Igneous and sedimentary 'limestones': the puzzling challenge of a converging classification

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Abstract: The vast majority of extrusive carbonatites are calcitic rocks which may be confused with sedimentary limestones, thus requiring a disambiguation criterion. Extrusive carbonatites are classified based on quantitative criteria that tend to avoid genetic mechanisms. Carbonatite nomenclature is in progress but regulated by the International Union of Geological Sciences norm for igneous rocks. Carbonate sedimentary rock nomenclature is mainly regulated by the Dunham, Embry and Klovan, and Sibley and Gregg classification systems. These limit the description of rock types from various depositional mechanisms and makes comparison with sedimentary rocks difficult. Igneous and sedimentary carbonate rocks display no apparent differences in the field and at meso–micro-scale. They may be layered, massive crystalline or show discrete clasts in a matrix, which make both rock types resemble one another. The study analyses the situations in which classification inconsistencies are most common. Adopting these guidelines may increase confidence, reliability and value in the petrographic classification of igneous and sedimentary lithologies. This study poses a challenging target. Can igneous carbonate rocks be classified using the same approach that is used for sedimentary carbonate rocks and vice versa? So far, the scheme chosen has been arbitrary or limited to the aim of the study being undertaken. The authors start an unexperienced dialogue for the first time between volcanologists and sedimentologists by examining a range of sedimentary and volcaniclastic rock textures which may resemble each other.

The authors dedicate this research work to the memory of Nikolay V. Vladykin, who devoted his life to the study of carbonatites

Volcaniclastic rocks form the bulk of explosive subaerial volcanoes. Volcaniclastic rocks are like clastic sedimentary rocks because they experience fragmentation, transport, grading, deposition and diagenetic processes. Mineralogical differences are a key criterion for differentiation, but this falls down when considering volcaniclastic rocks, which are not composed of silicate minerals but instead carbonate, especially calcites, such as those derived from carbonatites. Each can have the same essential mineralogy and show textures that are easily confused with those of sedimentary carbonate rocks.

The need to identify carbonatites is heightened because they can be indicators of critical metal deposits, which are essential for green and high-tech applications (Anenburg *et al.* 2021). Carbonatites are relatively rare rocks, but some sedimentary limestones may be misinterpreted as carbonatites, thus hindering further research and prospecting for ore deposits. A completely new insight into the origins of carbonatites came from observations of extrusive carbonatite volcanism, including features like the tear-drop lapilli stone at Kaiserstuhl, Germany and carbonatitic tuffs bombs at Fort Portal and Katwe–Kikorongo in Uganda (Keller 1981; Stoppa and Schiazza 2012). Extrusive carbonatites preserve astonishing evidence of quenching from high-temperature carbonatite liquids. On the other hand,

they show clasts similar in shape and structure to sedimentary carbonate rocks in the field (Fig. 1).

Classification based on grain size alone is unsatisfactory and, in any case, generates different terminologies for volcaniclastic rocks and sedimentary rocks (Fig. 2). Most geologists who classify sedimentary carbonate rocks use the schemes of Dunham (1962) and Embry and Klovan (1971). These classifications can also be partially adopted for many carbonatites, especially extrusive ones. It is necessary to establish reasonable criteria to distinguish sedimentary and igneous carbonate and to homogenize their classification terminology since there are ambiguities in their petrographic description. There is a certain disconnect between the classification schemes used for carbonatites, pyroclastic rocks in general and those used for sedimentary equivalents. This variability is understandable and a natural consequence of the different points of view in these different environments and historical reasons. To illustrate the extent to which misunderstanding of terminology is possible for the two groups of rocks, we can consider the following example: carbonatite means an igneous rock consisting of carbonates, which defines a group of minerals, while for sedimentologists 'carbonates' also defines sedimentary rock made up of carbonate. It is clear to all that the term carbonate indicates a compound formed by one or more cations linked to the CO_3^{2-} group forming a precise crystal lattice – a mineral, therefore, and not a rock. According to the International Union of Geological Sciences (IUGS) rules, when a rock is essentially made up of a single mineral, the name of the rock is formed by adding the suffix 'ite' to the name of the mineral. For example, if the dominant mineral is plagioclase, the rock's name becomes plagioclasite, pyroxene becomes pyroxenite, peridot becomes peridotite, etc. For the petrologists, who follow the IUGS, there is no problem forming the term carbonatite starting from the predominant carbonate. For example, when we want to indicate that a carbonatite is essentially made up of calcite, the name is calcite carbonatite and so on. If the rock contains less than 50% carbonate but more than 20%, then the adjective carbonatitic is added to the name of the rock, for example, carbonatitic nephelinite. If a carbonate is present in a noticeable and unexpected component in a rock, then the mineral name is added to that of the rock, for example, calcite-bearing syenite.

However, there is a notable nomenclatural argument in the current terminology used by igneous rock petrologists v. sedimentary rock petrologists. For example, the mineral dolomite forms a rock named dolostone (*dolomia*, It.) and not dolomitite. Since it is impossible to vary a consolidated terminology, we prefer to use the historical term limestone to highlight igneous calcitic carbonate rocks, for a

long time confused with limestones. Recent extrusive carbonatites are calcite carbonatite, with very few exceptions (Stoppa *et al.* 2000). On the other hand, buried old calciocarbonatites may undergo dolomitization processes (e.g. Bayan-Obo; Pengfei *et al.* 2021). We do not want to introduce a new terminology but to underline the terminological inconsistencies used despite a more rational classification. This review aims to recognize the circumstances in which inconsistencies, redundancies and confusion occur. We discuss guidelines that can be applied to increase confidence and reliability in a comparative classification.

In most cases, the geological context, such as association with other igneous rocks, explicit volcanic nature, etc., leads to an easy distinction between igneous and sedimentary nature. However, in some cases, both rock types show similar sedimentary structures such as dunes, ripples and gradation, including fossils and footprints (Fig. 1; Masao *et al.* 2016). Similar structures are also observed at the hand scale. To avoid confusion, many distinctive observations are necessary for a thin section study, including cathodoluminescence. The petrographic classification of igneous and sedimentary carbonate rocks will allow better data exchange within the world of mining research and academia. Additionally, this study aims to supply informed guidance to clarify and compare the use of those terms that are already widely adopted by igneous and sedimentary petrologists.

Troubling reconnaissance of igneous limestones

Both sedimentary and igneous carbonate rocks consist of more than 50% carbonate minerals, generally calcite. In igneous limestones, the carbonate has a magmatic origin (Le Maitre 2002). There is a lot to talk about regarding a deep-rooted historical discussion of the geological meaning of carbonatites concerning sedimentary carbonate rocks (Stoppa 2021). This is a technical problem and a philosophical issue arising from the peculiar composition of igneous carbonate rocks. In the nineteenth century, even to volcano specialists, it was not clear that carbonatites were igneous rocks crystallized from an elevated-temperature magmatic liquid. At the beginning of the twentieth century, a circular concept of 'sedimentary limestone melting' became a fashionable model (Foye 1915, 1916; Ginsberg 1916; Shand 1930, 1945). In the 1960s, scientists began to support a magmatic origin of carbonatite (e.g. Wyllie and Tuttle 1960). In the 1970s, scientists revised relevant sedimentary and magmatic limestones, defining genuine carbonatites (Wyllie 1974; Fitton and Upton 1987; Bell 1989). Even today, this question has not been entirely addressed as

Igneous and sedimentary limestones
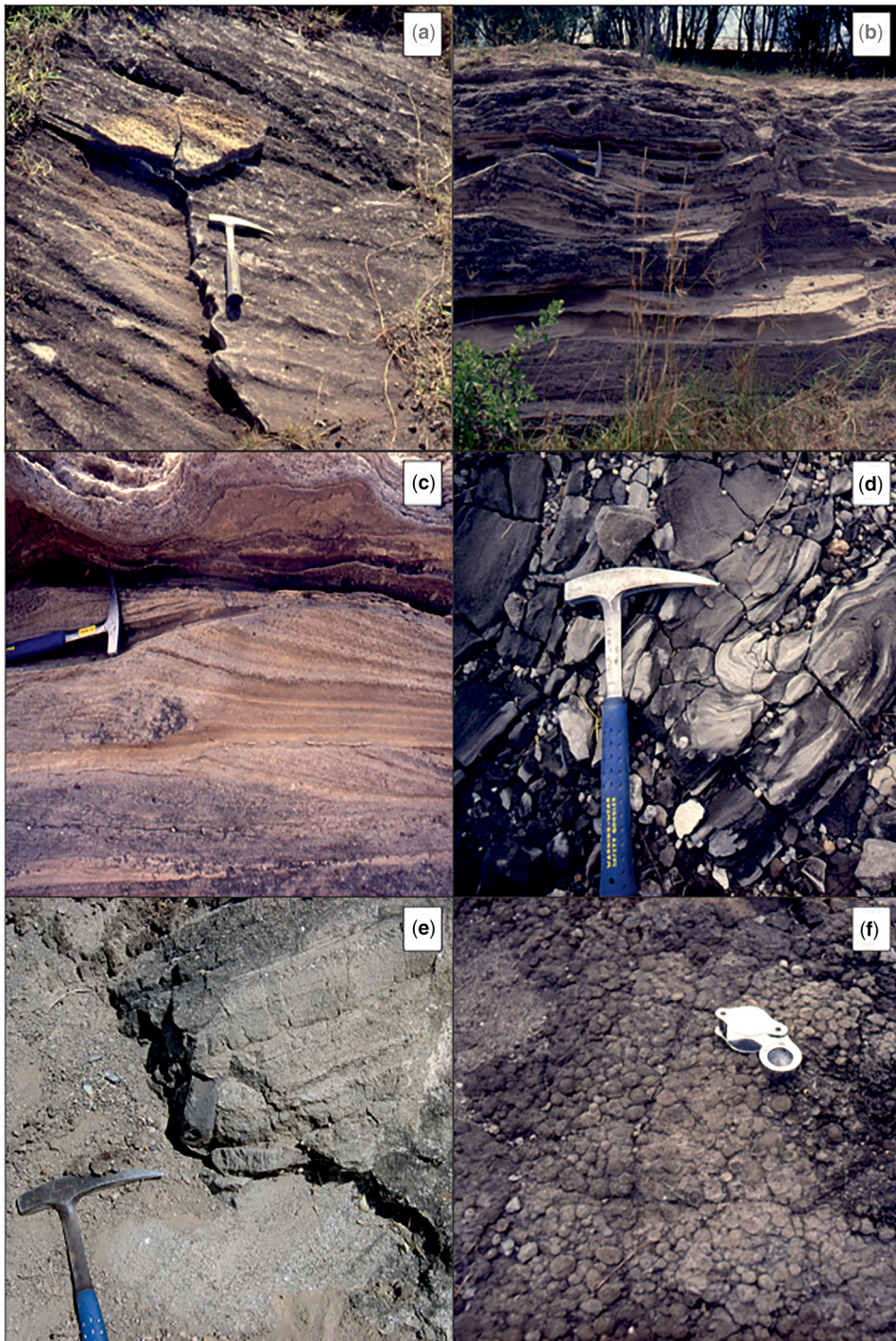
Fig. 1. Volcanic structures in extrusive carbonatites, which can be misinterpreted as sedimentary structures. (**a**) Ripple on dunes (Fort Portal, Uganda); (**b**) cross-lamination and progressive dunes (Katwe–Kikorongo, Uganda); (**c**) detail of (**b**); (**d**) reomorphic carbonatite ash slump (Fort Portal, Uganda); (**e**) graded layers in carbonatitic lapilli tuff (Calatrava, Spagna); (**f**) accretionary lapilli (Katwe–Kikorongo, Uganda).

GRANULOMETRY	SEDIMENTARY CLASTS	VOLCANICLASTIC FRAGMENTS	IGNEOUS CRYSTALLINE ROCKS	SEDIMENTARY CRYSTALLINE ROCKS	
				LIMESTONE	DOLOSTONE
4096–256 mm	boulders	bombs and blocks	pegmatoid	Sparstone (> 0.01 mm)	Very coarse crystalline
256–64 mm	cobbles				
64–4 mm	pebbles	lapilli	coarse grained		
4–2 mm	granules		medium grained		
2–1 mm	very coarse sand	coarse ash	fine grained		Coarse cryst.
1–0.5 mm	coarse sand				
0.5–0.25 mm	medium sand		micro-crystalline		Medium cryst.
0.25–0.125 mm	fine sand				Fine cryst.
0.125–0.063 mm	very fine sand				Very fine cryst.
0.063–0.004 mm	silt	fine ash		Microsparstone (< 0.01 mm)	Microcryst.
<0.004 mm	clay		crypto-crystalline		Cryptocryst.

