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Review article

On the settling of marine carbonate grains: Review and challenges

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ABSTRACT

Particle settling velocity is a fundamental parameter in sedimentology and engineering, and has accordingly received much attention in the literature. Grain properties, such as shape and drag coefficient, which affect terminal settling velocity, also control the threshold of initiation of motion and sediment entrainment into suspension. Terminal settling velocity therefore provides insights into sediment dynamics in modern and past depositional environments and is important for marine engineering works. Despite the global importance of resedimented carbonates the study of particle hydrodynamics is strongly biased towards terrigenous sediments. This paper presents a review of the settling hydrodynamics of carbonate grains and associated particle properties, such as shape, grain size and density. For carbonate grains these parameters are more complex than for siliciclastic counterparts due to their common biogenic origin, introducing a wide range of morphologies, densities and abrasion products as a result of the skeletal nature of such grains. This review includes an extensive database of published composition-specific settling velocities, as well as densities of common carbonate constituents. The database includes corals, coralline red algae, bivalves, brachiopods, gastropods, \textit{Halimeda} green algae, bryozoans, crinoids, echinoderms, Alcyonarian spicules, numerous benthic and planktic foraminifers, and fecal pellets. Grain density as a function of skeletal structure and mineralogy exerts another control on settling velocity, with unclarity in density definitions hampering effective communication in the literature. The variation in single-grain hydrodynamic behaviour implies careful application of previously proposed equations for the prediction of settling velocity of bulk sand. Despite a firm basis there is a need for additional systematic composition-specific investigations to enable the adequate prediction of carbonate particle hydrodynamics due to the broad spectrum of forms and densities. Emerging technologies such as automated particle velocimetry, computational fluid dynamics, machine learning and microtomography provide exciting avenues for future understanding of the hydrodynamic behaviour of particles with the complexity of natural carbonate grains.

1. Introduction

Carbonate grains are sediment particles that are dominantly composed of CaCO\textsubscript{3} with variable proportions of other elements such as Mg and Sr (Milliman, 1974). The three main groups include skeletal grains (carbonate bioclasts), non-skeletal grains (ooids, pisoids, oncoids) and lithoclasts (erosional products of limestones) (Wilson, 1975; Flügel, 2010). They occur in practically any marine carbonate depositional environment from shallow to deep water, in latitudes ranging from the tropics to the poles and spanning from the Proterozoic to today (Wilson, 1975; Flügel, 2010). Carbonate systems tend to produce large quantities of sediment (Langer et al., 1997; Jorry et al., 2020) affected by shallow-to-deep-water sediment transfer occurring through various processes like highstand shedding (Droxler and Schlager, 1985; Reijmer et al., 1988; Schlager et al., 1994). Carbonate grains are produced within the sedimentary system itself, in contrast to terrigenous (siliciclastic) sediments that are introduced from outside sources (Maiklem, 1968), with the exception of erosional

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products of limestones. The size and shape of terrigenous sediments are modified during significant source-to-sink transport into log-normal grain-size distributions (Reed et al., 1975) (or rather, into settling velocity bins, see Flemming, 2007) and sub-spherical morphologies (Twenhofel, 1945; Flemming, 1965). Transported carbonate sediments, on the other hand, are greatly influenced by the primary growth-size distribution and the skeletal structure which controls particle density, shape and break-down size (Maiklem, 1968; Force, 1969), as well as bioerosion that affects the grain-size spectrum (Chazottes et al., 2008).

Particle settling velocity is a fundamental hydrodynamic parameter that directly and indirectly governs sedimentary processes in a multitude of depositional settings. Settling velocity plays a key role in the redistribution of carbonate debris in turbidite systems (Herbig and Mamet, 1994; Hodson and Alexander, 2010; Kelham, 2011). Likewise, the settling velocity of planktic foraminifers is affected by test size, shape and density, as well as the temperature and density of seawater (Berger and Piper, 1972; Fok-Pun and Komar, 1983; Takahashi and Be, 1984). As such oceanographic parameters change on geological time scales, planktic foraminifers evolved to become smaller, larger or grow keels, among other strategies, as to regulate their settling velocity.

Fig. 1. Variety of natural sediments composed of carbonate grains. (A) Well-rounded coral sand from Molokai (Hawaii). (B) Coral and gastropod grains from the Caribbean (Tankah, Mexico). (C) Gravel-sized coral debris from South Korea (Jeju-do Island). (D) Bivalve gravel composed of clam and oyster fragments (Fort George Island, Florida). (E) Cool-water biogenic sand consisting of red algae, sponge spicules, sea urchin spines, bivalves, gastropods and foraminifers (Ireland). (F) Miocene bryozoan debris with gastropods and rare quartz grains (Savigné-sur-Lathan, France). (G) ‘Bermuda pink’: fragments of corals, bivalves, echinoids and foraminifers. The foraminifer *Homotrema rubrum* gives the pink colour (Bermuda, Atlantic Ocean). (H) Star sand: main component is the foraminifer *Baculogypsina sphaerulata* (Hatoma Island, Japan). (I) Foraminifer sand from the Tikehau Atoll (French Polynesia). (J) Maerl: predominantly rhodagel debris mixed with bivalve remains produced in temperate waters (Isle of Skye, Scotland). (K) Ooids from Joulters Caye off Andros Island (Bahamas). (L) Lithoclastic carbonate sand (Krk Island, Croatia). Reproduced by kind permission of www.sandatlas.org (A,B,C,E,G,L); www.splendidssands.com (D,F,K); and www.arenophile.fr (H,I). Photo in (J) published under Creative Commons.
The properties that control settling velocity also govern sediment entrainment thresholds (Rubey, 1933; Krumein, 1942; Allen, 1984; Komar and Clemens, 1986) at which sediment is entrained into bed load or suspension load (Van Rijn, 2007 and references therein). The understanding of settling behaviour, therefore, extends to providing insights into the mobilisation of carbonate grains under the influence of currents and waves (Allen, 1984; Prager et al., 1996; Kench, 1997; Olivera and Wood, 1997; Paphitis et al., 2002; Smith and Cheung, 2003, 2004, 2005; Yordanova and Hohenegger, 2007). Modern sedimentary environments include pure carbonate settings such as bioclastic beaches (Kench, 1997; Smith and Cheung, 2002; Jahner et al., 2012), carbonate tidal flats (e.g., Hardie, 1977; Rankey and Morgan, 2002; Rankey et al., 2004) and tidal inlets (Gonzalez and Eberli, 1997) and ooid shoals (Harris, 1979; Reeder and Rankey, 2008), but also mixed depositional systems in which carbonate material like shell remains (Lee et al., 1994; Neal et al., 2002; Weill et al., 2012; Smoës et al., 2016), rhodalgal maerl (Joshi et al., 2014), benthic foraminifers (Jorry et al., 2006), freshwater oncoids (Verrecchia et al., 1997), carbonate-volcaniclastic systems (Wilson and Lokier, 2002; Lokier et al., 2009) or multi-component bioclastic debris (Bourcart and Charlier, 1959; Larsonneur, 1975; Flemming, 1977, 2017; García et al., 2005) occur together with terrigenous sediment (see also Mount, 1984).

Of the different types of carbonate system, most produce grains of some sort. Therefore, understanding of carbonate particle hydrodynamics is required for sediment budget calculations. In source-to-sink studies (e.g., Morgan and Kench, 2016), settling velocities predict which components are likely to be transported from the factory under a given set of hydrodynamic conditions (Braithwaite, 1979). Such knowledge is crucial for marine engineering works in carbonate settings, for example dealing with beach erosion (Hohenegger, 2006), coastal construction (Murf, 1987; Lokier and Fiorini, 2016), dredging and replenishment projects (Ngn-Tillard et al., 2009; Gailani et al., 2016; Shen et al., 2019), protection of offshore structures against scouring (Mohr et al., 2016), and estimating resource capacity (Otten et al., 1995; Almagor et al., 2000). Carbonate particle settling velocities can also be used to infer palaeohydrodynamic conditions and processes in the geological record (Van Tassell, 1981; Babek and Kalvoda, 2001; Maurer et al., 2003). In addition, reworked carbonates in the subsurface are associated with large hydrocarbon reservoirs, which has sparked the interest from the energy industry (e.g., Poza Rica, Mexico: Enos, 1977; Louisk et al., 2011; Janson et al., 2011; Makassar Straits, Indonesia: Pireno et al., 2009; Tanos et al., 2012), and recently geothermal exploration (e.g., The Netherlands: Reijmer et al., 2017; Mozafari et al., 2019).

The relation between the diameter of spherical particles and settling velocity in the viscous laminar regime (low Reynolds numbers) was derived analytically by Stokes (1851). At larger Reynolds numbers, a wake develops on the lee side of the particle with the onset of flow separation. Analytical solutions have been derived also for fully turbulent conditions (DallaValle, 1948; Schlichting, 1979). However, the majority of natural sedimentation processes take place in the transitional regime and must rely on (semi)empirical equations (e.g., Dietrich, 1982; Cheng, 1997; Ahrens, 2003; Camenen, 2007; Shiyou et al., 2008). Carbonate particle settling is further complicated by unbalanced forces around falling grains, causing particles to rotate and hence deviate from a vertical settling trajectory (Stringham et al., 1969; Allen, 1984; Mercier et al., 2020).

There is a small but significant body of literature focused specifically on the settling of carbonate grains, showing that skeletal particles are more complex due to the introduction of shape effects. For example, non-spherical shapes complicate the choice of which grain size should be used for highly irregular particles. Preceded by the pioneering studies of Berthoïs and Le Calvez (1960), Berthoïs (1965), Maïklem (1968) and Braithwaite (1973), several authors have reviewed particular aspects relevant to the settling of carbonate grains, including sediment properties (Ford and Kench, 2012), application of shape parameters (Barrett, 1980; Blott and Pye, 2008), analytical techniques (Kench and McLean, 1996, 1997; Yin et al., 1999; Cuttler et al., 2017), hydrodynamic settling regimes (Allen, 1984; Smith and Cheung, 2003; Flemming, 2017), entrainment and transportability (Prager et al., 1996; Paphitis et al., 2002; Yordanova and Hohenegger, 2007; Kench, 2011; Riazi et al., 2020), and the variation in settling velocity of numerous carbonate-producing organisms (Hodson and Alexander, 2010).

The knowledge base of hydrodynamic behaviour of carbonate grains advanced in concert with progress made on the understanding of particle settling in general, which concentrated largely on siliciclastic sediments (Dey et al., 2019), but also dealt with volcaniclastic particles (Wilson and Huang, 1979; Oehmig and Wallrabe-Adams, 1993; Drutt, 1995; Gioni et al., 2014; Liu et al., 2015b), meteorological precipitation (Laws, 1941; Zikmund and Vali, 1972; Cheng et al., 2014), the dispersion of plant seeds (Varshney et al., 2011; Zhu et al., 2017), the settling and rising of bubbles and drops (Clift et al., 1978), and more recently microplastics (Khatmullina and Isaenko, 2017; Chubarenko et al., 2019) and industrial waste (Krueger et al., 2015). A common method for the investigation of carbonate particle hydrodynamics involves the use of settling tube experiments (Berthoïs and Le Calvez, 1960; Berthoïs, 1965; Maïklem, 1968; Berger and Piper, 1972; Braithwaite, 1973; Flemming, 1977; Wanless et al., 1981; Fok-Pun and Komar, 1983; Allen, 1984; Taghon et al., 1984; Takahashi and Be, 1984; Oehmig, 1993; Kench and McLean, 1996; Savarese et al., 1996; Kench, 1997; Verrecchia et al., 1997; Paphitis et al., 2002; Smith and Cheung, 2003; Jorry et al., 2006; Yordanova and Hohenegger, 2007; Weill et al., 2010; Kelham, 2011; Caromel et al., 2014; Joshi et al., 2014; Cuttler et al., 2017; Smoës et al., 2016; Briguglio et al., 2017; Rieuw et al., 2019; Wang et al., 2018; Li et al., 2020). Few studies conducted experiments on the hydrodynamic behaviour of calcareous ooze (Johnson et al., 1977; Buls et al., 2017).

The current paper aims to present an assessment of the research field of the settling of carbonate grains, wherein a compilation of the most relevant aspects of settling behaviour is provided. The focus lies on the settling of particles in marine environments, driven primarily by the relative scarcity of studies in non-marine settings such as lacustrine, fluvial, hypersaline and spring systems. A notable exception is the work on freshwater oncoinds by Verrecchia et al. (1997). First, an overview of the theoretical background is presented (Section 2), dealing with particle properties such as shape, grain size and density, followed by a review of the development of empirical settling equations (Section 3). The discussion (Section 4) comprises the as yet most complete literature compilation of existing data on the density of carbonate particles as well as the composition-specific settling velocity as a function of grain size. There is a lack of consistent data-reporting in the literature, often limited to regression curves omitting the original data points (recent work on benthic foraminifers and bivalves present a positive exception). Equations seem to capture the behaviour of the dataset used for their calibration, but their use in the prediction of terminal settling velocity for other populations may be problematic. This deviation is rooted in the large variation intrinsic to carbonate sediments, which contrasts with most terrigenous erosional products. Finally, recommendations for the improvement of systematic analyses of carbonate particle hydrodynamics are made (Section 5).

2. Particle properties

The effect of particle shape and density on settling velocity has been the topic of numerous investigations (Pettyjohn and Christiansen, 1948; Mckown and Malaka, 1950; Fontein, 1960; Alger and Simons, 1968; Stringham et al., 1969; Clift et al., 1978; Komar and Reimers, 1978; Gögüs et al., 2001; Le Roux, 1997, 2002, 2004, 2014; Riazi and Türker, 2019), some of which are dedicated to carbonate sediment (Maïklem, 1968; Braithwaite, 1973; Kench and McLean, 1996; Paphitis et al., 2002; Smith and Cheung, 2003; Hodson and Alexander, 2010; Wang et al.,
Grain size provides a reasonable estimate of the hydrodynamic behaviour of most terrigenous sediments, enabling the interpretation of environmental processes and depositional energy-level of siliciclastic sedimentary deposits (Reed et al., 1975; Lund-Hansen and Oehmig, 1992; Kench and McLean, 1997). The irregular nature of biogenic carbonate grains in terms of composition, shape and density, however, skews the grain-size distribution in sieve-based analyses (Kench and McLean, 1996; Blott and Pye, 2008; Cutter et al., 2017; Flemming, 2017). The grouping of carbonate particles in fractions based on settling velocity instead provides a more meaningful particle distribution in terms of hydrodynamic behaviour (Flemming and Ziegler, 1995; Kench and McLean, 1996; Flemming, 2017).

Biogenic grains exhibit a large variety of shapes as a consequence of the wide range of forms and habitual growth structures adopted by producing organisms. For example, gastropods and benthic foraminifers develop intricately chambered skeletons, whereas non-skeletal fecal pellets retain a sub-spherical form regardless of their size (Wanless et al., 1981; Taghon et al., 1984). Skeletal morphologies and their internal structure may grow increasingly complex as protrusions (branches and spines), and chambers and cavities develop as a function of grain size (Yordanova and Hohenegger, 2007; Ford and Kench, 2012). Conversely, grain size and shape are altered as sediment particles undergo fragmentation during transport (Ford and Kench, 2012). Maiklem (1968) therefore discriminated between an inherited distribution of shape and size, and a subsequent hydrodynamic modification that becomes progressively more important as skeletal sediment matures. Studies on bioerosional processes in tropical carbonate settings have revealed strong grain-size modification of entire sediment populations, for example eutrophication-related alteration of benthic communities in progressing more important as skeletal sediment matures. Studies on bioerosional processes in tropical carbonate settings have revealed strong grain-size modification of entire sediment populations, for example eutrophication-related alteration of benthic communities in combination with bioerosion (Chazottes et al., 1995, 2002, 2008) and parrotfish converting reef frameworks into sand-grade sediment (Perry et al., 2015). These processes also influence the shape of skeletal carbonate grains and hence their settling velocity (Ginsburg, 2005). In this section observations, methods and considerations regarding particle size (Section 2.1), shape (Section 2.2) and density (Section 2.3) are reviewed.

### 2.1. Particle size

Sieving sorts equant particles by their intermediate diameter, which is hence the most commonly used indicator of grain size (Fig. 2) (Braithwaite, 1973; Baba and Komar, 1981). For irregularly-shaped grains such as heterogeneous biogenic sand, however, the intermediate diameter is not necessarily perpendicular to the longest axis (Sahu, 1965). As a consequence, such grains may be assigned to sieve fractions adjacent to the theoretical ones (Kench and McLean, 1996). Furthermore, the intermediate diameter might be several times smaller than the long diameter, and several times larger than the short diameter. Thus, the phi-scale of Krumein (1934, 1938) works well for the description of spherical particles, but may fail to represent non-spherical shapes. A more meaningful descriptor of grain size is the nominal diameter $D_n$ (Wadell, 1932, 1933):

$$D_n = (D_l D_i D_s)^{1/3}$$

(1)

where $D_l$, $D_i$ and $D_s$ are the long, intermediate and short diameters of the particle. This method allows a direct comparison between the settling velocity of a skeletal particle and that of a nominal sphere with a diameter equal to the nominal diameter of the particle, the difference of which is thus to be attributed to shape effects (Komar and Reimers, 1978).

However, the nominal sphere need not have the same volume as the irregular particle it describes (see discussion in Li et al., 2020). Wang et al. (2018) introduced the concept of a volume-equivalent sphere with a diameter:

$$D_{v-eq} = \left(\frac{6 V_p}{\pi}\right)^{1/3}$$

(2)

where $V_p$ is the particle volume, which may be obtained from particle mass and density using a pycnometer (Wang et al., 2018). Another approach is the use of equivalent settling diameters, using velocities to derive grain-size distributions (Gibbs et al., 1971, see Section 3.2 below). These techniques include sieving, laser diffraction and image analysis (see Cutter et al., 2017 for a review). Buscombe (2020) created an automated tool called SedINet for the qualitative and quantitative assessment of the granulometric properties of sediment populations, using images of terrigenous, volcaniclastic and carbonate particles as input. Alternatively, grain dimensions can be imaged and quantified using three-dimensional microtomography (CT-scanning; Cnudde and Boone, 2013; Leißner et al., 2020; Maroof et al., 2020), as commonly applied in reservoir pore network characterisation studies (De Boever et al., 2012).

### 2.2. Particle shape

The ability to describe the fundamental shape of a sediment particle has been a longstanding venture (Griffiths, 1967; Barrett, 1980; Clark, 1981; Le Roux, 1997; Blott and Pye, 2008; Wang et al., 2018; Riazi and Türker, 2019). Numerous parameters have been proposed, but scaling issues have prevented the practice of a universal descriptor (Clark, 1981; Blott and Pye, 2008). Instead, a set of three shape classes operating both qualitatively and quantitatively at different orders of scale were suggested (Griffiths, 1967; Barret, 1980) (Fig. 2A): (1) form, describing overall particle shape; (2) roundness, indicating the degree of angularity of the particle corners; and (3) surface texture, dealing with the roughness of the grain surface. Form encompasses the dimensions and proportions of the particle, with roundness being subordinate to form, which itself is superimposed by surface texture (Barrett, 1980).

#### 2.2.1. First-order shape descriptor: form

Form is the fundamental description of the three-dimensional spatial distribution of a particle. The most straightforward method for the characterisation of form is probably a geometric approach using a triaxial orthogonal system with a long, intermediate and short diameter $D_l$, $D_i$ and $D_s$. The box that circumscribes the particle with edge length equal and parallel to the principal axes of the particle is called the bounding box of Krumein (1941a, 1941b). This circumscribing box slightly deviates from the minimal bounding box of Blott and Pye (2008) for which the particle axes may be rotated with respect to the axes of the box (see Fig. 4 of Bagheri et al., 2015 for a visual comparison). The long, intermediate and short diameters are the axes of the ellipsoid that approximates the particle form (Fig. 2B) (Barrett, 1980; Oakey et al., 2005; Blott and Pye, 2008; Heilbronn and Barrett, 2013).

Several ratios of first-order axial dimensions have been used as a measure of flatness ($D_l/D_h$) (Blott and Pye, 2008), elongation ($D_l/D_s$) (Luttig, 1956) and equancy ($D_l/D_s$) (Illenberger, 1992). The two most commonly used methods for the description of form are the Zingg (1935) classification and sphericity (Wadell, 1932; Sneed and Folk, 1958). Zingg (1935) recognised four end-members on the basis of flatness and elongation (translated to English by Krumein and Pettijohn, 1938 and Krumein, 1941a): equant particles or spheroids (neither flat nor elongate), plates or discs (flat but not elongate), rods (elongate but not flat) and blades (both flat and elongate) (Fig. 2B). Sphericity, on the other hand, is based on a particle’s deviation from being a sphere, first proposed by Wadell (1932) and later modified most notably by Sneed and Folk (1958) with the introduction of maximum projection sphericity. This model is associated with a ternary diagram that plots equancy along the vertical legs, and the disc-rod index ($D_l/D_s$) ($D_l-D_s$) along the base. There are three end-members in the apices: platy (oblate spheroids), elongate (prolate spheroids) and compact forms (spheroids) (Fig. 2B).
Fig. 2. (A) Shape classification on the basis of (B) first-order shape descriptor ‘form’ and (C) second-order shape descriptor ‘roundness’. $D_l$, $D_i$ and $D_s$ are the long, intermediate and short diameters of the particle. See Fig. 3 for third-order ‘surface texture’. Particle roundness after Wadell (1932). Angularity after Lees (1964). Circularity after Tickell (1931). Irregularity and convexity after Blott and Pye (2008).
Form distribution within skeletal carbonate sands is inherently more prevalent within silicilastic sediments (Kench and McLean, 1996). Preceded by the landmark papers of Maiklem (1968) and Braithwaite (1973) on the hydrodynamic behaviour of carbonate grains, most authors use a form classification based on Zingg classes (i.e., the degree of ellipsoid; Yordanova and Hohenegger, 2007; Li et al., 2020) or the Corey Shape Factor (i.e., maximum projection sphericity; see Section 2.2.4 below) (Corey, 1949; Brezina, 1979; Fok-Pun and Komar, 1983; Smith and Cheung, 2003). Blott and Pye (2008) compared the Zingg and Corey classes and concluded that the Zingg classification based on two independent properties (flatness and elongation) is most appropriate for form description of particles in most sedimentary environments, as discussed further below (Section 4.3).

2.2.2. Second-order shape descriptor: roundness

The prediction of transport and sedimentation behaviour of particles requires a second-order shape descriptor (Blott and Pye, 2008). Roundness is the overarching term to indicate grain smoothness (Barrett, 1980) operating independently of form (Fig. 2C) (Wadell, 1932; Krumein, 1941a, 1941b). For silicilastic particles, roundness can be considered a measure of sediment maturity as grains become more rounded by abrasion during movement (Twenhofel, 1945; Mazzullo et al., 1992; Pye, 1994; Boggs, 2001). Carbonate grains may likewise be subject to such processes, however, initial roundness and internal skeletal structure (composition) complicate a straightforward application of maturity.

A myriad of methods has been proposed for the quantification of particle roundness (Fig. 2C) (see reviews by Oakely et al., 2005; Blott and Pye, 2008; Heilbrunner and Barrett, 2013; Rodriguez et al., 2013). Particle roundness is the ratio (from zero to one) between average corner radius and the radius of the maximum inscribed circle (Wentworth, 1919; Wadell, 1932). Angularity, which is not simply the opposite of particle roundness, combines the angular relationships between cornerbounding planes with the distance to the particle centre (Lees, 1964), taking values ranging from 0 to over 1500. The calculation of the true three-dimensional particle roundness and angularity by including angular edges along three orthogonal axes is time-consuming and therefore practically infeasible (Blott and Pye, 2008; Rodriguez et al., 2013), unless automated (Bowman et al., 2001; Cox and Budhu, 2008). Consequently, most authors have used a two-dimensional projection instead (Barrett, 1980).

Alternative expressions of roundness include circularity, irregularity (termed solidity in ImageJ, http://imagej.nih.gov/ij) and convexity. Circularity is the two-dimensional sphericity, i.e., the ratio between particle area and the area of the smallest circumscribing circle (Peltland, 1927; Tickell, 1931; Riley, 1941). When the area of the circle is replaced by that of a convex hull, the ratio returns irregularity (Blott and Pye, 2008). The ratio between the perimeter of the convex hull and that of the particle computes convexity (Joshi et al., 2014). The choice of roundness indicator in studies on the settling of carbonate grains depends on the morphological complexity of the sediment, for example, a branched grain morphology may require a combination of parameters including convexity (Joshi et al., 2014; Liu et al., 2015a, 2015b).

2.2.3. Third-order shape descriptor: surface texture

The smallest-scale shape parameter describes the variability of the particle surface. Verrecchia et al. (1997) showed that differences in the surface texture of fresh-water Oncoids can cause variation in their hydrodynamic behaviour. The formation of surface texture depends on sediment maturity as well as on grain hardness controlled by primary composition. For example, carbonate grains are more susceptible to be altered by mechanical abrasion than much harder quartz-particles (Kotler et al., 1992; Ford and Kench, 2012). Three types of texture describe most of the variability (Pettijohn, 1957): striated, smooth (granular) and pitted surfaces (Fig. 3). The effects of abrasion and dissolution on the surface texture of benthic foraminifers and Halimeda green algae were studied more extensively by Kotler et al. (1992), proposing a comprehensive classification scheme (extended by Shroba, 1993) of taphonomic features of abrasion. Surface textures may be overprinted during chemical alteration by the replacement of primary crystalline structures by microcrystalline carbonate. Skeletal habitus may also affect surface features, for example protruding septate chambers upon abrasion of certain coral species (Scholle and Ulmer-Scholle, 2003; Flügel, 2010).

2.2.4. Quantification of shape

A variety of methods exist for the quantification of shape, thus the combination of form, roundness and surface texture. Methods range from comparison charts (Wadell, 1932; Krumein, 1941a) for which the arithmetic (Russell and Taylor, 1937) and geometric roundness grades (Pettijohn, 1949) were calculated, to more complex quantitative three-dimensional Fourier analysis (Bowman et al., 2001). Such quantitative indices are suitable for incorporation of a shape factor into settling equations (see Section 3 below), a number of which apply the Corey (1949) Shape Factor CSF for the quantification of form and the visual comparison chart of the Powers (1953) Roundness Index PRI for the quantification of roundness. The Corey Shape Factor is the square root of the product of flatness and equancy:

\[ \text{CSF} = \frac{D_i}{D_p} \frac{D_l}{D_p} = \frac{D}{\sqrt{D_i D_l}} \]  \hspace{1cm} (3)

The Corey Shape Factor has a maximum value of one for spherical particles and decreases toward zero with decreasing sphericity. The other widely used shape factor, the Powers Roundness Index, is a continuous scale on a visual comparison chart combining sphericity and roundness (Fig. 4).

An alternative shape factor, which should be explained here because of its later use in equations in Section 3 below, was proposed by Wang et al. (2018) and is based on both particle form and roundness. The Wang Shape Factor \( \Psi \) computes the ratio between two parameters: sphericity \( \Phi \) (Wadell, 1932; Sneed and Folk, 1958) and a newly defined inverse circularity \( X \). Sphericity is the ratio between the surface area \( A_{eq} \) of the volume-equivalent sphere (Eq. (2)) and the surface area \( \bar{A}_p \) of the particle (Haider and Levenspiel, 1989; Ganser, 1993; Chien, 1994; Li et al., 2020):

\[ \Phi = \frac{A_{eq}}{\bar{A}_p} \]  \hspace{1cm} (4)

where \( A_{eq} = \pi (D_{eq})^2 \). Since \( A_p \) is very difficult to determine for irregularly-shaped carbonate particles, Wang et al. (2018) approximated the surface area of the particle by taking the surface area \( A_{ell} \) of an ellipsoid with axes equal to the three orthogonal axes of the particle:

\[ A_{ell} = \pi (D_1 D_2 D_3)^{\frac{1}{3}} \]  \hspace{1cm} (5)

where \( \kappa = 1.6075 \) (note that Wang et al., 2018 accidentally reported a wrong value of \( \kappa = 1.0675 \), however, the correct value was used in their calculations, pers. comm. Y. Wang, 2020). The Wang inverse circularity parameter \( X \) is a two-dimensional shape factor defined by the ratio of two parameters derived from the maximum projection area of the particle in the \( D_i-D_l \)-plane: the perimeter of the maximum projection area of the particle \( P_{p-max} \) over the perimeter of a circle that has a surface area equal to the maximum projection area \( P_q \):

\[ X = \frac{P_{p-max}}{P_q} \]  \hspace{1cm} (6)

Wang et al. (2018) defined a new shape descriptor \( \Psi \) for the characterization of irregular carbonate particles as the ratio of sphericity \( \Phi \) and inverse circularity \( X \):
2.3. Sediment density

In addition to grain size and shape, the settling velocity of a particle is governed by its density. The density variation in terrigenous sediment populations due to the occurrence of heavy or light minerals has been widely acknowledged. However, differences in the density of bioclastic carbonates may be more significant as a result of composition-dependent in-situ production and subsequent hydrodynamic modification (Maiklem, 1968; Kench and McLean, 1996; Kench, 1997). The intricate bio-architecture of certain organisms (Driscoll and Weltin, 1973; Kotler et al., 1992; Shroba, 1993; Ford and Kench, 2012) results in complex primary relationships between grain size and particle density (Oehmig, 1993; Kench and McLean, 1997; Yordanova and Hohenegger, 2007; Kelham, 2011). Likewise, the growth dynamics of ooids and their abrasion mechanisms are not as straightforward as for siliciclastic particles (Trower et al., 2017).

Contrary to terrigenous sediment, the density of biogenic carbonate grains is affected by skeletal porosity due to the empty space within the architecture of the skeleton (or intragranular porosity in the case of nonskeletal grains such as fecal pellets), as well as by microporosity as a result of the arrangement of crystals in the solid mineral composing the skeleton. For example, some hyaline foraminifers feature canal systems in their test walls for protoplasm flow, whereas porcelaneous foraminifers construct pore-like structures to promote gaseous exchange (Hottinger, 1977 and Hansen and Dalberg, 1979 in Yordanova and

\[ \psi = \frac{\phi}{X} \] (7)

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Hohenegger, 2007). There is abundant empty space between the prismatic calcite crystals in the wall of porcelaneous tests (visualised by Macintyre and Reid, 1998), which is filled by seawater after the post-mortem decay of organic matter (Hansen and Dalberg, 1979 and Debenay et al., 2000 in Yordanova and Hohenegger, 2007). Such empty space in the wall structure (thus not being part of the skeletal porosity) lowers the density of the solid carbonate material by as much as 30% compared to the mineral density of calcite (Yordanova and Hohenegger, 2007).

Some advanced studies on foraminifers incorporate both skeletal and microporosity (Caromel et al., 2014). Microporosity affects also the skeletons of most other carbonate-producing organisms.

The degree of alteration is an important secondary factor controlling

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**Fig. 4.** The continuous Powers Roundness Index PRI. Modified from Powers (1953). See Russell and Taylor (1937) for corresponding arithmetic means and Pettijohn (1949) and Powers (1953) for geometric means.

**Fig. 5.** Different types of density. Solid or mineral density considers only the weight of the carbonate material, thus excluding pore volume. Bulk density takes the carbonate weight and the empty pore volume. Particle density is the combination of the weight of the carbonate and water occupying the pore volume. Effective density calculates the density that the equivalent sphere (with particle’s nominal diameter, Eq. (2)) should have in order to reach the terminal settling velocity of the particle. The pore volume \( \varphi \) in the equations is the skeletal (intragranular) porosity. Microporosity is not described here (image from Macintyre and Reid, 1998).
particle density. For example, cement may fill skeletal porosity or replace the original aragonite or calcite, adjusting the particle density (James and Bone, 2011). The interplay between mechanical abrasion and dissolution may lead to differential alteration within a single particle, as some parts of the skeletal structure may be more resistant than others (Kotler et al., 1992; Shroba, 1993). In spite of its importance, diagenetic alteration is not consistently reported in hydrodynamic studies of carbonate grains. The diagenetic history of bioclastic sediments therefore prevents the indiscriminate use of a generalised database containing a ‘standard’ density of constituents. Yet, there is a need for a density database (Cuttler et al., 2017) that should be used for the calibration of equations and experiments (Prager et al., 1996; Hodson and Alexander, 2010; Alcereca et al., 2013; Li et al., 2020).

Several types of density circulate in the literature (Fig. 5), some with contrasting definitions, including bulk density (Oehmig, 1993), dry bulk specific density (Weber et al., 1969), bulk skeletal density (Sadd, 1984), skeletal density (Morgan and Kench, 2014), solid density (Allen, 1984), mineral density (Milani et al., 1999), material density (Smith and Cheung, 2003), sediment density (Prager et al., 1996; Papiths et al., 2002; Joshi et al., 2004; Fick et al., 2020), sediment grain density (LaBarbera, 1981), grain density (Kench and McLean, 1997), particle density (Kench and McLean, 1997; Cuttler et al., 2017), object density (Caramol et al., 2014), average sediment density, (Neumann and Land, 1975) sphere-equivalent density (Michels, 2000), average density (Diedericks et al., 2018; Li et al., 2020), apparent density (Jorry et al., 2006), relative density (Dey, 2003) effective density (wanless et al., 1981; Fok-Pun and Komar, 1983; Kench and McLean, 1996) and specific gravity determination (Jell et al., 1965) (Table S1 in Supplementary Data). Some of these definitions are the same, others use the same term but yield different definitions. Again other studies do not specify the density or its derivation at all. The unclarity surrounding density terminology hampers efficient communication in the literature.

The mineral density of quartz is 2.65 g/cm$^3$, whereas that of pure calcium carbonate ranges from 2.72 g/cm$^3$ for calcite to 2.94 g/cm$^3$ for aragonite (Milliman, 1974), yet discrepancies between the settling velocity of quartz and carbonate particles extend beyond differences expected on the basis of mineral density alone. Yordanova and Hohenegger (2007) pointed out that solid density need not be equal to mineral density due to the common spacious arrangement of crystals in biogenic carbonate material referred to as microporosity. Particle density is a term that may lead to confusion as some authors take it to be the sum of the product of solid density and solid volume, and the product of water density and pore space volume: $\rho_{\text{particle}} = \rho_{\text{solid}}V_{\text{solid}} + \rho_{\text{water}}V_{\text{porosity}}$ (e.g., Cuttler et al., 2017). A grain’s particle density sensu Cuttler et al. (2017) is thus lower than its solid density. The literature is not always sufficiently concise in distinguishing the abovementioned densities (e.g., Jell et al., 1965; Prager et al., 1996; Kench and McLean, 1997; Verrecchia et al., 1997). Bulk density can be defined as $\rho_{\text{bulk}} = \rho_{\text{solid}}(1 - \rho_{\text{pore}})$, or rewritten $\rho_{\text{bulk}}V_{\text{particle}} = \rho_{\text{solid}}V_{\text{solid}}$ (e.g., Cuttler et al., 2017). In case air fills the porosity, some authors use dry bulk density instead (e.g., Weber et al., 1969). Potential miscommunication may also arise from the use of different porosities, namely intragranular (within a particle) and intergranular (between particles). In studies focused on the hydrodynamic behaviour of the remains of certain carbonate-secreting species, in particular foraminifers, effective density is frequently used (Berthois and Le Calvez, 1960; Berger and Piper, 1972; Fok-Pun and Komar, 1983; Yordanova and Hohenegger, 2007). Effective density is the density that a sphere with the nominal diameter of an irregular particle (Eq. (2)) should have to match the settling velocity of that particle (Fok-Pun and Komar, 1983).

Taking a step back however, where does the interest in density originate from? The parameter that all these studies seek to approximate is particle mass. This is straightforward for studies estimating carbonate chemistry budget, for example aimed at reconstructing changes in the mass of calcium carbonate at system-scale (Stearn et al., 1977; Land, 1979; Grigg, 1982; Sadd, 1984; Hubbard et al., 1990, as discussed in Cuttler et al., 2017). As will become clear in Section 3 below, also settling studies seek to find the mass of the falling particle. Particle mass yields submerged weight, which is the force that leads to acceleration until terminal velocity is reached. Because the relevant force is submerged weight, the buoyancy (i.e. the mass of the displaced volume of the medium which in most cases is water) needs to be accounted for. Most authors do this in the equation itself, hence requiring the mass and volume of only the solid (i.e. solid density $\rho_{\text{solid}}$). Other studies already account for the mass of the displaced water volume while reporting the density, a method which works only if the volume of the solid and the porosity-filling water is considered subsequently. Caution is warranted therefore if densities and densities documented in different studies are combined.

Recent work on the hydrodynamics of carbonate sediment have emphasized the need for more consistent reporting of density (Alcereca et al., 2013; Cuttler et al., 2017; Li et al., 2020). Cuttler et al. (2017) provided a literature compilation of carbonate sediment densities, which has been extended here (Fig. 6; Table S1 in Supplementary Data), paying particular attention to the type of density reported, which was amended here if terminology was deemed contradictory or potentially confusing. Despite in-class variation, certain trends between environments are revealed in the visual comparison in Fig. 7. An additional factor influencing settling velocity in different environments is water temperature, which leads to significant variations in the viscosity of water, for example water is twice as viscous at 1°C than at 30°C. The large range in the density of foraminifers is in part due to complex density-size relationships (Fig. 8) (Oehmig, 1993; Yordanova and Hohenegger, 2007; Kelham, 2011). The explicit lack of a universal density of foraminifers likely results from the diverse chamber architecture of some species.

3. Hydrodynamics of settling carbonate grains

3.1. Parameters controlling particle settling

A particle suspended in a viscous (Newtonian) fluid settles if the contrast between the density of the particle $\rho_p$ and that of the fluid $\rho_f$ is positive and the particle exceeds colloidal size ($>0.1$ $\mu$m) because of Brownian motion (Krumbein and Pettijohn, 1938). The submerged weight of the particle $F_G$ is given by:

$$F_G = g(\rho_p - \rho_f) V_p$$

(8)

submerged particle weight where $g$ is gravitational acceleration and $V_p$ is particle volume. This force pulls the particle down through the fluid, causing the particle to accelerate until a balance of forces is achieved such that $F_G = F_C$ and the particle reaches terminal settling velocity $w$.

The use of dimensionless numbers is common practice in solving problems of fluid dynamics like particle settling (e.g., Southard, 2006). Comparison between dimensionless numbers rather than actual parameters has the advantage of bringing forth versatile solutions. The parameters involved in the settling of a particle through a quiescent and viscous fluid are the fluid density $\rho_f$ and viscosity $\mu$ and the terminal settling velocity of the particle $w$, as well as a length scale such as the particle diameter $D$. These four parameters may be combined such that a new dimensionless parameter is obtained, for example a Reynolds number (Reynolds, 1883):

$$Re_p = \frac{\rho_f D V}{\mu} \text{ inertial forces}$$

(9)

$Re_p$ thus reflects the influence of density, velocity and a length scale on the one hand (representing inertial forces), and fluid viscosity on the other.

In the settling problem, the aim is to establish the relationship between $Re_p$ and a dimensionless form of the drag force, called the drag coefficient $C_D$. The drag coefficient is obtained by dividing the drag
### Composition

<table>
<thead>
<tr>
<th>Authors</th>
<th>Density</th>
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<tbody>
<tr>
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</tr>
<tr>
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<tr>
<td>Neumann and Land (1975)</td>
<td>Ca, Mud</td>
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**Fig. 6.** Compilation of density in the literature. See Table S1 in Supplementary Data. Abbreviations: Ba: brachiopods; Bacu sp.: Baculogypsina species; B.Fm: benthic foraminifers; Bn: barnacles; Bac: bivalves; Ca: coralline algae; Calc sp.: Calcarina species; Cl: corals; Co: calcareous oozes; Cr: crustaceans; Ec: echinoids; Fm: foraminifers; Fo: freshwater oncoids; Ga: green algae; Gp: gastropods; Hal: Halimeda; Hfp: hardened fecal pellets; Lc: lithoclasts; Ln: lime mud; Ma: Maerl; Marg: Marginopora; Mi: molluscs; Num: Nummulites; Oi: ooids; P.Fm: planktic foraminifers; Pi: peloids; Ra: red algae; Sc: Alcyonarian spicules; Sfp: soft fecal pellets; So: sponges; Su: serpulids; Ug: unidentified grains. See Fig. 5 for the different types of density.
force by a combination of (some of) the relevant parameters in the settling problem such that the drag coefficient becomes dimensionless:

$$C_D = \frac{F_D}{\rho_f w^2 (A/2)}$$  \hspace{1cm} (10)$$

where $A$ is an area by convention, representing the square of the length scale. Recall that once terminal settling velocity has been achieved: $F_D = F_G'$. Substitution of Eq. (8) into Eq. (10) leads to:

$$C_D = 2 \frac{V}{A} \left( \frac{\rho_p - \rho_f}{\rho_f} \right) \frac{1}{w^2}$$  \hspace{1cm} (11)$$

where $V/A$ represents a ratio of volume to area. The characteristic value of $A$ is typically chosen to be the maximum cross-sectional area of the grain. For spheres $V = (\pi/6)D^3$ and $A = (\pi/4)D^2$. The drag coefficient of spheres therefore takes the form:

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{Visual overview of the variation in the literature compilation of density studies. (A) Density as a function of composition. (B) Density as a function of environment. See Table S2 in Supplementary Data.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8.png}
\caption{Effective density as a function of particle size for a number of (A) Amphistegina and (B) other foraminifer species. Modified from Yordanova and Hohenegger (2007) and Kelham (2011), respectively.}
\end{figure}
C_{D, sph} = \frac{4}{3} \delta \left( \frac{\rho_p - \rho_f}{\rho_f} \right) \frac{D}{w^2} \quad (12)

Rearranging for general settling velocity yields:

\[ w = \sqrt{\frac{2 \delta}{A} \left( \frac{\rho_p - \rho_f}{\rho_f} \right) \frac{1}{C_D}} \quad (13) \]

and for spheres:

\[ w_{sph} = \sqrt{\frac{4}{3} \delta \left( \frac{\rho_p - \rho_f}{\rho_f} \right) \frac{D}{C_D}} \quad (14) \]

An analytical solution for the drag coefficient at very low Reynolds numbers in the viscosity-dominated laminar regime was proposed by Stokes (1851) for spheres and by Oberbeck (1876) for ellipsoids. However, at higher Reynolds numbers pressure forces become important such that \( C_D \) cannot be solved analytically and must rely on numerical solutions based on empirical data. Additional complexity arises for particles that deviate from being spherical. Such irregular grain shapes require the introduction of a shape factor into the solution.

The two fundamental dimensionless parameters \( C_D \) and \( Re_p \) may be mathematically manipulated to create other dimensionless parameters. In order to maintain the general applicability of solutions to the settling equation, authors working with carbonate grains have often used dimensionless forms of the settling velocity and particle diameter (Dietrich, 1982; Alcerreca et al., 2013; Wang et al., 2018; Li et al., 2020).

Dimensionless settling velocity is a parameter that should depend on...
settling velocity $w$, but not on particle diameter $D$. Manipulation of Eqs. (9) and (12) for spheres gives:

$$w_s = \left( \frac{4}{3} \frac{R_p}{C_{D,sp}} \right)^{1/3} = w \left[ \left( \frac{\rho}{\rho_f} \right) \left( \frac{\rho_p - \rho_f}{\rho_f} \right)^{1/3} \right]$$

(15)

Dimensionless particle diameter, on the other hand, should include particle diameter $D$, but exclude settling velocity $w$. Manipulation of Eqs. (9) and (12) for spheres yields:

$$D_o = \frac{3}{4} \left[ \frac{R_p}{C_{D,sp}} \right]^{1/3} = D \left( \frac{\rho_p - \rho_f}{\rho_f} \right)^{1/3}$$

(16)

The flow pattern around a settling particle is a function of the Reynolds number (Peregrine, 1985; Fornberg, 1988). Once an (empirical) relationship between the Reynolds number and the drag coefficient is established, the settling velocity $w$ for any specified particle diameter $D$ can be determined using Eqs. (15) and (16). Curves plotting the $R_p$-$C_D$ (or $D$-$w$) relationship of spherical particles (determined empirically by flow experiments around fixed cylinders by Fornberg, 1988) are shown in Fig. 9. The hydrodynamic behaviour of irregular particles such as carbonate grains is described by modifications of the $R_p$-$C_D$ relationship for spheres, by the introduction of a shape factor as further discussed below. The $R_p$-$C_D$ relationship also provides insight into the transport behaviour of sediment in flows with a longitudinal exponent (e.g., Brugiglio et al., 2017; Flemming, 2017).

3.2. Settling velocity

For particles settling under $R_p < 1$, viscous forces (skin friction due to the attraction of fluid molecules to the particle surface) dominate over inertial forces. In this laminar regime, the analytical solution of Stokes (1851) predicts the terminal fall velocity of spheres:

$$w_s = \frac{1}{18} \frac{\rho_p - \rho_f}{\mu} g D^2$$

(17)

Oberbeck (1876) later modified the Stokes equation for ellipsoids (Happel and Brenner, 2012). The corresponding linear relationship between drag coefficient and Reynolds number in the Stokes-regime (dashed line in Fig. 9) is:

$$C_D = \frac{R_p}{24}$$

(18)

When inertial forces begin to dominate over viscous forces and $R_p > 1$, the Stokes equation no longer applies due to the introduction of a significant pressure drag (form drag). For perfect spheres of quartz mineral density this transition occurs at diameters exceeding 0.14 mm (Rubey, 1933). Following partial account of inertial forces (von Rittinger, 1867; Oseen, 1910; Goldstein, 1929), Rubey (1933) combined the full effect of viscous resistance (Stokes, 1851) and fluid impact (Newton, 1687) on the settling particle in an analytical solution:

$$w_o = \left( \frac{\sqrt{2 g} (\rho_p - \rho_f)}{\rho_f} \right)^{3/2} \frac{9 \mu^2}{\rho_f}$$

(19)

where $r$ is the radius of the spherical particle. Empirical modifications were proposed by Janke (1965), Graf and Acaroglu (1966) and most comprehensively by Gibbs et al. (1971), on the basis of experiments using glass beads of constant shape and density:

$$w_o = \frac{\sqrt{g} (\rho_p - \rho_f) D^2}{\rho_f}$$

(20)

Eq. (20) is used for the calculation of equivalent Gibbs spheres to compare between the settling velocity of skeletal grains and siliciclastic particles (Fok-Pun and Komar, 1983; Wanless et al., 1981; Kench and McLean, 1997; Papititis et al., 2002; Weill et al., 2010; Cutterl et al., 2017). For example, a carbonate particle that has a 50% Gibbs equivalent settling diameter has a settling velocity similar to that of a 50% smaller sphere of quartz composition. The Gibbs equation (Eq. (20)), however, does not account for shape. Hence, several empirical permutations incorporating a shape factor were put forward (Dietrich, 1982; Hallermeier, 1981; Haider and Levenspiel, 1989; Swamee and Ojha, 1991; Le Roux, 1997, 2002, 2004, 2014; Ganser, 1993; Chien, 1994; Cheng, 1997; Ahrens, 2003; Jiménez and Madsen, 2003; Ferguson and Church, 2004; Came- nen, 2007; Zhiyao et al., 2008; Dioguardi and Mele, 2015; Wang et al., 2018; Riazi and Türker, 2019; Li et al., 2020).

The Dietrich (1982) settling velocity $w_{D.5}$ which is based on an extensive compilation of siliciclastic settling studies, is popular because it accounts for particle density, size, form and roundness (Goossens, 1987; Ferguson and Church, 2004; Le Roux, 2005):

$$w_{D.5} = R_1 \left( 10^{R_2 - R_3} \right)$$

(21)

where the residuals $R_1$, $R_2$ and $R_3$ are:

$$R_1 = -3.76715 + 1.929444 \log D_{a,b} - 0.09815(\log D_{a,b})^2 - 0.00575(\log D_{a,b})^3 + 0.00056(\log D_{a,b})^4$$

(22.1)

$$R_2 = \log \frac{1 - 1 - CSF - 0.85}{- (1 - CSF)^2 \tanh (\log D_{a,b} - 4.6)}$$

(22.2)

$$R_3 = \frac{0.65 - CSF}{2.85} \log \left( \frac{1 - 1 - CSF}{\tanh (\log D_{a,b} - 4.6)} \right)^{1.5(3.5 - PRI)}$$

(22.3)

which are empirically fitted to the Corey Shape Factor CSF (Eq. (3)) and the Powers Roundness Index PRI (Fig. 4). Dietrich (1982) proposed CSF = 0.7 and PRI = 3.5 to be representative for the typical shape and roundness of natural quartz sand. The dimensionless nominal particle diameter $D_{a,b}$ used in the residuals is:

$$D_{a,b} = D_{a,b}^{1.5}$$

(22.4)

where $D_{a,b}$ is the dimensionless particle diameter given in Eq. (16), calculated using the nominal particle diameter $(D = D_{a,b})$.

A simplification of the Dietrich settling velocity was proposed by Ferguson and Church (2004) (for application see for example Pyles et al., 2013), based on the Stokes settling equation for larger grains in the transitional regime $(1 < R_p < 1000)$. Ferguson and Church (2004) incorporated two constants $C_1$ and $C_2$ to describe the grain shape of some natural siliciclastic sands (Table 1):

$$w_{o,D} = \frac{\sqrt{g} (\rho_p - \rho_f) D^2}{\rho_f C_1 + C_2 \sqrt{g} (\rho_p - \rho_f) D^2}$$

(23)

Hodson and Alexander (2010) presented a graphical compilation of selected experimental settling-velocity data from the literature, which they compared with theoretical values based on the Ferguson and
Church settling equation (Eq. (23)) using sediment density as the controlling variable. They demonstrated that the settling velocity of selected carbonate particles corresponds to the settling velocity of spherical quartz grains with a density in the range of 1200–1650 kg m\(^{-3}\), despite the much higher mineral densities of calcite (2.72 g cm\(^{-3}\)) and aragonite (2.94 g cm\(^{-3}\)) (Milliman, 1974). This deviation testifies to shape and porosity effects playing a dominant role in the settling of carbonate particles (see Section 2.3 above).

Thus, the heterogeneity of skeletal sand has prohibited a straightforward application of empirical settling equations, as presented above, for carbonate particles. Alcerreca et al. (2013) proposed an equation aimed specifically at predicting the hydrodynamic properties of carbonate sand:

\[
R e_{p,a} = \left( \frac{22 + 1.13D^2}{4.67} \right)^{3/2}
\]

(24)

where \(D\) is the dimensionless particle diameter given in Eq. (16), calculated using the nominal particle diameter \(D = D_n\).

Wang et al. (2018) also provided hydrodynamic equations dedicated to natural sand composed of irregular carbonate particles:

\[
C_{D,n} = 0.945 \frac{C_{D,ph}}{\Psi} R e_p^{-0.01}
\]

(25)

where \(\Psi\) is the Wang shape factor (Eq. (7)) and \(C_{D,ph}\) is the drag coefficient for spheres (Eq. (12)). The exponent \(f(Re)\) is given by:

\[
f(Re) = 0.641 Re_p^{0.153}
\]

(26)

The empirical relation for the drag coefficient \(C_{D,ph}\) has been adopted from Clift and Gauvin (1971), which is valid for \(Re_p < 3.0 \times 10^5:\)

\[
C_{D,ph} = \frac{24}{Re_p} \left( 1 + 0.15 Re_p^{0.667} \right) + 0.42 \left( 1 + \frac{42500}{Re_p+1} \right)
\]

(27)

Wang et al. (2018) concluded that their model is better-fitting than several other hydrodynamic equations, namely those of Haider and Levenspiel (1989); Swamee and Ojha (1991); Ganser (1993); Chien (1994); Cheng (1997) and Dioguardi (2015).

Other equations are fitted specifically for the prediction of the settling velocity and drag coefficient of platy shell fragments such as the settling velocity equation of Li et al. (2020):

\[
W_{vi} = 10^{0.84165 \log(D) + 0.5316 \log(CSF) + 0.3091}
\]

(28)

where \(D\) is the dimensionless particle diameter (Eq. (16), using \(D_n\) in the range \(D_c: 25–200\), and \(CSF\) is the Corey Shape Factor (Eq. (3)) in the range \(CSF: 0.02–0.20\). It has not been tested whether the Wang equation (Eq. (25)) can predict the behaviour of the platy shell fragments studied in the Li et al. (2020) dataset.

Most recently, Riazi et al. (2020) were the first to apply the strategy of Göğüş et al. (2001) in splitting the drag coefficient into two components: a frictional drag coefficient \(C_{D,fr}\) that is dominant at low \(Re_p\) in the laminar regime, and a pressure drag coefficient \(C_{D,pr}\) prevailing at high \(Re_p\) in the turbulent regime. They used the dataset of Smith and Cheung (2003) and a small number of their own grains to derive the constants in Eq. (29) for natural carbonate sand:

\[
C_{D,n} = C_{D,fr} + C_{D,pr} = \left[ 9.50v \frac{D_{sph}^{3.3}}{g} + 0.76 \right]^{2.92} + \left[ 20.47v \frac{D_{sph}^{1.3}}{g} + 1.02 \right]^{-4.15}
\]

(29)

where \(v\) is kinematic viscosity. This combined drag coefficient is introduced into a modified settling velocity equation (compare with Eq. (14)) incorporating the Corey Shape Factor:

\[
W_{vi} = \frac{11}{15} \left( \frac{\rho_s - \rho_i}{\rho_i} \right) D_n \frac{C_{SF}}{C_{D,fr}^{CSF}CSF^{3/}}
\]

(30)

3.3. Hydrodynamic behaviour

3.3.1. Turbulence and the drag coefficient

As a particle settles, fluid moves upward around it. This process takes place in one of three flow regimes constrained by characteristic values of the particle Reynolds number \(Re_p\) (Eq. (9)), which increases as settling velocity and grain size increase (Fig. 9; Clift et al., 1978; Middleton and Southard, 1984; Le Roux, 2005). Small particles settle at low velocities with particle Reynolds numbers in the Stokes regime \((Re_p<1)\) marked by laminar, viscosity-dominated flow around the particle. The upward flow around larger settling particles is governed by inertial forces that cause flow separation and turbulent eddies to form immediately above the particle, generating additional drag. In this transitional flow regime \((1<Re_p<10^3)\) the Stokes equation (Eqs. (17) and (18)) no longer applies. Prediction of settling velocity in the transitional flow regime, which is typical for natural quartz grains in the range of 100 \(\mu m\) to 4 mm, is problematic (Ferguson and Church, 2004). Once a fully turbulent wake \((Re_p>10^3)\) develops above particles, hydrodynamic conditions once again become more predictable as the drag coefficient approaches a constant value \((C_D \approx 0.5\) for spheres, Fig. 9; Forberg, 1988; Goossens (2019) recently provided an overview of empirical correlations for the drag coefficient of rigid spheres as a function of Reynolds number.

Quantification of the transition from dominantly viscous to inertial forces is complex for non-spherical particles (Rouse, 1949; Middleton and Southard, 1984). However, the relationship between Reynolds number and drag coefficient, calculated from experimental settling velocity and grain-size data, provide insight into transitions between regimes and associated flow patterns. In addition to size, particle shape is an important factor governing hydrodynamic behaviour of settling particles by the introduction of retarding effects and complex flow patterns (Fig. 10). Using particle Reynolds numbers and drag coefficients, Alger (1964) and Komar and Reimers (1978) quantified the effect of shape on the settling velocity of siliciclastic sand as a function of grain size (Fig. 10B). The same method is used by Joshi et al. (2014) to investigate this relationship for rhodagl alaei debris (Fig. 10B), by Smith and Cheung (2003) for bioclastic carbonate sand from Hawaii (Fig. 10C), and by Li et al. (2020) for platy shell fragments (Fig. 10D). These authors showed that with higher degrees of non-sphericity (lower values of the Corey Shape Factor) the transitional flow regime was extended. The break-up of laminar flow took place at lower values of \(Re_p\) and the development of fully turbulent flow was shifted toward higher values of \(Re_p\), which contributed to particles settling at lower terminal velocities. Such trends for individual (and intact) bivalve species, however, are less straightforward (Fig. 10E, F) (Allen, 1984; Olivera and Wood, 1997).

3.3.2. Fluid properties

The properties of the fluid medium through which the particle settles influence its velocity. The most relevant ones in case of terminal settling in water include water density, viscosity, depth of the water column and, if there is a horizontal velocity component, mean flow velocity (Le Roux, 2005). The submerged density of the particle, i.e., the difference between the densities of the grain and the ambient medium, in large part controls the settling velocity (Stringham et al., 1969). In

Table 1

<table>
<thead>
<tr>
<th>Grain type</th>
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<th>(C_2)</th>
</tr>
</thead>
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<tr>
<td>Smooth Spheres</td>
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<td>0.4</td>
</tr>
<tr>
<td>Natural Sand (Sieve Diameters)</td>
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<td>1.0</td>
</tr>
<tr>
<td>Natural Sand (Nominal Diameters)</td>
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<td>1.1</td>
</tr>
<tr>
<td>Highly Angular Sand</td>
<td>24</td>
<td>1.2</td>
</tr>
</tbody>
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</tbody>
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(caption on next page)
Fig. 10. Reynolds number versus drag coefficient as a function of particle shape. The transitional flow regime extends as particle form deviates from being spherical. (A) Well-defined curve of classic settling data compiled by Rouse (1949) obtained from experiments using a range of solids and liquids. Note the deviation of discs and foils. Adapted from Komar and Reimers (1978). (B) Settling data for non-spherical grains (Alger, 1984). Adapted from Komar and Reimers (1978). Shown in red are the settling data for rhodagalal maerl debris (Joshi et al., 2014). (C) Settling data for non-spherical bioclastic carbonate sand from Hawaii (Smith and Cheung, 2003). (D) Settling data for platy shell fragments (Li et al., 2020). The authors reported the corresponding Φ shape factor of Haider and Levenspiel (1989) for the plotted curves. (E, F) Settling data for a number of bivalve species (Allen, 1984; Olvera and Wood, 1997).

The case of marine carbonate sediment, the density of sea water is controlled by the amount of dissolved solids (approximated by salinity) and water temperature. The density of water increases as salinity increases, or as water temperature drops, which combine to retard a grain’s settling velocity. A decreasing water temperature also raises the fluid viscosity, leading to a significant lowering of the settling velocity. Gibbs et al. (1971) provided a library of settling velocities of spheres at different water temperatures and salinities. An extensive discussion on water properties with regard to settling velocity was provided by Flemming (2007), noting the necessity for a standard temperature conversion because of the non-linear temperature effect on fluid viscosity and so on settling velocity (Rouse, 1936). Temperature shifts in nature as a result of seasonality can exert a significant control on sediment settling velocity and associated depositional processes (Anderson, 1983; Krogel and Flemming, 1998; Chang et al., 2006; Flemming, 2007; Flemming, 2012). Measurements using standardised water conditions are lacking from carbonate settling literature. Reported experiments cover temperatures of 3-26.5 °C and salinities of 0-36.5 ppt (see compilation in Table S2 in Supplementary Data). Joshi et al. (2014) provide a rare example of a study performing settling experiments in both fresh and saline water conditions. Temperature effects were discussed for settling velocities of planktonic foraminifers by Carmel et al. (2014).

3.3.3. Settling motion

Particles settle with their largest projection area normal to the fall direction (McNown and Malaika, 1950; Komar and Reimers, 1978; Song and Yang, 1982). Settling behaviour, therefore, is largely controlled by the shape of the largest cross-sectional area (Wadell, 1934; Krumbein, 1942; McNown and Malaika, 1950; Maiklem, 1968; Komar and Reimers, 1978; Song and Yang, 1982), gastropods present a notable exception in particular when air bubbles are trapped in their apex (Maiklem, 1968).

Along the edges of irregular particles, flow separation and associated turbulence generation occur. In addition, compression of flow lines creates local pressure maxima. Such unequal pressure distributions together with moments of inertia (controlled by the location of the centre of mass and particle form) govern the readjustment of grain orientation, commonly such that the maximum surface area is oriented normal to the particle’s propagation direction (Stringham et al., 1969; Clift et al., 1978; Middleton and Southard, 1984). This instability introduces a horizontal component in the settling path of, in particular, flat grains (for example certain foraminifers, Yordanova and Hohenegger, 2007). Along such complicated trajectories, the theoretical settling velocity based on grain size alone is not attained (Hodson and Alexander, 2010).

Non-spherical particles thus orient themselves as a function of geometric shape (the first-order shape descriptor form) and the location of the centre of mass. Second-order shape effects caused by grain angularity (low roundness) also lower the settling velocity (Williams, 1966; Komar and Reimers, 1978; Baba and Komar, 1981; Yee, 1994). The degree to which, however, is disputed partly due to the difficulty of discriminating between the independent influence of shape, roundness and surface texture. For example, Williams (1966) detected up to 25% lower velocities for angular shapes with respect to rounded artificial discs and cylinders, and up to 5% for rough versus smooth surface textures (see also Kumar and Shrangaya, 1989). In natural siliciclastic sand, however, Baba and Komar (1981) found no measurable effects with regard to grain-shape irregularities (expressed as Powers roundness). Dietrich (1982), on the other hand, argued that shape and roundness contribute equally to lowering the settling velocity of larger particles, but Fourier shape analysis suggests a secondary importance of roundness and surface texture (Goldbery and Richardson, 1989). Experimental studies using ornamented bivalve shells (Allen, 1984), fresh-water oncoids (Verrecchia et al., 1997) and maerl (Joshi et al., 2014), however, show that increased surface texture yields higher drag forces and thus lower settling velocities.

Studies focused on the hydrodynamic behaviour of carbonate grains in particular, commenced with the papers of Berthois (1965) on bivalve fragments and Maiklem (1968) on modern reef constituents. These authors proposed characteristic settling paths as a function of shape, yet regardless of size (Fig. 11A), with lower settling velocities than theoretically predicted by Rubey (1933) on the basis of the mineral density of aragonite and calcite. Braithwaite (1973) expanded the study of Maiklem (1966) by including grain size and density, defining four settling modes through which all grains must pass with increasing particle Reynolds number (Fig. 11C). This concept differs from the shape-specific settling modes of Maiklem (1968), although Braithwaite (1973) commented that certain grain types are dominated by specific settling modes. With increasing particle Reynolds number, settling particles may go through the following fall patterns (note that the maximum Reφ reached by some particles is lower than the threshold for the transition into some of the ‘higher’ fall patterns, as Reφ may be limited by grain size): (1) straight: the particle is aligned with the largest horizontal axis perpendicular to the settling direction without rotation or oscillation; (2) spinning: the particle spins with an axis of rotation contained within the particle; (3) spiral: the particle spirals with an axis of rotation outside the grain; (4) unstable: the particle spirals unstably with superimposed rocking and wobbling motions.

A key contribution on settling motions is the work of Allen (1984), wherein settling, overturning and entrainment behaviour were reported for bivalve shells. The author described the settling regimes as steady, mixed and unsteady (Mehta et al., 1980). Allen (1984) further quantified spinning, spiral and pitching motions using the dimensionless Strouhal number (Clift et al., 1978), demonstrating an inverse relationship between rotation frequency and elongation. Interestingly, it is the elongation of the shell that controls the settling regime rather than the Reynolds number. Other investigations of settling motion include the work of Stringham et al. (1969) and Mercier et al. (2020) using artificial discs (Fig. 11B), and Verrecchia et al. (1997) on oncoid fall patterns.

4. Discussion

In the foregoing sections, particle properties (Section 2) and hydrodynamics (Section 3) relevant to the settling of sediment grains were presented in a review-like manner outlining the historic development of the research field, in which the study of carbonate particles advanced (usually with some delay) following concepts proposed using siliciclastic sediment. In this section, the progress made on the hydrodynamic behaviour of carbonate grains is discussed more specifically. It is first shown how the properties of several skeletal grain types affect their settling velocity (Section 4.1). Then the universal carbonate settling equation is evaluated (Section 4.2), followed by a consideration of the most appropriate shape classification scheme and documentation methods for hydrodynamic properties of carbonate grains (Section 4.3). Finally, the link between carbonate sediment transport and settling velocity in quiescent water is explored (Section 4.4).
4.1. Parameters controlling the hydrodynamic behaviour of bioclasts

The settling velocity of carbonate grains depends on the size, shape and density of particles, and fluid properties. However, these parameters are not reported in a consistent manner in literature. Together with the historic paucity of settling studies that are focused specifically on carbonate grains, this limits the comparison of empirical results. As an inventory, a database of settling velocities for various types of carbonate particle is compiled (Table S2 in Supplementary Data). Data are grouped on the basis of composition and comparable shape (Fig. 12). Foraminifers have been subdivided further into form class, because of their inordinate abundance in the literature (Fig. 13). For all investigated carbonate grain types, settling velocity increases with particle size. However, the increase in settling velocity halts for those grain types that reach the gravel range (>2 mm) and for some the settling velocity even starts decreasing from thereon (e.g., Halimeda green algae, crinoids, Alcyonarian spicules, and few benthic foraminifers). Planktic foraminifers do not reach the gravel size and hence do not display such a trend. Overall, the number of studies is limited compared to the myriad of species susceptible to differential settling velocities.

For example, large benthic foraminifers such as nummulitids may develop increasingly complex skeletal structures as they grow in size (Jorry et al., 2006; Yordanova and Hohenegger, 2007; Briguglio and Hohenegger, 2009; Briguglio et al., 2017). On the other hand, non-skeletal carbonate grains such as fecal pellets keep their ellipsoidal shape and ooids retain their round morphology regardless of size (Wanless et al., 1981; Taghon et al., 1984; Sipos et al., 2018; Trower et al., 2018).

Grains are typically reworked and fragmented during transport. Hence, the grain-size distribution of sandy biogenic carbonate sediment is controlled by a combination of the inherited grain-size distribution and its subsequent hydrodynamic modification (Ford and Kench, 2012). While inherited grain-size distribution is relevant in particular for immature particles, hydrodynamic modification controls the grain-size distribution of mature sediments (Maiklem, 1968). These factors are governed by various sedimentary, biological and chemical processes.

Several approaches have been used to study the effects of hydrodynamic modification or breakdown of carbonate particles, including tumbling-barrel experiments (Chave, 1960; Moberly, 1968; Force, 1969; Mitchell-Tapping, 1980; Hoskin et al., 1983; Peebles and Lewis, 1991; Kotler et al., 1992; Beavington-Penney, 2004; Ford and Kench, 2012; Gorzelak et al., 2013; Trower et al., 2019), dissolution experiments (Peebles and Lewis, 1991; Kotler et al., 1992; Shroba, 1993), in-situ surveys of marine abrasion and/or microboring (Mitchell-Tapping, 1980; Shroba, 1993; Lescinsky et al., 2002; Newell et al., 2007) and artificial fragmentation of bivalve shells by manual breaking to produce calcareous debris (Rieux et al., 2019). Rieux et al. (2019) is one of few studies that combines data on mechanical breakdown and hydrodynamic behaviour, showing lower settling velocities for certain bivalve species.
species when compared with the some of the bivalve data from Berthois (1965), Braithwaite (1973) and Paphitis et al. (2002) (Fig. 12B, C). This divergence in hydrodynamic behaviour could be the result of an artificial sharpness introduced by manually breaking of the shells. However, bivalve skeletons may also exhibit different morphologies associated with variation in the composition of internal structures, for example thin foliated sheets in *Anomia ephippium* and mechanically weaker inter-stratified chalky calcite in oyster shells *Magallana gigas* and *Ostrea edulis*, suggesting that a greater diversity of hydrodynamic behaviour exists among different bivalve species (Rieux et al., 2019). Another aspect is pointed out by recent work in the Maldives demonstrating that parrotfish are important contributors to the generation of coral-reef detritus.
such that animal-induced grain-shape modification is yet to be included as an additional factor. Thus, shape properties are not solely a result of mechanical or chemical breakdown. Primary skeletal and mineral grain properties may prohibit uniform degradation, although some studies suggest that flat shapes, such as shells, will eventually shift from flat to equant (Rieux et al., 2019). Force (1969) observed in tumbling-barrel experiments that during the breakdown of bivalves and gastropods specific architectural units of the shell produce characteristically-sized particles; layers tend to breakdown into 250–500 μm, sublayers into 4–32 μm, and unit crystals...
generate 0.125–0.5 μm fragments. Folk and Robles (1964) described the breakdown of coral and *Halimeda* reef sediments by sequential steps of discrete grain sizes, as controlled by their internal structure and breakdown mechanism. Overall, shape modification of carbonate grains as a result of abrasion has received more attention than its relation to hydrodynamic properties.

Investigations of the skeletal durability of biogenic sediment performed using tumbling-barrel experiments (Driscoll and Weltin, 1973; Kotler et al., 1992; Shroba, 1993; Ford and Kench, 2012) demonstrate that variation in durability originates from differences in skeletal structure and mineral density. Experiments have shown that form may be retained during abrasion depending on abrasion intensity. For example, Ford and Kench (2012) pointed out that particle form was preserved but that grain roundness had increased for two coral species in their experiments. In contrast, the primary skeletal morphology of certain organisms, such as some thin-wall foraminifers, can be entirely obliterated (Kotler et al., 1992; Shroba, 1993). The rounding of particles can be counteracted if grain fragmentation creates fresh angular surfaces (Maiklem, 1968; Barrett, 1980). Yet, the remains of certain organisms likely respond differently to abrasion processes than others. Shroba (1993) observed both rounding and enhanced surface roughness for different carbonate organisms in a set of various abrasion and dissolution experiments, showing a well-constrained relation with skeletal structure. Both roundness and surface roughness affect hydrodynamic behaviour, for example reducing the settling velocity (Williams, 1966) and likely affecting particle-related turbulence (Murray, 1970; Wilson and Huang, 1979; Pye, 1994).

Roundness varies also as a function of morphological complexity, for example, determination of convexity descriptors captures the increase of maërl branch complexity with grain size (Joshi et al., 2014). Ford and Kench (2012) suggested that skeletal structures with protuberances, such as *Acropora* *sarmantosa* and *A. nasuta*, have coralities which are prone to early-stage abrasion processes. Morphological complexity, however, appears independent of grain size. For example, variation in Zingg shape was constant throughout size intervals for some coarse fluvial siliciclastic sands (Milan et al., 1999). It should be further explored whether this trend is also characteristic of carbonate sands.

### 4.2. Universal carbonate settling equations

The most studied aspect of hydrodynamic behaviour is settling velocity, which has been investigated typically through settling tube experiments. Attempts have been made to develop normative classification schemes for carbonate sand. For example, Kench (1997) applied principal component analysis and experimental settling velocity for the discrimination of bioclastic deposits. The proposed classification is based on several settling ranges, from very slow (0.39-0.78 cm/s) to very fast (25-50 cm/s), for sediment sizes from very fine sand to pebbles (Table 2). However, settling studies testing bulk carbonate sand are sparse compared to investigations using siliciclastic sediment. Likewise, Li et al. (2020) advocated an approach based on dimensionless settling velocity and particle diameter in combination with the Corey Shape Factor (Eq. (28)), using modified siliciclastic settling equations of Dietrich (1982), Haider and Levenspiel (1989) and Soulsby (1997). Li et al. (2020) calculated the diameter of the Gibbs equivalent sphere (Gibbs et al., 1971), which is a quartz sphere with the same settling velocity as the investigated grain, for platy shell fragments in order to facilitate comparison between datasets. In conclusion, a number of settling equations have been calibrated for several datasets, but their universal applicability is problematic because of the large variability between such datasets. A settling equation, therefore, will always require parameters to be included that are specific to a biological assemblage or environment. A start has been made constructing a library containing such parameters, but a collaborative effort is needed toward consistent data-reporting allowing replication, testing and calibration of equations with different datasets.

### 4.3. Documenting hydrodynamic behaviour

Numerous strategies involving the calculation and reporting of different parameters have been employed in the research of particle hydrodynamic behaviour. In settling studies of carbonate grains, data points typically include a representative particle diameter and a settling velocity, which are plotted against one another. A curve is then created using regression analysis to calculate a settling velocity trend (e.g., Maiklem, 1968; Braithwaite, 1973; Paphitis et al., 2002) and subsequently used to define settling envelopes.

More recently, Alcerreca et al. (2013) proposed an equation for the prediction of the settling velocity of bulk carbonate sand (Eq. (24)), which they tested with the siliciclastic dataset of Hallermeier (1981) and a newly obtained carbonate dataset. Wang et al. (2018) subsequently incorporated the findings of Alcerreca et al. (2013) and empirically obtained an equation for the drag coefficient of carbonate sand particles (Eq. (25)). Wang et al. (2018) employed the novel approach of combining form deviation from a sphere with morphological complexity by using a ratio between sphericity and inverse circularity (Eqs. (4) and (6)). This method awaits further evaluation with different carbonate sediments. Riazi et al. (2020) employed three-dimensional scanning techniques and the dataset of Smith and Cheung (2003) to evaluate the parameters of the drag coefficient of Gögö et al. (2001). They consider the laminar and turbulent effects separately (Eq. (29)), using a modified version of the general settling equation that incorporates the Corey Shape Factor.

#### Table 2

<table>
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<tr>
<th>Settling velocity range (g)</th>
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<td>–5.24 to –7.22</td>
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<tr>
<td>3.4</td>
<td>6.25-12.5</td>
<td>Fast-moderate</td>
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<tr>
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<tr>
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<td>0.39-0.78</td>
<td>Very slow</td>
<td>1.06 to 1.65</td>
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</tbody>
</table>

shape variation of carbonate sediment cause a higher degree of scatter in which outliers with extreme values are more common. Not all studies report the scattered data points however. Also, statistical descriptors, such as standard deviation and regression coefficient, are not always included in the publication, which limits the evaluation of the published regression curve. The literature compilation of settling velocity data presented here (Figs. 12, 13 and Table S2 in Supplementary Data) is therefore limited in the sense that it lacks these descriptors. Such additional descriptors are important because two datasets with different data scatter may produce similar regression curves. The question is therefore: if two settling-velocity datasets display similar regression curves, do they also exhibit similar hydrodynamic behaviour? A first step toward solving this issue is to adopt a common practice of including raw data and statistical descriptors in the publication, or in supplementary data. A second question is what a regression curve through highly scattered settling data actually represents. In effect, the regression curve and statistical descriptors represent the spread of density, shape, size and composition of the constituent carbonate grains. The extent to which the regression curve reflects the bulk behaviour of the sediment, however, awaits further investigation.

For the reporting of grain size, both the nominal diameter (Fok-Pun and Komar, 1983; Verrecchia et al., 1997; Smith and Cheung, 2003; Yordanova and Hohenegger, 2007; Li et al., 2020) and sieve diameter are frequently used (Joshi et al., 2014; Rieux et al., 2019), irrespective of the study objective. Alternatively, equivalent settling diameters (Paphitis et al., 2002; Weill et al., 2010), based on the settling velocity of a sphere of equal size and density, can be implemented (see also Gibbs et al., 1971; Komar and Clemens, 1986).

The choice of the most suitable area parameter, however, is often steered by the composition of the grains under investigation. For example, the maximum cross-sectional area is straightforward to be used for spheroidal grains such as fecal pellets (Wanless et al., 1981), which fall through the fluid in a random position. Maximum projection area, on the other hand, is considered more appropriate for platy grains such as bivalve fragments (Allen, 1984; Li et al., 2020), because of their orientation perpendicular to the settling-velocity vector. For heterogeneous bulk carbonate sand composed of diverse constituents and on the assumption that grains approach spherical forms, the maximum cross-sectional area of the nominal sphere seems most practical (Smith and Cheung, 2003).

Another parameter useful for the comparison of hydrodynamic behaviour between carbonate datasets is the drag coefficient (Mehta et al., 1980; Allen, 1984; Takahashi and Be, 1984; Oehmig, 1993; Savarese et al., 1996; Oliveira and Wood, 1997; Verrecchia et al., 1997; Smith and Cheung, 2003; Joshi et al., 2013; Wang et al., 2018; Rieux et al., 2019; Li et al., 2020; see also Göğüş et al., 2001). The drag coefficient is typically reported as a function of the Reynolds number, revealing the relation of grain size and shape with flow regime, which together affect a grain’s settling mode, entrainment and transportability. Discussion, however, exists about which grain diameter and which area parameter are most appropriate for calculation of the drag coefficient and Reynolds number (e.g., Li et al., 2020).

There are numerous approaches to shape characterisation, including ellipsoid-based (modified) Zingg shape (Maiklem, 1968; Braithwaite, 1973; Hohenegger, 2006; Li et al., 2020), composition- and biota-specific shape (Wanless et al., 1981; Taghon et al., 1984; Takahashi and Be, 1984; Savarese et al., 1996; Paphitis et al., 2002; Weill et al., 2010; Simon et al., 2016; Bruguglio et al., 2017; Rieux et al., 2019), quantified shape (Verrecchia et al., 1997; Carmel et al., 2014), Corey Shape Factor (Fok-Pun and Komar, 1983; Verrecchia et al., 1997; Smith and Cheung, 2002; Smith and Cheung, 2003; Li et al., 2020), combinations of orthogonal ratios and symmetry coefficients (Oliveira and Wood, 1997; Jorry et al., 2006), and two-dimensional perimeters, axial ratios and area-based parameters (Joshi et al., 2014). Shape description is often reported together with surface area and/or volume as additional parameters (Berthois, 1965; Savarese et al., 1996; Bruguglio and Hohenegger, 2009; Simões et al., 2016; Cuttler et al., 2017). Simões et al. (2016) used a weight-per-surface-area descriptor combining shape and composition to discern between the settling behaviour of dorsal and ventral brachiopod valves. This method is similar to the Unit Immersed Mass index of Allen (1984) for bivalves, later adopted by Savarese et al. (1996) to study the settling of circular and pentaradial crinoid columns.

The plethora of carbonate–particle shape classifications is rooted in a lack of consensus and the diverse objectives set by the hydrodynamic studies using them. Deviation between shape classifications complicates cross-literature comparisons between biota-specific shapes and their hydrodynamic behaviour. The literature databases presented here (Table S1 and S2 in Supplementary Data) emphasise the need for consistent reporting of grain properties, advocating either standardisation of grain-shape classification or at least reporting the raw data from which parameters in other classifications can be obtained.

The two most common shape diagrams are the Zingg (1935) classification, which is a rectangular diagram with elongation and flatness along its axes, and the ternary diagram of Sneed and Folk (1958) with compact, oblate and prolate spheroids in the apices (Fig. 14). Le Roux (2004) argued that the arbitrary subdivision of the Zingg diagram has no bearing on the hydrodynamic behaviour of grains. Also, Illenberger and Reddering (1993) reasoned that the Zingg diagram incorrectly implies that blades are a shape end-member, whereas the Sneed and Folk diagram preserves the continuum that exists between the natural three end-members (see also Fig. 14G–I).

Most settling equations apply the Corey (1949) Shape Factor (CSF, Eq. (3)) as it provides a single value which facilitates the fitting of equations to empirical datasets. That the Corey Shape Factor crosses several form classes is demonstrated when CSF is plotted in the Zingg and Sneed and Folk diagrams (Fig. 14A, E; see also Blott and Pye, 2008). The Corey Shape Factor can indeed not differentiate between discs, blades and rods in the Zingg diagram, and between prolate and oblate spheroids in the Sneed and Folk diagram, in particular for low values of CSF. However, such inability is only relevant if particles with the same value of CSF have different settling velocities or exhibit distinctly different settling motions.

Returning to the mechanics discussed in Section 3.1, terminal settling velocity is reached once the drag force equates the submerged weight of the particle. Weight is a function of particle volume, whereas drag force depends on an area parameter for which typically the maximum projection area is chosen. