulet, C. & Azema, J. (1989). Amphibolites from Panama: anticlockwise P-T paths from a pre-upper cretaceous metamorphic basement in Isthmian Central America. *Journal of Metamorphic Geology* **7**, 539–546. https://doi.org/10.1111/j.1525-1314.1989.tb00616.x.

Triboulet, C. (1980). Les métabasites entre Concarneau et Lorient : un exemple de métamorphisme prograde polyphasé en Bretagne méridionale. *Bulletin de Minéralogie* **103**, 92–100. https://doi.org/10.3406/bulmi.1980.7378.

Turkina, O. M. (2023). Variations in trace element and isotope composition of Neoarchean Mafic granulites of the Southwest Siberian Craton: a consequence of various mantle sources or crustal contamination. *Petrology* **31**, 204–222. https://doi.org/10.1134/s0869591123020066.

Turkina, O. M. & Nozhkin, A. D. (2014). Geochemistry and origin of metabasites from the granulite-gneiss complex of the Angara-Kan block, southwestern Siberian craton. *Geochemistry International* **52**, 829–841. https://doi.org/10.1134/s0016702914100097.

Turner, F. J. (1981) *Metamorphic petrology. Mineralogical, Field and Tectonic Aspects*. New York McGraw-Hill, p.552.

Vallance, T. G. (1974). Spilites and spilitic rocks. 59–68. https://doi.org/10.1007/978-3-642-88230-2_5.

Villaseca, C., Castiñeiras, P. & Orejana, D. (2015). Early Ordovician metabasites from the Spanish central system: a remnant of intraplate HP rocks in the Central Iberian zone. *Gondwana Research* **27**, 392–409. https://doi.org/10.1016/j.gr.2013.10.007.

Vincenzo, G. D., Palmeri, R., Talarico, F., Andriessen, P. A. M. & Ricci, G. A. (1997). Petrology and geochronology of eclogites from the Lanterman Range, Antarctica. *Journal of Petrology* **38**, 1391–1417. https://doi.org/10.1093/petroj/38.10.1391.

Walia, D. (1996) *Petrology, petrochemistry, and structure of the precambrian rocks of Pamuru area, Prakasam district, Andhra Pradesh*. Doctoral thesis. Gauhati University, Guwahati, Assam, India.

Walker, J. R. & Murphy, M. P. (1995). Low-grade metamorphism of mafic rocks. *Geological Society of America Special Papers*, 141–156. https://doi.org/10.1130/spe296-p141.

Walker, K. R., Joplin, G. A., Lovering, J. F. & Green, R. (1959). Metamorphic and metasomatic convergence of basic igneous rocks and lime-magnesia sediments of the precambrian of North-Western Queensland. *Journal of the Geological Society of Australia* **6**, 149–177. https://doi.org/10.1080/00167615908728504.

Walters, J. B., Cruz-Uribe, A. M. & Marschall, H. R. (2020). Sulfur loss from subducted altered oceanic crust and implications for mantle oxidation. *Geochemical Perspectives Letters*, 36–41. https://doi.org/10.7185/geochemlet.2011.

Wang, S.-J., Teng, F.-Z., Li, S.-G. & Hong, J.-A. (2014). Magnesium isotopic systematics of mafic rocks during continental subduction. *Geochimica et Cosmochimica Acta* **143**, 34–48. https://doi.org/10.1016/j.gca.2014.03.029.

Warr, L. N. (2021). IMA–CNMNC approved mineral symbols. *Mineralogical Magazine* **85**, 291–320. https://doi.org/10.1180/mgm.2021.43.

Weakliem, J. H. (1984) *The Petrological Evolution of Garnet-Rich Meta-Igneous Bodies in the Southeastern Adirondack Mountains, New York*. Masters thesis. Lehigh University, Bethlehem, Pennsylvania, United States.

Weber, S., Hauke, M., Martinez, R. E., Redler, C., Münker, C. & Froitzheim, N. (2022). Fluid-driven transformation of blueschist to vein eclogite during the Early Eocene in a subducted sliver of continental crust (Monte Emilius, Italian Western Alps). *Journal of Metamorphic Geology* **40**, 553–584. https://doi.org/10.1111/jmg.12638.

van der Wegen, G. (1978). Garnet-bearing metabasites from the Blastomylonitic Graben, western Galicia, Spain. *Scripta Geology* **45**, 1–95.

Wei, C.J., and Duan, Z.Z. (2019) Phase relations in metabasic rocks: Constraints from the results of experiments, phase modelling and ACF analysis. In: Zhang L., Zhang Z., Schertl P., and Wei C. J., *Geological Society Special Publication*. Geological Society of London, London, v. **474**, p. 25–45, https://doi.org/10.1144/sp474.10.

Wenk, E., Schwander, H. & Stern, W. (1974). On calcic amphiboles and amphibolites from the Lepontine Alps. *Schweizerische Mineralogische und Petrographische Mitteilungen* **54**, 97–150. https://doi.org/10.5169/seals-42191.

Whipple, E. R., Speer, J. A. & Russell, C. W. (1984). Errors in FeO determinations caused by tungsten carbide grinding apparatus. *American Mineralogist* **69**, 9–16.

Whitney, D. L., Fornash, K. F., Kang, P., Ghent, E. D., Martin, L., Okay, A. I. & Brovarone, A. V. (2020). Lawsonite composition and zoning as tracers of subduction processes: a global review. *Lithos* **370-371**, 105636. https://doi.org/10.1016/j.lithos.2020.105636.

Widmer, T. (2001). Local origin of high pressure vein material in eclogite facies rocks of the Zermatt-Saas-Zone, Switzerland. *American Journal of Science* **301**, 627–656. https://doi.org/10.2475/ajs.301.7.627.

Wilcox, R. E. & Poldervaart, A. (1958). Metadolerite dike swarm in Bakersville-Roan Mountain Area, North Carolina. *GSA Bulletin* **69**, 1323–1368. https://doi.org/10.1130/0016-7606(1958)69[1323:mdsibm]2.0.co;2.

Wilson, A. F. (1976). Aluminium in coexisting pyroxenes as a sensitive indicator of changes in metamorphic grade within the mafic granulite terrane of the Fraser Range, Western Australia. *Contributions to Mineralogy and Petrology* **56**, 255–277. https://doi.org/10.1007/bf00466825.

Wilson, J. R. & Leake, B. E. (1972). The petrochemistry of the epidiorites of the Tayvallich Peninsula, north Knapdale, Argyllshire. *Scottish Journal of Geology* **8**, 215–252. https://doi.org/10.1144/sjg08030215.

Winchester, J. A. & Floyd, P. A. (1976). Geochemical magma type discrimination: application to altered and metamorphosed basic igneous rocks. *Earth and Planetary Science Letters* **28**, 459–469. https://doi.org/10.1016/0012-821x(76)90207-7.

de Wit, M. J. & Strong, D. F. (1975). Eclogite-bearing Amphibolites from the Appalachian Mobile Belt, Northwest Newfoundland: dry versus wet metamorphism. *The Journal of Geology* **83**, 609–627. https://doi.org/10.1086/628144.

Worthing, M. A. & Crawford, A. J. (1996). The igneous geochemistry and tectonic setting of metabasites from the emo metamorphics, Papua New Guinea; a record of the evolution and destruction of a backarc basin. *Mineralogy and Petrology* **58**, 79–100. https://doi.org/10.1007/bf01165765.

Yan, Q., He, Y., Zhu, C., Wu, H. & Shi, Q. (2022). Reduction of iron with no systematic isotope fractionation during continental subduction observed in metamorphic rocks from the Dabie-Sulu orogen, China. *Journal of Asian Earth Sciences* **225**, 105054. https://doi.org/10.1016/j.jseaes.2021.105054.

Yui, T.-F., Tsai-Way, W. & Jahn, B.-M. (1990). Geochemistry and plate-tectonic significance of the metabasites from the Tananao Schist Complex of Taiwan. *Journal of Southeast Asian Earth Sciences* **4**, 357–368. https://doi.org/10.1016/0743-9547(90)90006-Y.

Yûjirô, N. (1971). Regional metamorphism of the Nishiki-chô District,Southwest Japan. *Journal of Science of the Hiroshima University. Series C, Geology and Mineralogy* **6**, 203–268.

Zelt, G. A. D. (1980). Granulite-facies metamorphism in Namaqualand, South Africa. *Precambrian Research* **13**, 253–274. https://doi.org/10.1016/0301-9268(80)90007-8.

Zen, E. (1974). Prehnite- and Pumpellyite-bearing mineral assemblages, west side of the Appalachian Metamorphic Belt, Pennsylvania to Newfoundland 1. *Journal of Petrology* **15**, 197–242. https://doi.org/10.1093/petrology/15.2.197.

Zhang, Z., Xiao, Y., Hoefs, J., Liou, J. G. & Simon, K. (2006). Ultrahigh pressure metamorphic rocks from the Chinese Continental Scientific Drilling Project: I. Petrology and geochemistry of the main hole (0-2,050 m). *Contributions to Mineralogy and Petrology* **152**, 421–441. https://doi.org/10.1007/s00410-006-0120-5.

Zhang, R. Y., Lo, C. H., Chung, S. L., Grove, M., Omori, S., Iizuka, Y., Liou, J. G. & Tri, T. V. (2013). Origin and tectonic implication of ophiolite and eclogite in the Song Ma Suture Zone between the South China and Indochina Blocks. *Journal of Metamorphic Geology* **31**, 49–62. https://doi.org/10.1111/jmg.12012.

Zhang, H. L., Cottrell, E., Solheid, P. A., Kelley, K. A. & Hirschmann, M. M. (2018). Determination of $Fe^{3+}/\Sigma Fe$ of XANES basaltic glass standards by Mössbauer spectroscopy and its application to the oxidation state of iron in MORB. *Chemical Geology* **479**, 166–175. https://doi.org/10.1016/j.chemgeo.2018.01.006.

Zwanzig, H. V. & Bailes, A. H. (2010). Geology and geochemical evolution of the northern Flin Flon and southern Kisseynew domains, Kississing–file lakes area, Manitoba (parts of NTS 63K, N). *Manitoba Innovation, Energy and Mines Geoscientific Report*, GR2010–GR2011.

Journal of Petrology, 2024, **65**, egae120
https://doi.org/10.1093/petrology/egae120
Letter