Fig. 2. Comparison of the terminology of different grain size carbonate sedimentary and igneous volcanic rocks. The adopted schemes for crystalline sedimentary rocks are from Wright (1992) for limestones and Chatalov (2013) for dolostones.

carbonatites can be generated in several diverse ways and may not show the features typical of a silicate igneous rock (Gittins 1989; Moore and Wood 1998; Wyllie and Lee 1998; Mitchell 2005; Brooker and Kjarsgaard 2011; Jones *et al.* 2013; Stoppa *et al.* 2019). Indeed, the chemistry and mineralogy of carbonatites, or better their perception by non-specialists, are not enough to overcome the idea that calcite carbonatites are melted limestones. Carbonatites are often confused with other rocks, mainly when isolated, altered, metamorphosed and/or tectonized. In addition, extrusive carbonatites are pyroclastic, while lava flows are sporadic (Woolley and Church 2005). Both sedimentary and igneous carbonate rocks are highly susceptible to syn-depositional and post-depositional alteration. Alkali-rich carbonatites (natrocarbonatites) can convert into calciocarbonatites very rapidly (Zaitsev and Keller 2006).

Similarly, for sedimentary carbonates, where recrystallization or replacement has obliterated the primary textures, crystalline limestone or crystalline dolostone is used to describe the lithology (Dunham 1969*a*, *b*; Fig. 2), making these rocks texturally remarkably like subvolcanic, fine-grained carbonatites (alvikites) and recrystallized magnesiocarbonatite. The texture of extrusive carbonatite requires a specific terminology based on various criteria, exactly as sedimentary rocks. If we avoid genetic classification, the other possible classification criteria are based on grain size, grain shape and their internal structure, grain compaction and textural arrangement, clast/matrix ratio, composition and the presence of primary and secondary types of cement (referring only to carbonatites). These criteria converge towards sedimentary classifications, but the terminology evolved in isolation and may be entangled for field sedimentologists, who are not familiar

with tuffs, tufites, tuffisites, tufas and many other similar terms.

Carbonatites, particularly extrusive carbonatites, can be fleeting in the geological environment, but remnants of intrusive carbonatites (some locally converted to magnesiocarbonatite) are known to occur that are as old as *c.* 3 Ga (Bizzarro *et al.* 2002; Woolley and Kjarsgaard 2008*a*, *b*). Thus, it is possible that sedimentary carbonate rocks originated from the contribution of carbonatite magmatism to the primordial hydrosphere and atmosphere and that carbonatite-derived carbon has been fixed in rocks by biological activity through time. This concept parallels the concept that all sedimentary rocks are derived from pristine magmatic activity on Earth. This is a central point of interest for sedimentologists who work on large temporal scales and study ancient limestones outcrops.

Pseudocarbonatites or carbomigmatites?

With the growing interest in carbonatites, an increasing number of reports of rocks that may have a texture like carbonatites have appeared in the scientific spotlight. These rocks do not have a genuine igneous origin and are not linked to mantle-derived carbonatites. Instead, they are products of metasomatism or melting, in particular conditions of pressure, temperature and volatiles, which lead to the melting of sedimentary carbonates inside the crust. Mitchell (2005) proposed that these rocks be termed pseudo carbonatites. However, this name indicates that these rocks may resemble a carbonatite somehow but are not a carbonatite. The equivalent term would be 'carbonatitoid', but both terms only classify the rock for what it is not. Instead, we

suggest the term carbomigmatite because although these rocks may display traces of fluidity, they do not move much within the crust relative to the point of formation and are often concordant or distributed in lenses in their carbonate protolith, just like a migmatite. Although this specific aspect is far from the scope of this work, it is crucial that sedimentologists and geologists in general, who may be not familiar with igneous limestones, understand the nature of the problem of misinterpretation of rocks of carbonate composition that have some aspect related to thermal phenomena but do not constitute natural carbonate magmas and instead are metamorphic or metasomatic carbonate rocks (marble, calcite skarn etc.). In addition, carbomigmatites are frequently found in the orogenic system, which is not typical of carbonatite (Sklyarov *et al.* 2009).

Sedimentary carbonate features

Carbonate sediments are mainly derived from biological, biochemical, mechanical and chemical processes in modern and ancient sedimentary environments. Most sediments are deposited as loose carbonate particles of different grain sizes. A large proportion of carbonates in peculiar environmental settings are related to organic builders.

Mineralogical composition

The two most common carbonate polymorphs are aragonite and calcite. The latter may occur as low-magnesium calcite with less than 4 mol% $MgCO_3$. High-magnesium calcite has concentrations typically ranging between 11 and 19 mol% $MgCO_3$. Aragonite and high-magnesium calcite are metastable and convert to low-magnesium calcite through a neomorphic process during burial diagenesis. This process, including recrystallization and inversion, is commonly the origin for mosaics of calcitic crystalline textures. Although marine waters are typically oversaturated with dolomite, its direct precipitation is inhibited by series of kinetic factors, and precipitation of aragonite and/or high-Mg calcite is more favourable (the Dolomite paradox; Arvidson and Mackenzie 1999). The products of late diagenetic dolomitization commonly result in a coarse-grained dolostone showing a mosaic of dolomite crystals which may partially obliterate the precursor texture (Moore 2001; Ahr 2008).

Diagnostic components of sedimentary carbonate rocks

The textural composition of sedimentary carbonate rocks varies based on the relative proportions of components commonly grouped into skeletal and non-skeletal grains, micrite, matrix and cement.

Skeletal and non-skeletal carbonate particles. The first group refers to the biomineralized calcareous parts of organisms (fossils). They occur as whole tests or as fragments and are termed bioclasts. Most skeletal grains present a diagnostic organic microfabric (skeletal structure). The non-skeletal group includes coated grains, peloids, aggregates and intra- and extraclasts. The coated grains group includes those grains showing a nucleus surrounded by a laminar microfabric (e.g. ooids, oncoids and pisoids) or by a micrite envelope (cortoids; Tucker 2001; Scholle and Ulmer-Scholle 2003; Flugel 2004). The main difference between *ooids* and *pisoids* is the grain size, the first ranging from 0.25 to 2 mm in diameter, the latter larger than 2 mm. A particular type of *pisoid* (vadose pisoids) forming within the freshwater vadose or marine vadose environment shares similarities with pyroclastic grains (i.e. concentric-shelled, coated grains). The coating shape is commonly irregular and asymmetrical and exhibits downward thickening. Other terms used for these grains are cave pearls, caliche and vadoids (Peryt 1983).

Oncoids are unattached, rounded, millimetre- to centimetre-sized, coated grains, showing concentric, often irregular laminations around a bio- or lithoclastic nucleus (Peryt 1983). Oncoids differ from ooids and pisoids, which are commonly smaller and have regular concentric laminae.

Peloids is a generic term for allochems composed of micro- and cryptocrystalline carbonate micrite (Flugel 2004). Their shape is subrounded, spherical, ovoid or irregular, and their size ranges between <0.02 and about 1 mm, commonly 0.1–0.5 mm. Peloids differ from ooids and oncoids by the absence of concentric or radial internal structures. *Aggregates* (e.g. grapestones, botryoids, lumps) consist of composite grains, initially separated, stuck together with microcrystalline cement or bound and coated by algal films (Flugel 2004).

Resediments (extra- and intraclasts) are fragments of lithified rocks or partly lithified sediments, eroded and redeposited. Extraclasts are eroded from lithified carbonate rocks exposed in a source area different from their initial sedimentary environment. Intraclasts refer to rock fragments of penecontemporaneous, commonly weakly consolidated, carbonate sediments that have been eroded and redeposited near or within the same depositional environment (Flugel 2004).

Micrite and matrix. The term *micrite* (abbreviation of 'microcrystalline calcite') generally refers to <4 μm carbonate particles and crystals (Tucker 2001; Flugel 2004), which support larger grains

(mud-supported texture) or fill interstitial spaces as in some grain-supported textures (e.g. packstone).

Matrix refers to the interstitial fine-grained material (small-sized crystals and/or particles) between larger grains and includes micrite, calcisiltite and microspar (Tucker 2001; Flugel 2004). The latter consists of calcareous mud with a crystal size ranging from 4 to about 10 μm and, like pseudospar (crystal size 10–50 μm), forms through replacement processes during diagenesis (Tucker 2001). A peloidal matrix comprises a fine-grained matrix with abundant very small spheroidal–subspheroidal mud lumps (peloids), commonly densely packed and showing a clotted fabric (e.g. thrombolite fabric *sensu* Aitken 1967; Flugel 2004).

Fabric. In sedimentary carbonates (sediments and rocks) three types of fabrics (macro/mesoscale) are differentiated: clastic/grained (grainstones), crystalline (coarse dolomite, pseudoesparite), and organogenic (boundstone). The term microfabric (microscale) is applied to describe the internal structure of components.

Classification schemes for sedimentary carbonate rocks

The Folk (1962) and Dunham (1962) classification schemes are the most widely adopted for sedimentary carbonate rocks. Originally the Folk classification was more widely used; however, in recent years, there has been a marked shift to the Dunham scheme (1962), expanded by Embry and Klovan (1971). Separate schemes have also been devised for mixed siliciclastic carbonate lithologies (Mount 1985) and dolomite textures (e.g. Sibley and Gregg 1987). The Dunham scheme focuses on textural properties evaluated on the mud content to provide helpful information about energy in the depositional environment (Fig. 2).

Embry and Klovan (1971) (Fig. 3) introduced a more detailed definition of organically bound texture, subdividing it into three categories and adding a scheme for the carbonate-dominated rock where more than 10% of the volume is made up of >2 mm grains.

Crystalline carbonate. Dunham (1962) includes in this category all of the sedimentary carbonate rocks (limestones and dolostones) for which the original textures are not recognizable owing to their destruction by diagenetic processes. One of the most common diagenetic processes is neomorphism, which takes place during burial diagenesis. It includes all transformations between a mineral and itself (e.g. calcite to calcite) or a polymorph (aragonite to calcite). It may occur as microspar (microsparite), a fine-grained calcareous mud with crystal sizes from 4 to 10 μm and pseudospar with crystals from 10 to 50 μm. Pseudospar can be confused with sparite cement but can be distinguished by the presence of (1) irregular crystal boundaries and grain-size distribution, (2) cloudy crystals, locally with impurities, commonly cutting across grain boundaries, (3) ghosts of grains floating in the neomorphic pseudospar, (4) relics of precursor textures and (5) marked texture discontinuities owing to patchy recrystallization of micrite to microspar and in places to pseudospar.

Regarding dolostones and dolomite textures, fine to medium crystalline dolostones, with good to excellent fabric preservation, are commonly classified accordingly to the Dunham (1962) scheme expanded by Embry and Klovan (1971), who added the

Original components not bound together during deposition						Original components organically bound together during deposition				Depositional texture not recognizable
Dunham, 1962				**Embry & Klovan, 1971**						**Dunham, 1962**
less than 10% of the components are >2 mm				greater than 10% of the components are >2 mm		bound by organisms that act as baffles	bound by organisms that encrust and bind	bound by organisms that build a rigid framework	original components were organically bound at the time of deposition but building mode is not identifiable	
contains lime mud			no lime mud							
mud-supported		grain-supported		matrix-supported	grain-supported by the >2 mm size fraction					
grains <10%	grains >10%									
Mudstone	Wackestone	Packstone	Grainstone	Floatstone	Rudstone	Bafflestone	Bindstone	Framestone	Boundstone	Crystalline

Fig. 3. Sedimentary carbonate classifications are based on Dunham (1962) and Embry and Klovan (1971).

mineralogical definition (e.g. dolomitic mudstone), or by using the suffix 'dolo' (e.g. dolomudstone).

A specific classification is used for coarse-grained dolostones characterized by a mosaic of dolomite crystals which may partially or totally obliterate the texture of the precursor limestone (Sibley and Gregg 1987). In planar-e textures, most of the dolomite crystals are euhedral rhombs with straight crystal boundaries supporting the framework. Two subvarieties of the idiotopic fabric are (a) planar void-filling (idiotopic – C), consisting of euhedral dolomite crystals surrounding cavities or patches of other minerals (i.e. gypsum, calcite), and (b) planar porphyrotopic (idiotopic – P), where isolated euhedral dolomite crystals, replacing precursor limestones, are floating in a lime matrix (matrix-supported texture). Most of the dolomite crystals in the planar-s texture (hypidiotopic fabric) are subhedral with straight compromise boundaries, and many crystals have preserved face junctions; euhedral rhombs are rare. In non-planar textures, most dolomite crystals are anhedral with curved, lobate, indistinct or irregular intercrystalline boundaries. Other classification schemes were adopted based on the main crystal size for crystalline limestones (Wright 1992) and dolostones (Chatalov 1971, 2013; Fig. 1).

Mixed siliciclastic and carbonate rocks

The Folk (1962), Dunham (1962), Embry and Klovan (1971) and Sibley and Gregg (1987) classifications are good complementary schemes for the petrographic characterization and nomenclature of limestones and dolostones containing more than 90% carbonate components. Although these deposits, defined as 'pure', constitute most sedimentary carbonates, various systems can occur in modern and ancient environments. A carbonate rock is considered 'mixed' when it contains more than 50% carbonate components and more than 10% siliciclastic elements (e.g. quartz, K-feldspar, plagioclase, lithic fragments, mica and clay; Mount 1985; Chiarella and Longhitano 2012). Even if siliciclastic and carbonate settings are generally widely separated, several factors can be involved in mixing these antithetic sediments (Mount 1984; Chiarella et al. 2017). Such processes include: (1) reworking of shallow water siliciclastics into carbonate platforms following occasional disruptive storm events (punctuated mixing *sensu* Mount 1985); (2) post-mortem deposition of autochthonous calcareous organisms (e.g. foraminifers, molluscs, brachiopods and echinoderms) living in siliciclastic-dominated shelves (*in situ* mixing, *sensu* Mount 1985); and (3) a gradational lateral transition between carbonate and terrigenous facies (facies mixing *sensu* Mount 1985). Different nomenclatures and classification schemes

have been adopted to describe mixed siliciclastic and carbonate rocks (e.g. Pettijohn 1954; Dunham 1962; Zuffa 1980; Mount 1984; Chiarella and Longhitano 2012). In particular, Zuffa (1980) proposed a scheme for miscellaneous sandstones (hybrid arenites), characterized by a tetrahedral diagram. The vertices of the latter represent four distinct framework components: (1) non-carbonate extrabasinal (e.g. quartz, feldspar, lithics and mica); (2) carbonate extrabasinal (e.g. calcareous and/or dolomitic extraclast); (3) non-carbonate intrabasinal (e.g. glauconite, gypsum, iron-oxides and phosphate); and (4) carbonate intrabasinal (e.g. skeletal and non-skeletal allochems). Consequently, the Zuffa (1980) classification scheme considers both the compositional (carbonate or non-carbonate) and genetic (intra- or extrabasinal) features of mixed deposits. Mount (1985) proposed a classification scheme based mainly on mixed deposit compositional and textural parameters. This classification considers four main components characterizing mixed deposits: (1) siliciclastic sand (silicates and other heavy minerals of 0.0625–2 mm in grain size); (2) siliciclastic mud (siliciclastic sediments finer than 0.0625 mm); (3) allochems (carbonate particles larger than 20 μm, e.g. ooids, bioclasts, intraclasts, peloids); and (4) micrite (e.g. lime mud). In this view, a mixed calcareous rock, having a large abundance of siliciclastic sand, can be classified as 'sandy allochem limestone' or 'sandy micrite', depending on the predominant carbonate elements. In the same way, the terms muddy allochem limestone and muddy micrite are used when the siliciclastic fraction is silt and clay particles. The petrographic classification of mixed carbonate can also be integrated with a recently developed index, known as the bioclastic/siliciclastic ratio (Chiarella and Longhitano 2012), to quantify the relative proportions of the two antithetic components.

Igneous limestones and their ambiguous interpretation

Identifying carbonatites can be highly challenging. The tectonomagmatic environment is an applicable initial criterion to help in identification as most carbonatite volcanism occurs in continental rift settings. However, carbonatites can also occur in intraplate ocean islands, in rare cases related to major tectonic discontinuities (e.g. Fuerteventura in the Canary Islands and Cabo Verde). Some occurrences have also been described relating to transient post-collisional environments (Goodenough et al. 2021).

Carbonatites are typically characterized by an abundance of calcite (or aragonite), as well as minor dolomite, ankerite, magnetite, apatite, fluorite, celestine and other minerals. While these minerals

are typical of carbonatites, the elements in these minerals also occur as chemical constituents in sedimentary carbonate rocks and other sedimentary rocks. Few minerals are exclusively associated with carbonatites and none that are ubiquitous. The presence of pyrochlore ($(Na, Ca)_2Nb_2O_6(OH, F)$) and/or some rare earth element (REE) carbonate minerals (e.g. bastnäsite, monazite, ancylite) are typical indicators for carbonatites. A clear mineralogical and chemical distinction is not apparent when carbonatites are barren in niobium and REEs. Coarse-grained, plutonic carbonatite (sövite or beforsite) are equigranular crystalline rocks mainly composed of limpid calcite and/or dolomite (Fig. 3). Owing to cumulus processes, these rocks may be devoid of heavier minerals such as olivine, magnetite and phlogopite, and therefore very similar to marble. Subvolcanic, fine-grained carbonatites (alvikite) show mosaic-textured, twinned calcite and dolomite, which may resemble recrystallized sedimentary limestones. Very fine-grained extrusive carbonatites resemble micrites. Single euhedral carbonate crystals may have the same zoning as carbonate crystals precipitated from saturated water. In addition, high pressure and temperature aragonite may be preserved in some cases as inclusions or pseudo-hexagonal euhedra, excluding a possible distinction based on the presence of organic low-temperature aragonite (Humphreys *et al.* 2010; Hurai *et al.* 2013).

A thick sequence of carbonatitic pyroclastites and epiclastites is typical as a component of continental deposits in large carbonatitic provinces such as Calatrava (Spain; Stoppa *et al.* 2011) and the Western Branch of the African rift (Uganda; Stoppa and Schiazza 2012). Such deposits show similar textural features to travertine, caliches and clastic sedimentary rock. In addition, extrusive carbonatites may contain fossils (Raichlen *et al.* 2010; Stoppa and Schiazza 2012). Some carbonatite minerals may resist weathering and erosion, such as monazite, zircon, rutile and ilmenite (Simandl and Paradis 2018), but these minerals can also occur in association with other igneous rocks and so are not distinctive indicators of a precursor carbonatite. Clasts produced by melt fragmentation during eruption/emplacement at the surface may resemble calcareous sedimentary clastic rocks and, when of a carbonatitic composition, are particularly entangling because some volcano-sedimentary processes mimic those of the epigenetic sedimentation (Fig. 1). Layering, cross and parallel lamination, grading, tractive structures, imbrication and clast shape and structure may be misinterpreted as calcarenites and tidal or continental sedimentary limestones and travertines. Quench textures in carbonatite, especially, may resemble biogenic travertine or algal structures.

Among the most confusing landforms are dunes and ripples, which are easily found in extrusive carbonatites deposits emplaced by a violent blast of CO_2, which produce a turbulent current of carbonate particles arranged with pinch and swell cross-lamination structures. Hot carbonatite ash may be remobilized owing to its very low viscosity and form slumps (Fig. 1). Slumps are also formed in wet carbonatite ash or carbonatite mudflows. Several kinds of clasts are present in extrusive carbonatites. They differ in size, composition, shape and internal structure. A vast range of clasts are generated from surficial tension in a semi-liquid state, rotation and liquid droplets or dust accretion. Dominant factors include the presence of condensed water (mud) or volatiles (CO_2). Pyroclasts can be juvenile, connate and accidental. Juvenile pyroclasts, especially lapilli, are the more interesting and can be produced in the magmatic conduit under high-velocity gas flow that produces a spray of droplets in rapid rotation (spin lapilli). Centrifugal forces orientate the crystallizing minerals concentrically. If a solid fragment is present in the magmatic convoy, it becomes a condensation nucleus allowing the droplets to adhere to its surface and agglutinate. These same droplets may quench in a micromosaic texture or show concretion-like zoning. Changes in temperature, velocity and gas–liquid–solid ratios produce further layer formation, resulting in concentric-shelled lapilli (Stoppa *et al.* 2003; Junqueira-Brod *et al.* 2005; Gernon *et al.* 2012). A similar structure forms when, after forming a volcanic column and dropping in temperature, water condensation attracts solid ash-size particles forming larger mud droplets.

Mud droplets go up and down in the column convective cells, increasing their size and accreting mud layers around the central kernel. These dusty-shelled lapilli are called accretionary lapilli. When accretionary lapilli are too large and heavy to be buoyant, they fall to the soil, agglutinate with other lapilli and may flow on an inclined surface (rheomorphism), forming slump structures. Carbonatitic mudflows can be easily confused with secondary mudflows carrying accidental lithics. Pyroclastic carbonatites offer the best examples of both concentric-shelled lapilli and accretionary lapilli. In addition, carbonatites have such a low viscosity that it is relatively easy to form rheomorphic structures such as folding in hot tuffs. All of these features may resemble the shape, transport and depositional mechanism of common sedimentary carbonate rocks.

In epigenetic conditions, carbonatites can form sediments like calcarenite sands. While the genesis may be very different, many rounded, concentric lapilli resemble similarly shaped sedimentary clasts owing to rolling. Concentric shelled carbonatite lapilli and oncolites often have a central kernel with concentric laminations. In both cases, the average size is a few centimetres. They often show plastic deformation and may be flattened. When the kernel

is an organic fragment or a mantle nodule, the difference is apparent, but the distinction is not immediate if the kernel is a limestone fragment or other crustal rock. Carbonatite droplets and oolites contain concentrically arranged carbonate crystals, but the main difference is that carbonatite droplets attained their shape by superficial tension in a melted state. The rotation of a droplet (spin lapilli) may orientate these crystals but, to be free to move, they must float in a liquid. This generates a porphyritic structure, which is not observed in oolites. Pisolites and accretionary lapilli are very ambiguous because both form in water condensed conditions and are produced by the accretion of very fine-grained carbonate particles with a comparable size rarely exceeding 1 cm.

Volcaniclastites v. epiclastites

Volcaniclastic is an extensive term used to describe any rock composed in part of igneous clasts independent of their genetic origin, size, shape, depositional mechanism and geological environment (Fisher and Smith 1991). The term is widespread with many different interpretations and paradoxes as completely igneous fragmental rocks can be classified as rocks containing only 10% of an igneous component. From this point of view, any volcanic clast is defined as a fragment originating from either primary or secondary geological processes. This is unsatisfactory, and we suggest limiting the term volcaniclastics to rocks with igneous clasts between 75 and 25%. Likewise, the term pyroclastic should be limited to rocks with >75% igneous clasts (dominantly juvenile), but some volcanic rocks have more than 25% sedimentary and metamorphic (mantle or crustal) fragments and can be named volcaniclastics. Rocks whose deposition occurred under completely exogenous media are named epiclastites and are sedimentary rocks.

Pyroclastites and volcaniclastites can be deposited in subaerial, underwater or subvolcanic primary conditions and emplaced by volcanic transport mechanisms. The contribution of an exogenous mechanism (wind, rain) is neglected during primary deposition (co-eruptive). However, the most critical factor to be considered when a pyroclastic or volcaniclastic rock is described is the origin of the igneous clasts themselves. Are they derived from a cooling igneous liquid (juvenile clasts) or already cooled igneous rocks (non-juvenile)? Furthermore, what is the nature of the other clasts? Sedimentary, metamorphic, biogenic? The dominance of clasts of primary igneous origin (juvenile pyroclasts) defines a pyroclastic rock, hitherto not a consolidated criterion in literature. Componentomery is the key, but componentometry is often highly complex and may be complicated when approaching a heterogeneous rock containing possibly dozens of different types

of grains (Le Pera et al. 2021). Componentometry also implies a grain size distribution analysis, which can factorialize the number of cases to be considered. This is an exhaustive approach but a very time-consuming method. The main obstacle is the presence of competent (consolidated) rocks, which can be challenging to disaggregate, and thus componentometry is generally limited to unconsolidated pyroclastites and volcaniclastites (tephra). Clast origin and depositional mechanisms are also crucial. A plethora of name modifiers and qualifiers exist owing to the size, shape, structure and composition of volcanic clasts, making these rocks the most complex and varied in petrography. Usually, igneous petrologists follow the classification owing to the IUGS norms. This concept is familiar to volcanologists in that pyroclastites are formed by clasts of four main granulometric sizes directly derived from an explosive eruption. Mixed pyroclastic–epiclastic rocks are not sensible as the two genetic mechanisms do not work concurrently but may form alternate layers in a sequence. The above consideration implies that a new classification scheme should consider genetic mechanisms, even if they can be subjective, as, in volcanological practice, these features are of the same importance as the size or structure of the clast. Although the IUGS discourages the use of a genetic classification, in the case of volcanoclastic rocks it is a necessity for which the risks can be minimized by using an accurate facies analysis performed during fieldwork. This may be a point of contact with sedimentary rocks, including non-clastic rocks. Here, we simplify the classification scheme of Gillespie and Styles (1999), which is entangling to some extent.

Components of volcaniclastic rocks. Rocks (not deposits) derived by explosive volcanic activity may be classified by grain size, clast shape, primary depositional features and composition (Fig. 4). Pyroclastic fragments are generated by magma disruption as a direct result of explosive volcanic action. Three principal types of pyroclastic fragment can be genetically distinguished (Heiken and Wohletz 1985, 1991; Marshall 1987; Fisher and Smith 1991).

(1) *Juvenile fragments* formed directly from magma cooling before primary deposition. Juvenile pyroclastic fragments are discrete crystals. Their fragments are mainly formed in intratelluric conditions (before the eruption); glass fragments are formed by violent magma boiling owing to juvenile gas exsolution or violent steam production owing to contact with their water or ice. In addition, juvenile pyroclasts can be formed by melt turbulence in the conduit and breccia fluidification.

(2) *Cognate fragments* formed at depth during earlier cooling of the melt in a magma chamber or

Pyroclastites (Pyroclasts >75%)				Vulcaniclastites (pyroclasts 75 to 25%)	Epiclastites (pyroclasts 75 to 25%)
Competence	cohesive/compacted/welded/agglutinated/cemented		loose	cemented or loose	loose/cohesive
Components	juvenile rounded pyroclasts		juvenile angular pyroclasts	juvenile and accidental rounded pyroclasts	juvenile and accidental angular pyroclasts	reworked pyroclastic and accidental fragments
>64 mm	bomb agglomerate		pyroclastic breccia (jaloclastitic, ignimbritic)	block or bomb tephra	heterolithic breccia	tuffaceous conglomerate/breccia
64-2 mm	tuff (subaerial) tufite (underwater)	tuffisite (subvolcanic)	lithic tuff/tufite	tephra	tuff (sub-aerial) tufite (underwater)	tuffite (Subaerial-underwater)
	lapilli tuff/tufite (ash matrix>50%) lapilli stone (grain supported) crystalline tuff/tufite (crystals>lapilli and ash)	concentric-shelled lapilli tuffisite		tephra tuff/tufite	heterolithic tuff (subaerial) heterolithic tufite (underwater)	tuffaceous crystal-rich sand
<2 mm	coarse-ash tuff/tufite	spin droplet tuffisite	coarse-ash lithic tuff/tufite	coarse-ash tephra	heterolitic ash tuff/tufite	tuffaceous siltstone
<1/16 mm	fine-ash tuff/tufite		fine-ash lithic tuff/tufite	fine-ash tephra	heterolitic fine-ash Tuff/tufite	residual soils
may contain fossils		may contain fossils			may contain fossils
classify the matrix nature					
classify the clast nature					

Fig. 4. Simplified scheme for pyroclasts and lithics.

a conduit (cumulates), being later eroded and erupted by the same crystallizing magma.

(3) *Accidental fragments* are any kind of rock not related to the magma producing the eruption. They can relate to the melt source (both mantle or crust) and any other geological layers intruded or even rocks collected, for example, by pyroclastic flows on the pre-eruptive substrate.

Another subdivision that considers the granulometric criterion (the only one supported by IUGS) considers bombs, blocks, lapilli and ashes. Bombs are fragments whose mean diameter exceeds 64 mm and have many shapes, from rounded to 'bread crust', indicating that they were moulded by surface tension or rotation during ejection. Blocks are fragments with a mean diameter exceeding 64 mm, as in the case of bombs, but which have an angular or subangular shape indicating that they were solid before the eruption. Lapilli are fragments of any shape with a mean diameter of 2–64 mm. Finally, ashes have a mean diameter of <2 mm, and they are subdivided into coarse ash grains (0.032–2 mm) and fine ash grains (<0.032 mm).

Bombs are fragments that attained their shape during transport after the eruption. Therefore, bombs are always juvenile. Being large fragments, their transport is not substantially influenced by wind and follows a ballistic trajectory. Their distribution can be concentric around the vent if the ejective eruptive column is vertical or distributed in an ellipse if the column is inclined. Lava fountains produce lava slurries which are very plastic, and when impacting the ground form spatters and welded piles of discoidal fragments ('cow-dump' shaped). Bombs are internally vesiculated, ranging from pumice (density <1) to scoria (density >1), and tend to form a glassy crust owing to rapid cooling at the contact with the atmosphere. Their surface is often reddish owing to oxidation from atmospheric oxygen. Bombs formed by strombolian activity have a sub-spherical, pyriform, almond or ribbon shape. A variety of combinations of the previous shapes, up to convolution, is possible owing to rotation during their ballistic trajectory. The glassy crust, which is rigid, is often fractured because the internal vesiculation of the hotter core continues to exsolve gases that strain the rigid surface. This mechanism produces the typical bread-crust surface well developed on the bomb surface that did not penetrate the ground. This structure is observed in both small (decimetric) and large (metric) bombs. There are a variety of bomb types owing to the accretion of one or more lava shells around a kernel, which can be of any nature (armoured bombs), or they can be composite

owing to the presence of multiple kernels or the welding of more bombs of smaller fragments subsequently coated by a lava shell. The presence of bombs suggests a proximal vent and that the magma is not highly fragmented, thus indicating a low explosive degree. Bombs are rare in carbonatite volcanism owing to the extremely low viscosity of carbonatitic melts, which are more prone to spraying smaller fragments. However, vesiculated carbonatite bombs have been described in detail in the literature (Stoppa *et al.* 2000).

Blocks represent a large family of different lithologies (igneous, metamorphic or sedimentary) having a sharp angular shape owing to the mechanical fragmentation of fragments that were already solid before the eruption. The definition of blocks, being not genetic, has a vast and inconsistent classification. Many volcanologists tend to consider blocks as mainly accidental fragments that existed before the eruption and belong to any rock that was transported or collected by the magma before and after the eruption. However, blocks may be generated in many other ways, for example, during the collapse of a solid lava protrusion (spine) or the slow growth and debris flow of a viscous lava dome. In this specific case, blocks are juvenile. Blocks are typical of Vulcanian eruption, where the conduit is obstructed by previous solidified lava. The pressure of juvenile gases produces a vent-opening breccia also involving the conduit walls. Large blocks are carried by mudflows, lahars and pyroclastic flows. In this case, blocks are from the destruction of obstacles encountered during the mass flowing on the volcano and beyond. Jaloclasts are juvenile fragments produced by glassy crust or rolling pillows of hydrovolcanic eruptions. Connate blocks are also juvenile fragments produced by crystal cumulates in the magma chamber, collecting in pockets of the conduit and then scavenged by the melt flowing towards the surface. They become blocks, but they are also linked to the eruptive magma cooling and are therefore juvenile. In addition, many autoliths are juvenile despite some volcanologists considering any reworking of erupted material not to be so (such as any rheomorphic re-arrangement). Autholiths can form in many ways, e.g. agglutination of ash-mud around a solid kernel in mudflows or bank erosion. In lava flows, part of the scorias derived by lava crust trituration is carried and accumulated on the side of a lava embankment and can have the shape and size of a block. These juvenile fragments may be like blocks but are usually simply defined as a scoria embankment.

Lapilli are the most typical products of an explosive eruption. They have similar features to bombs and blocks, with a similar genesis, but are smaller. Juvenile lapilli are extremely interesting and vary between lava drops and filaments (Pelè's tears and hair), formed by gas or wind through very low viscosity lava fountains. This kind of lapilli is massive, not vesiculated and porphyritic or aphyric. Even if lapilli classification is not genetic, it is worth making a distinction among subvolcanic lapilli (formed in the conduit during magma fluidification), particle rotation lapilli (spin lapilli, concentric-shelled lapilli, formed by magma vesiculation – pyromagma), discrete, vesiculated lava fragments (pumice and scoria lapilli) and the agglutination of wet ash particles around a kernel in the eruptive column (accretionary lapilli). Small connate fragments or autoliths are also juvenile lapilli. Intratelluric, medium, large and megacrysts are also lapilli, as is any small fragment of pre-eruptive rocks (igneous, metamorphic or sedimentary).

Ashes, in most high explosive eruptions, form the bulk of the erupted material. Extreme magma vesiculation and bubble explosions produce glassy shards. In this case, ash fragments have a cuspate or calotte shape. Generally, this kind of ash is entirely produced by magmatic phenomena and is juvenile. If magma fragmentation is produced by contact with the hydrothermal system, vadose or superficial water or ice (hydrovolcanism), magma can be quenched and ash attains a blocky shape, remaining juvenile. Any other accidental fragment of tiny size classifies as ash independent of the origin and composition. Fine-grained intratelluric crystals are also ash.

Pyroclasts can agglutinate in larger fragments by several mechanisms prior (e.g. concentric-shelled lapilli, spin lapilli), during (e.g. armoured and composite bombs) and after (e.g. accretionary lapilli) the eruption and can be deformed during the deposition if plastic or soft (spatters). In this work, any modification induced by transport or syndepositional process (i.e. rheomorphism) is considered part of the volcanic processes and genetically linked to endogenous phenomena even if concomitant with exogenous phenomena like rain and wind.

Groundmass and matrix. The term groundmass refers to a medium of glass and microphenocrysts generally 20 times smaller than the phenocrysts. The groundmass is often vesiculated. Groundmass has different textures owing to the arrangement of granular and prismatic minerals. When prismatic crystals and glass are present, the texture is intersertal. It is intergranular when granular crystals are surrounded by laths of plagioclase or other tabular crystals. Often the two textures are retained. The term mesostasis indicates part of the groundmass with residual characteristics and can evolve more from the rest of the rock. Carbonatite groundmass is highly fine grained, and in some cases, the presence of carbonate 'glass' has been speculated, although glass, in general, is silicate.

Matrices are generally of ash size and differ from groundmass, being porous and not vesiculated. However, if the matrix of a volcaniclastic rock is an ash-mud, steam can produce vesiculation, a clear sign of the presence of water during deposition. Any ash can form an ash matrix, but carbonatites form from a mixture of silicate sharp ash and carbonate droplets. This is due to the presence of a viscous silicate liquid associated with a co-eruptive very low viscosity carbonatite (Stoppa *et al.* 2019). Matrices can be competent owing to ash electrostatic attraction, compaction owing to the lithostatic load, welding owing to the preserved high temperature and the presence of primary or secondary cement. In the case of hot deposition, ash appears flattened and develops a sub-parallel grain distribution (eutaxitic texture). In addition, ash may be altered by hydrothermal fluids to clay minerals and zeolites. Matrices develop in both subvolcanic breccias and subaerial or underwater primary volcaniclastic deposits.

Classification of volcaniclastic rock types. From a granulometry point of view, root names may be used for defining volcaniclastic fragments, sedimentary rocks and sediments, bearing in mind that sorting of any deposit is essential as the better the sorting is, the easier the classification.

Pyroclastites. Volcaniclastic rocks containing more than 75% pyroclastic fragments by volume, plus any other kind of clasts, including fossils, may be named pyroclastites. If consolidated, they should be classified as tuffs. If not consolidated, they should be classified as tephra. Most pyroclastite root names are based on representative grain sizes, but many different qualificator or modifier names must be added when describing complex components and variable grain sizes (Fig. 3). In general, in well-sorted pyroclastites, the root names derive from the representative class of specific grain size or nature in 75% of the volume of all pyroclasts. The names agglomerate or pyroclastic breccia should be applied to a rock where more than 75% of the pyroclastic fragments exceed 64 mm. The relative proportions of angular (i.e. block) and rounded (i.e. bomb) may be allocated as follows. An agglomerate consists essentially of rounded or spattered welded fragments (i.e. bombs). If the bombs are not welded, the equivalent term is bomb-tephra or block-tephra. A pyroclastic breccia is essentially composed of sharp angular fragments (i.e. blocks). Composite names, whose criterion is valid for all the volcaniclastic rocks, derive from the dominant component, e.g. block-bomb tephra or bomb-block tephra. However, a combination of various grain sizes may generate very complex root-name modifiers. The name lapilli-tuff or tephra is used for rocks in the lapilli grain size if lapilli are between 25 and 75 vol% of the rock. A rock composed of blocks, lapilli and ash in equal proportions is ash–lapilli–breccia. The name ash tuff or tephra should be used where the average size of more than 75% of the pyroclastic fragments is less than 2 mm. Special modifiers for pyroclastic rocks derive from the nature of the component, lithics, crystals and glass. Thus, a lithic lapilli tuff or tephra comprises rock fragments, a crystal lapilli tuff comprises crystal fragments and so on. If a pyroclastic rock is composed of tangent lapilli (grain supported), sometimes the term lapilli stone is used because the ash matrix is less than 50 vol%. Special qualifier terms may be used to divide tuffs and ashes into coarse tuff and coarse ash, which have an average pyroclast size of 2–0.032 mm, and fine tuff and fine ash, which have an average pyroclast size of less than 0.032 mm (Fig. 5). Some qualifier terms relate to depositional conditions.

The most common pyroclastites are subaerial or underwater. Subaerial pyroclastites maintain the name tuff, but if deposited in water without reworking, they are named tufite. A subvolcanic tuff is called tuffisite; if specific lapilli are present, they are added as modifier names, such as concentric-shelled lapilli tuffisite. Pyroclastites composed of ash sized lapilli formed in subvolcanic conditions can be termed spin droplet tuffisite. A rock composed of juvenile angular lapilli deposited subaerially or underwater is lithic tuff or tuffite, and so on. Some other pyroclasts may be defined by their genetic origin owing to external or internal magmatic mechanisms, such as hydroclasts and autoclasts. In this case, a descriptive genetic name may be assigned to the corresponding pyroclastites, such as hydroclastic breccia or tuff.

Volcaniclastites. Rocks composed of 75–25% pyroclasts may be named volcaniclastites. They contain both juvenile and accidental angular pyroclasts. If their grain size is >64 mm, the name is heterolithic breccia. If the gran size is 64–2 mm, the name is heterolithic tuff or tufite. If the deposits are mainly composed of ash, the name is heterolytic ash tuff or tufite. The prefix tuffaceous should be used with standard root names for clastic sediments and sedimentary rocks to produce root names such as tuffaceous-sand and tuffaceous-mud for unconsolidated deposits, for which the consolidated equivalents would be tuffaceous-sandstone and tuffaceous-mudstone. The prefix volcaniclastic should be used with standard root names for clastic sediments and sedimentary rocks to produce root names such as volcaniclastic-sand and volcaniclastic-mud for unconsolidated deposits, for which the consolidated equivalents would be volcaniclastic-sandstone and volcaniclastic-mudstone, respectively (Critelli and Ingersoll 1995; Gillespie and Styles 1999; Critelli *et al.* 2002; Marsaglia *et al.* 2016).

Igneous and sedimentary limestones

Fig. 5. Comparison among volcanic and sedimentary clasts.

Epiclastites. If a pyroclastic or volcaniclastic rock is reworked, mobilized, fragmented, sorted, transported and deposited by exogenous processes, not concomitant with the eruption, it becomes an epiclastite. Epiclastites cannot be a mixture of tufites (underwater tuffs) and epiclastites, as suggested by the IUGS, because these are different rocks generated by different depositional mechanisms. Epiclastites are genuine sedimentary rocks, formed subaerially or underwater, for which a sedimentary-like nomenclature may be applied with the addition of 'tuffaceous' to suggest that they mainly derived from the disaggregation of igneous rocks. Epiclastites contain between 75 and 25% of pyroclasts and are made from reworked pyroclasts and accidental fragments. If the representative grain size is >64 mm, the name tuffaceous conglomerate or breccia can be used. If it is in the size of lapilli, the term tufite is to be used. For epiclastites in the size of the coarse ash, the name is tuffaceous siltstone. Most of the finer-grained epiclastites make the transition to residual soils.

Comparison between igneous and sedimentary rock classification schemes

Inhomogeneous and inconsistent classification of sedimentary and igneous carbonate rocks is typical. The term 'carbonate' is used as a rock type by sedimentologists to describe limestones and dolostones and igneous petrologists to qualify the different types of carbonate forming carbonatites. The classification of Dunham refers to 'carbonate rocks' and not only to calcareous rocks (limestones), and specifies that the various texture terms, when recognizable, need the suffix dolo if they refer to dolostone, e.g. dolowackestone. The crystalline carbonates of Dunham classification include both crystalline limestone and crystalline dolostone, which the operator is required to specify in the description. Other specific classification schemes introduce more detailed definitions of the different types of coarse crystalline dolostones (Friedman 1965; Sibley and Gregg 1987; Chatalov 2013). A challenging project would be to adapt this system to carbonatites, but we

must admit that this is not easy and would require several modificatory names, which magmatologists are not used to, to clarify differences between the two rock types.

The problem is crucial because intrusive carbonatites show close similarities to crystalline dolostones. The addition of qualifiers would help discriminate and better describe these lithotypes. It is necessary to describe components, structures, texture mineralogy or any other characteristic that helps describe and correctly interpret crystalline limestones and carbonatites. Given the considerable variety of textures and components for both groups of rocks, the role of modifiers is to provide a more detailed and helpful description but, in the meantime, to provide tools to be used only where they highlight a significant element, in terms of both the lithology and texture descriptions and genetic interpretation. In addition to naming important textural parameters (e.g. minerals, grains, types of cement and matrix), modifiers can also be employed as an adjective to convey more information about rock textures.

The current adopted Dunham scheme implies the use of additional terms to detail the classification (e.g. peloidal wackestone, oncoidal grainstone and bioclastic packstone). Among clasts of an igneous nature, there is a good possibility of obtaining different internal structures owing to magma rising towards the surface, fragmenting, agglutinating or welding fragments. Additional features derive from internal gas expansion, cooling fracturing and the action of centrifugal forces or superficial tensions. All of these features are scale invariant, with the only limit being the ability of the transport medium to carry them. Figure 5 shows a variety of pyroclastic fragments compared with clasts having similar morphology and internal structure in sedimentary rocks. Figures 6 and 7 show a comparison between igneous and sedimentary limestone textures.

Cathodoluminescence

Cathodoluminescence (CL) is a useful petrographic tool (Marshall 1988) and an effective technique revealing a vast amount of textural and compositional information invisible to ordinary optical observation. Elements that produce luminescence are called 'activators', and those which prevent luminescence are called 'quenchers'. The levels of these activators and quenchers are well below the detection limits of the EDS microprobe. Among the numerous factors that control CL in calcite and dolomite, the Mn/Fe ratio in the lattice is one of the most important (Machel and Burton 1991; Budd *et al.* 2000; Machel 2000). Most calcite types of cement precipitate from oxidizing to reducing waters containing a different proportion of Mn^{2+}, an activator

of luminescence, and Fe^{2+}, a quencher. The Fe^{2+}/Mn^{2+} ratio in the calcite lattice exerts control on at least the intensity of luminescence. Calcite crystals precipitated by burial fluids are generally depleted in Mn^{2+} and enriched in Fe^{2+}, showing a dull luminescence. During early to intermediate burial diagenesis, the relatively high Mn^{2+}/Fe^{2+} ratio in the calcite types of cement produces bright luminescence under reducing conditions. Moreover, the combined light and CL microscopy analyses distinguish early cement affected by recrystallization and other neomorphism processes and reconstruct the cement stratigraphy.

Igneous and sedimentary carbonate rocks are particularly well suited to study by CL since major minerals (calcite, dolomite and apatite) luminesce. Carbonatite calcite may be like sedimentary calcite with Mn^{2+}, Fe^{2+}, orange, bright yellow to orange-yellow luminescence. However, the presence of REEs (Eu^{2+}, Eu^{3+}) may produce blue/red or violet CL colour. In Italian carbonatite, calcite occurs in various textural forms: phenocrysts, amygdales, groundmass, matrix and veinlets cross-cutting (Stoppa and Woolley 1997; Stoppa *et al.* 2019). The calcite in carbonatites may be sparry, polycrystalline or microcrystalline. The blue luminescence is caused by Eu^{2+} and red-luminescing Eu^{3+} produced by anomalous amounts of REE substitution for Ca^{2+} in the structure.

In some cases, different generations of calcite luminesce in yellow passing to violet owing to a combination of yellow and blue and, finally, show a marked blue colour owing to late extreme REE enrichment. This is not observed in sedimentary carbonate rocks. Figures 8–11 show various examples of CL of igneous and sedimentary limestone.

## Geochemistry of sedimentary and igneous carbonate rocks

Trace element geochemistry of igneous carbonatites is typified by high contents of large ion lithophile element (LILE) elements such as Sr, Ba, P and REEs with generally high La/Lu ratios linked to the extent of their magmatic differentiation (e.g. Woolley and Kempe 1989). For example, young extrusive carbonatites have Sr + Ba in the range of 475 and 21 730 ppm (Cabezo Negro, Toscani *et al.* 2020; Brava Island, Mourao *et al.* 2010), while REEs span from 33.3 to 6973 ppm (Cabezo Negro, Toscani *et al.* 2020; Tamarzert, Bouabdellah *et al.* 2010; Fig. 12). These significant variations are related to differentiation processes with the LILE- and REE-poorer occurrences interpreted as near-primary mantle melts. The supporting evidence is the presence of mantle debris in these extrusive carbonatites and the LILE and REE contents like

Igneous and sedimentary limestones
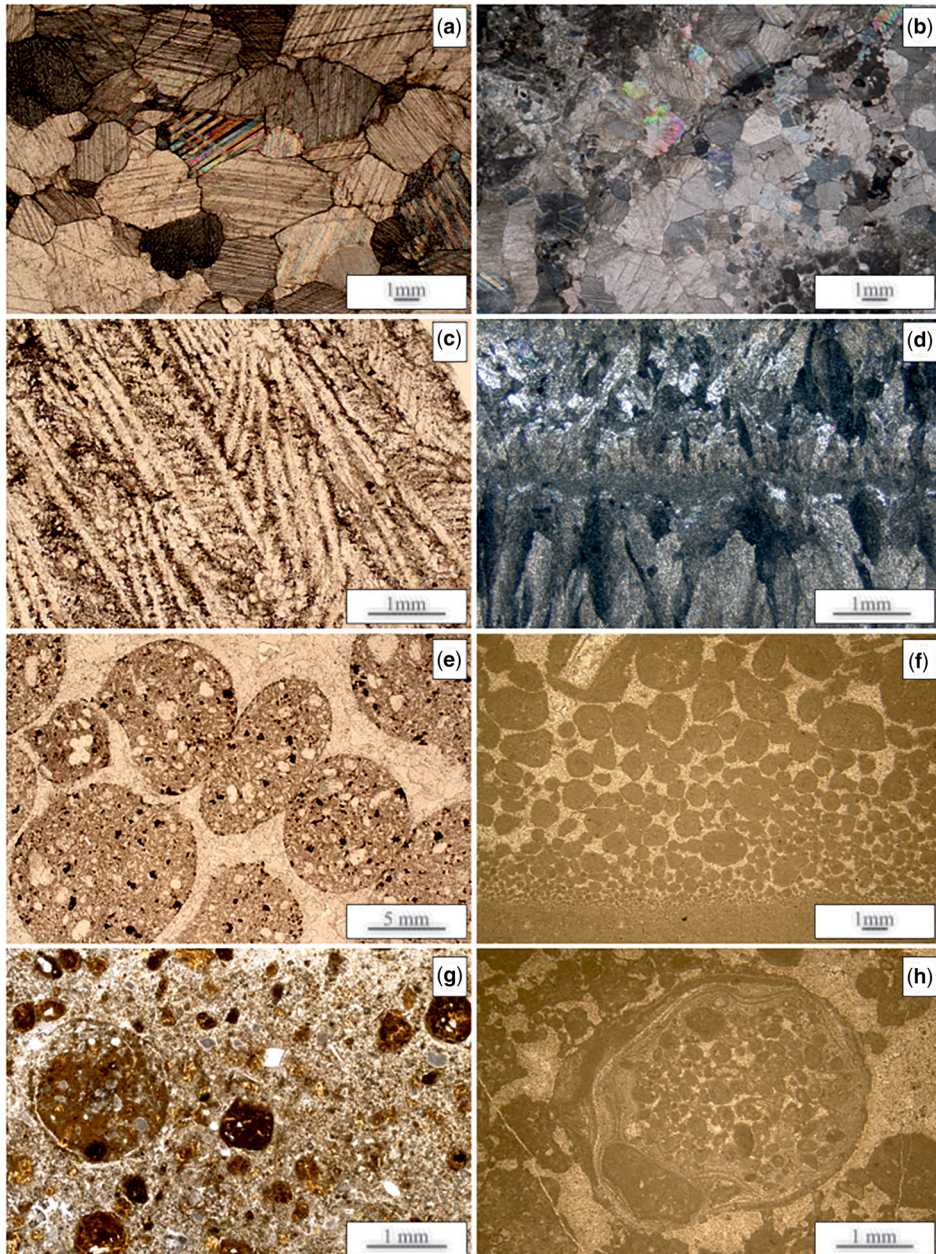
Fig. 6. Comparison between igneous (left) and sedimentary (right) limestone textures. (**a**) Sövite from Badberg Kaisersthull Germany: medium-grained carbonatite with phlogopite, magnetite, apatite, pyrochlore and perovskite (Keller 1981); CP. (**b**) Blocky calcite cement (crystalline fabric) in a grainstone (Calcare Massiccio Fm, Jurassic, northern Apennines, Italy); cross polarized (CP). (**c**) Spinifex-comb texture in alvikite from Kaisersthul, with long prismatic calcite crystals owing to the rapid cooling of a carbonatite melt; plane parallel light (PPL). (**d**) Brownish fibrous calcite cement (crystalline fabric) in a serpulid boundstone (Triassic, NE Apennines, Italy); CP. (**e**) Lapilli tuff from Henkenberg near Niederrottweil, Germany, extrusive carbonatite in the form of a lapillistone composed of carbonatitic spherical lapilli in a calcite matrix; PPL. (**f**) Vadose pisoids and a mosaic of fine calcite cement in a caliche (Calcare Massiccio Fm, Jurassic, northern Apennines, Italy); PPL. (**g**) Lapilli tuff from Cupaello, Italy, with spherical lapilli in a micritic calcite matrix. (**h**) Detail of a composite vadose pisoid in a caliche (Calcare Massiccio Fm, Jurassic, northern Apennines, Italy); PPL.
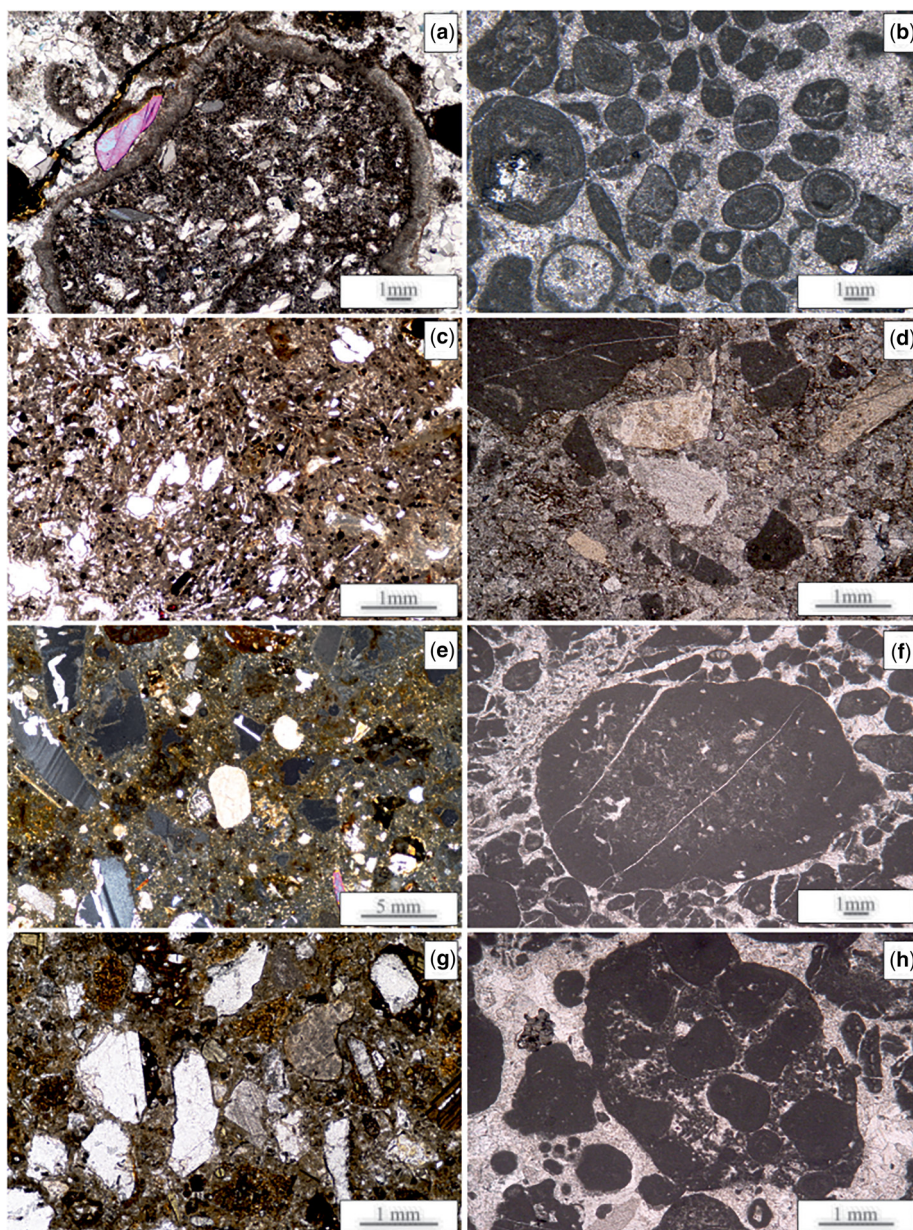
Fig. 7. Comparison between igneous and sedimentary limestones texture. (**a**) Tuffisite from Ficoreto carbonatitic diatreme, with concentric-shelled carbonatitic lapilli cemented by sparry calcite (Stoppa *et al.* 2019); CP. (**b**) Oolitic grainstone – ooids show a concentrically laminated microfabric and are partially micritized. Primary porosity is filled by fibrous cement (first generation) and calcite blocky cement (second generation; Calcare Massiccio Fm, Jurassic, northern Apennines, Italy); PPL. (**c**) Calcite microlaths in cryptocrystalline calcite, apatite, melilite, groundmass; CP. (**d**) Intraclast–bioclast wackestone with fine to medium grain-sized neomorphosed matrix (Corniola Fm, Jurassic, northern Apennines, Italy); CP. (**e**) Carbonatitic microbreccia from Oricola, Italy, with silicate and carbonate crystals in a micritic calcite groundmass (Stoppa *et al.* 2005); CP. (**f**) Oncoid–peloid grainstone (clastic fabric). Note microfissures filled by fine calcite cement inside the central oncoid (Calcare Massiccio Fm, Jurassic, northern Apennines, Italy). (**g**) Calcite microlaths in cryptocrystalline calcite, apatite, melilite, groundmass. (**h**) Algal aggregate–peloid grainstone (clastic fabric) shows a calcite mosaic cement (Calcare Massiccio Fm, Jurassic, northern Apennines, Italy); PPL.

Igneous and sedimentary limestones
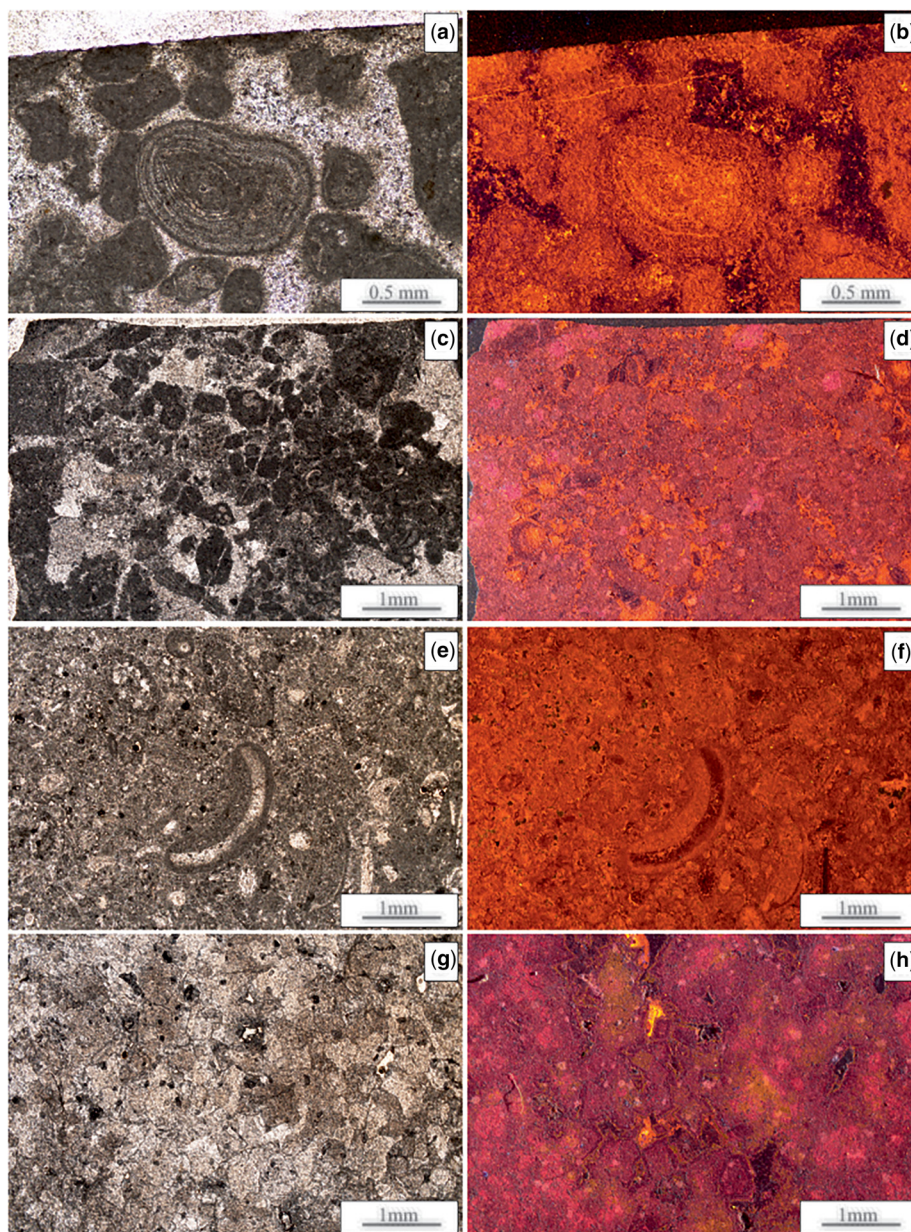
Fig. 8. Carbonate sedimentary textures in PPL (left) and cathodoluminescence (CL; right). (**a, b**) Pisoid–peloid grainstone. The primary porosity is filled by a first generation of thin fibrous cement, brownish in PPL and orange-red luminescent at CL as the grains. Equigranular not luminescent cement fills the centre of the cavity (Calcare Massiccio, Jurassic, Apennines, Italy). (**c, d**) Peloidal–bioclastic packstone with patches of neomorphic spar and microspar, the latter orange-red luminescent. The grains are deeply micritized and show a low red-violet luminescence (Calcare Massiccio Fm, Jurassic, northern Apennines, Italy). (**e, f**) Bioclastic wackestone–packstone, bioclasts show algal-micritic coatings; neomorphic microspar is present Bioclasts are very weakly luminescent, the micritic envelopes are red luminescent and the microspar red to orange luminescent (Calcare Massiccio Fm, Jurassic, northern Apennines, Italy). (**g, h**) Planar E and Planar S dolomite. The dolomite rhomboids show a non-luminescent to weakly luminescent core, indicating iron-rich diagenetic fluids. The outer crystal zones are bright orange luminescent, suggesting a pore fluid enriched in Mn^{2+} (Castel Manfrino Dolostones, Montagna dei Fiori, Central Apennines, Italy).
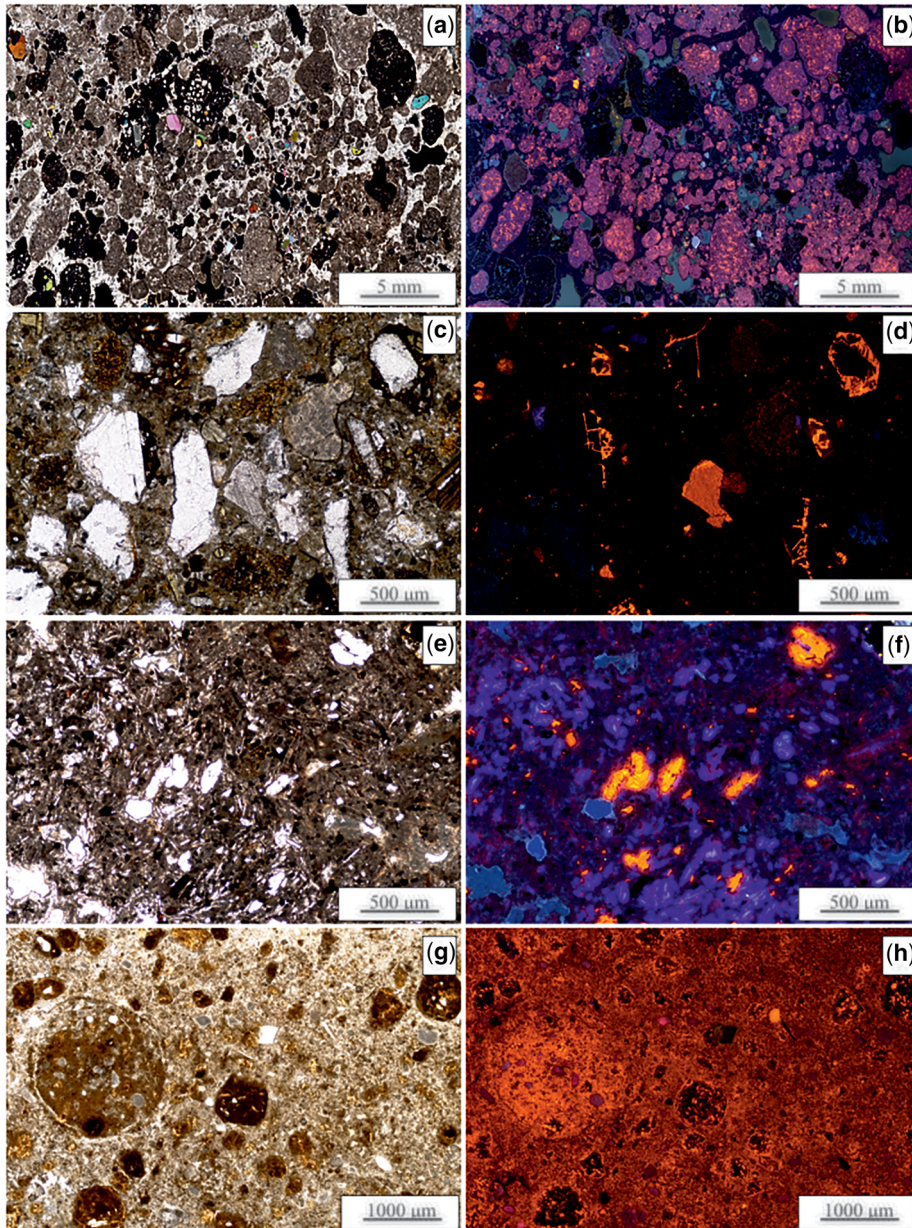
Fig. 9. PPL, CP and CL images of Italian carbonatites. (**a, b**) Ficoreto carbonatite tuffisite (Stoppa *et al.* 2019), the groundmass carbonate is largely non-luminescent, with faint brown/orange luminescence in the last growth zones. It might luminesce faint blue, but at high exposures, this could be from stray light. The rounded carbonate minerals in the melilite-bearing leucitite lapilli is the same as in the carbonate matrix. The carbonatite lapilli consist of very nicely oscillatory zoned calcite, with twinning common. Carbonate lapilli groundmass is quite altered and forms a purple-orange mixed colour in athodoluminescence images. (a) CP; (b) CL. (**c, d**) Oricola carbonatite tuff showing three different calcite types: 1, brightly luminescent calcite cementing grains; 2, brightly luminescent calcite monocrysts which are largely recrystallized; 3, darker, less-luminescent calcite, possibly primary. (c) PPL; (d) CL. (**e, f**) Vulture carbonatite (Stoppa *et al.* 2008). The calcite grains show spectacular zoning for both rare earth elements and Mn. (e) PPL; (f) CL. (**g, h**) Cupaello carbonatite tuff, highly recrystallized (Stoppa and Cundari 1995). Both tuff and lapilli are largely replaced by homogenous bright orange calcite. Remnant calcite grains in the lapilli luminesces red-purple. (g) PPL; (h) CL.

Igneous and sedimentary limestones
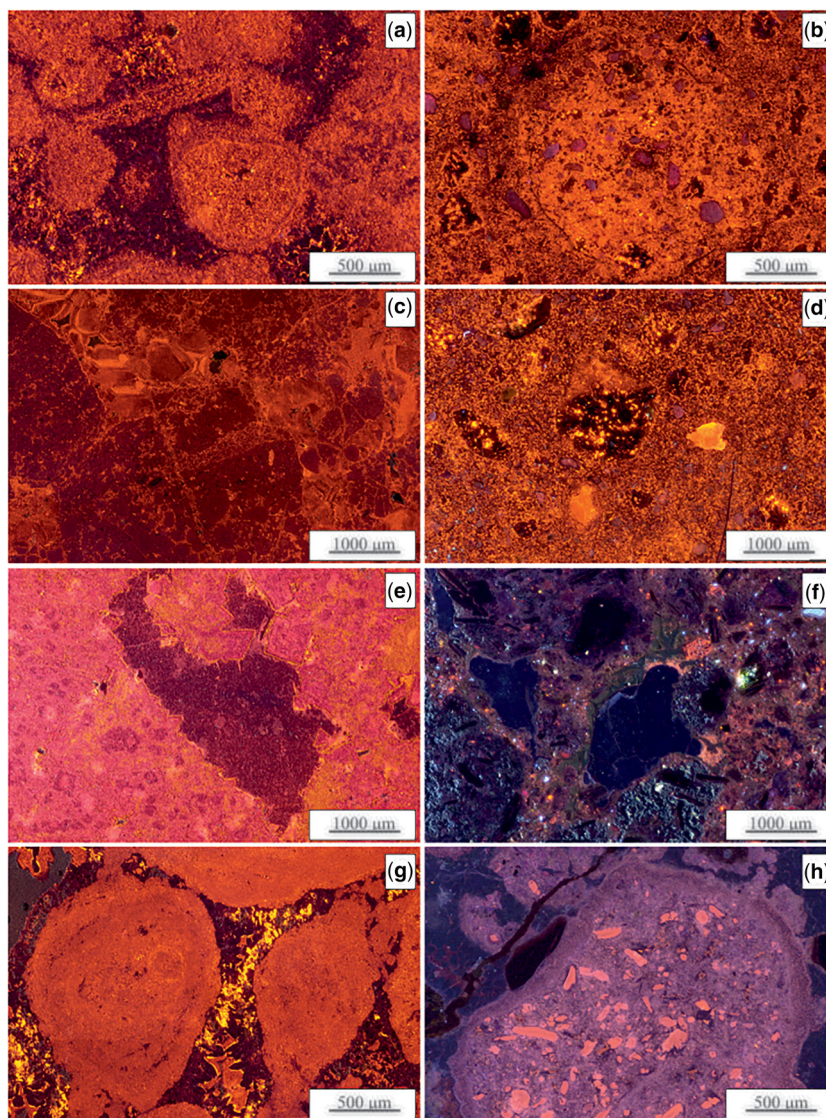
Fig. 10. Cathodoluminescence images of sedimentary and igneous grains, matrix and types of cement. (**a**) Pisoid–bioclast grainstone; the primary porosity shows the first generation of thin fibrous cement, showing the same orange luminescence of grains. It could represent the first phase of early cementation by marine waters enriched in Mn^{2+}. The cavity centre is filled by non-luminescent calcite cement precipitated from iron-rich diagenetic fluids during a later diagenetic phase. (Calcare Massiccio Fm, Jurassic, northern Apennines, Italy). (**b**) Cupaello carbonatite tuff recrystallized carbonate lapillus. (**c**) Peloid–intraclast packstone, not luminescent, with patches of the neomorphic spar and microspar weakly orange luminescent. Cavities are empty or partly filled with several generations of fine crystalline cement, orange luminescent. (**d**) Oricola recrystallized tuff with melilititic and carbonate lapilli in a carbonate matrix. (**e**) A large dissolution cavity within a planar E–planar S dolomite texture, filled by a non-luminescent calcite cement, precipitated by diagenetic Fe^{2+}-rich pore fluids. The CL pattern of rhombohedral dolomite crystals shows non-luminescent to weakly purple luminescent turbid cores surrounded by thin rims of different luminescent, orange–yellow–purple dolomite. The differences in luminescence reflect changing pore water redox conditions (Castel Manfrino Dolostones, Montagna dei Fiori, Central Apennines, Italy). (**f**) Polino carbonatite tuffisite lapilli in calcite matrix/cement. (**g**) Oncoid grainstone with a first thin isopachous fibrous cement, red-luminescent as the oncoid, followed by a non-luminescent dogtooth cement, and by a third generation of bright yellow luminescent cement (Calcare Massiccio Fm, Jurassic, northern Apennines, Italy). (**h**) Ficoreto carbonatite lapillus with zoned calcite laths.
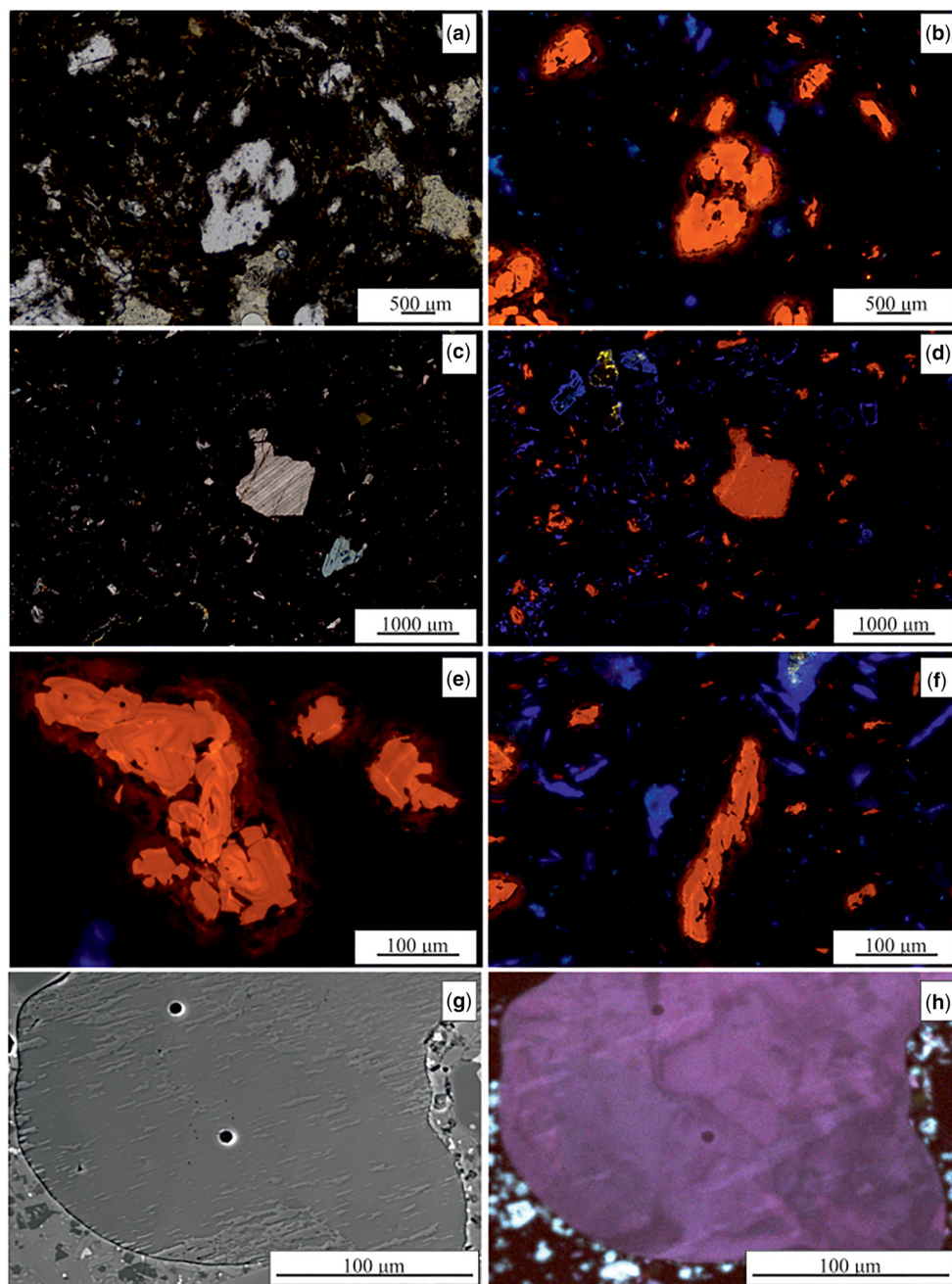
Fig. 11. Details of CL in igneous calcite. (**a–f**) PL and CL of carbonatite scoria spatter from Vallone Toppo del Lupo vulture, Italy. (**g**, **h**) Back-scattered electron and CL images of amoeboid calcite ocelli in Forcinelle tuffisite, Bolsena volcanic complex, Italy.

immiscible carbonate globules trapped in mantle xenoliths (Rosatelli *et al.* 2007). Sedimentary carbonate rocks, instead, have generally lower contents of Sr + Ba (<900 ppm) and REE <30 ppm (Fig. 12), unless strongly contaminated by detrital terrigenous particulate material (Zhang *et al.* 2017). Accidental sedimentary carbonate lithics are frequent in extrusive carbonatites. However, textural
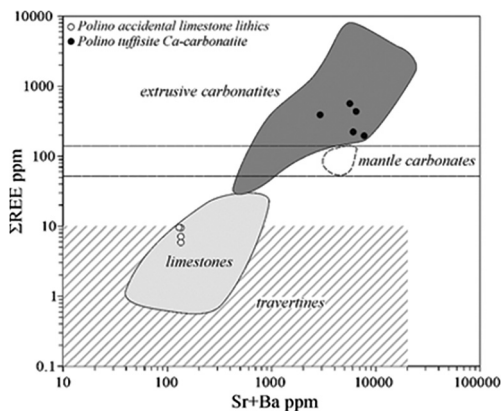
Fig. 12. Chemical distinguishing features of igneous and sedimentary carbonate rock, and the example of Polino igneous and accidental sedimentary lithics of carbonate rocks. Database compilation made by the authors.

differences and geochemistry can be used for discriminating these rocks. Direct comparison of REE contents in carbonatite and sedimentary carbonate rock accidental lithics (Fig. 12) indicates that carbonatite is at least one order of magnitude richer in REE than sedimentary carbonates (e.g. Rosatelli *et al.* 2010).

Carbonatite ash deposits might be confused with caliches and travertines; however, fine petrography and geochemistry can help distinguish these. In travertine, LILE contents are highly variable. Sr may range from 9 up to 14 000 ppm in thermogenic travertine (Fouke *et al.* 2000). Similarly, Ba ranges from a few ppm to 280 ppm (Shiraishi *et al.* 2020). In travertines, Sr and Ba contents are related to the aragonite–calcite transition during diagenesis. Sr and Ba tend to be incorporated in aragonite that transformed into calcite, reducing its LILE content (Shiraishi *et al.* 2020). REE + Y in travertines is generally very low (<10 ppm) because of low element uptake and loss during water–rock interaction (Yıldırım *et al.* 2020). Hot spring travertines generally have four orders of magnitude lower REE + Y contents (e.g. Yıldırım *et al.* 2020).

Carbon and oxygen isotopes of extrusive carbonatites

Intrusive carbonatites have a pretty distinctive carbonate stable isotopic compositions, generally within or near the Primary Igneous Carbonate (PIC field; Taylor *et al.* 1967) characterized by $\delta^{13}C$ ranging between −5.0 and −8.0‰ (‰ relative to VPBD) and $\delta^{18}O$ within 6.0–9.5‰ (‰ relative to SMOW). However, intrusive carbonatites might display greater variation in $\delta^{13}C$ in the range of −9.5 to

−4‰ and $\delta^{18}O$ from 4 to 11‰ (e.g. Tappe *et al.* 2017). Within the crust, the differentiation of carbonatite melts through Rayleigh fractionation or sedimentary carbonate assimilation processes produces a shift towards higher $\delta^{13}C$ and higher $\delta^{18}O$ values (Fosu *et al.* 2021) relative to PIC. Post-emplacement, low-temperature alteration (epigenetic or supergene isotopic exchange) of carbonates in carbonatites produces enrichment in heavy ^{18}O, increasing the $\delta^{18}O$ values, while the $\delta^{13}C$ ratios remain substantially unchanged. Young extrusive carbonatites and carbonates in kimberlites, lamprophyres and basalts (e.g. Deines *et al.* 1989; Demény and Kázmér 1994; Demény and Harangi 1996; Giuliani *et al.* 2014) are characterized by variable stable isotopes ratios usually shifting linearly towards higher light ^{12}C and higher heavier ^{18}O contents than PIC. An example can be considered Polino Ca-carbonatite tuffisite (Fig. 13). In contrast, carbonates forming marine sedimentary rocks usually have higher $\delta^{13}C$ (ranging between 1 and 3‰) and higher $\delta^{18}O$ (from 24.6 to 30‰) away from typical carbonatite values (Fig. 13). Continental sedimentary carbonate rocks such as travertines show very variable stable isotopic ratios, $\delta^{13}C$ may range from −9.2 to 12‰ and $\delta^{18}O$ spans from 18.6 to 30.0‰ (Minissale 2004) and may overlap the field of extrusive carbonatites. The most ^{12}C enriched values can be related to the mantle CO_2 degassing accompanying alkaline-carbonatite magmatism. Mixing between surficial and deep carbon in surficial waters produces a shift towards lighter $\delta^{13}C$
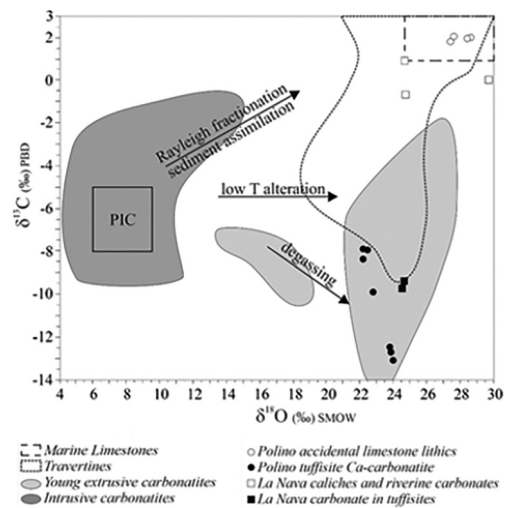
Fig. 13. Stable isotopes are a distinguishing feature among igneous and sedimentary limestones. The main fractionation processes (black arrows) are after Giuliani *et al.* (2014). Database compilation made by the authors.

values of continental carbonates (Minissale 2004). Accidental limestone lithics, generally abundant in carbonatite and carbonatitic tuffs, have distinct stable isotope ratios. As an example, Figure 12 shows extrusive Polino tuffisite Ca-carbonatite (Rosatelli *et al.* 2010) and accidentally mixed limestone, as well as La Nava (Calatrava) igneous Ca-carbonates in melilite–carbonatite tuffs and caliche plus sedimentary fluvial limestones (Bailey *et al.* 2005). Magmatic carbonates have distinct $\delta^{13}C$ ratios while $\delta^{18}O$ ratios might overlap in the range of 21–27‰.

Conclusions

The IUGS recommends not using genetic features to classify rocks but using analytical data such as granulometry and textures. We have depicted the most common granulometric and textural aspects of sedimentary and igneous carbonate rocks and their chemical features. Differences between sedimentary carbonate rocks and igneous carbonate rocks seem equally vast from both a genetic and a chemical point of view, whereas textural and granulometric features are convergent. From this work, the Dunham system (1962), expanded by Embry and Klovan (1971), seems to be the most suitable scheme for classifying sedimentary carbonate textures and we verify that it could also be in some measure adapted to carbonatites. However, as shown by this study, it is evident that texture and granulometry are not enough to distinguish sedimentary and igneous carbonate rocks efficiently.

Extrusive carbonatites are clastic rocks having textures that may resemble peritidal limestones owing to the presence of layering and rounded clasts (lapilli) like oncoids or pisoids. More accurate studies could correctly attribute these deposits to a volcanic origin. The resemblance is easily overcome by microscope observation. However, without this analysis, many extrusive carbonatites may be superficially confused with a broad spectrum of sedimentary rocks, especially those deposited in shallow-water carbonate settings (e.g. carbonate platforms, carbonate ramps) or continental deposits (e.g. travertine and tufa). Recent unconsolidated sand requires more attention, but in our classification scheme, these are not carbonatites but epiclastites that – independent of their photoliths – are sedimentary rocks anyway. The composition may give additional information on the origin of the clasts, but the classification remains that of sedimentary rock. Finally, igneous carbonates are very reactive in epigenetic conditions and can obliterate the primary igneous footprints. In this case, mineral assemblages are often diagnostic owing to classic carbonatite minerals like pyrochlore or REE phases. Some sedimentary carbonate rocks in which diagenetic processes drastically change the original mineralogy and textures can result in confusingly similar rocks. In this case, more detailed observations at the scale of microstructure and ultrastructure, like zoning in calcite (or dolomite) crystals, may be diagnostic and require CL imaging. For example, the differences in the luminescence of zoned calcite or dolomite crystals in sedimentary rocks could reflect changing pore water redox conditions during the early diagenesis occurring in a sedimentary environment. Similarly, the presence of isopachous types of cement, showing the same luminescence pattern of grains, points to a rock's sedimentary origin, while in carbonatites, elements introduced in the igneous calcite during crystallization, often Mn but also REE, produce a progressive change from yellow to violet to blue.

Another problem emerging from this study is that petrologists currently do not follow any 'sedimentological' type of classification. This results in an alarming lack of consistency in the description of igneous carbonate rocks and implies the possibility of many misinterpretations and failures in recognizing many igneous carbonate rocks. This problematic situation is aggravated by a series of alteration and substitution processes typical of both rock types and has confused both petrologists and sedimentologists. The most debated igneous limestone outcrops are linked to old sedimentary deposits affected by pervasive diagenetic effects or to carbonatites having undergone tectonic, metasomatic and metamorphic processes.

This review shows that an accurate and exhaustive classification of carbonate lithologies is best achieved by combining and integrating observations at different scales and using all of the available datasets concerning igneous and sedimentary carbonate rocks. These are texture, granulometry, componentry, mineralogy and geochemistry. The final purpose of this work is to provide an integrated scheme based on the leading and most common textural parameters of both groups of rocks that show some convergence as fabric or morphology in order to facilitate their future recognition first in the field and then under the microscope, and with more sophisticated analyses such as the CL.

In this sense, this paper does not intend to develop a new classification system but to clarify the use of the existing systems, introducing some discriminatory elements that add greater diagnostic specificity to the classifications and allow easy use for igneous and sedimentary petrologists and to make them aware of possible misinterpretation. The Dunham classification system (1962), expanded by Embry and Klovan (1971), is by far the most frequently used scheme for classifying carbonate rocks textures. This popularity is an affirmation of the robustness of the Dunham system, and beyond the

minor changes and clarifications suggested here, there is no reason for a new carbonate classification system.

Data availability No datasets were generated or analysed during the current study.

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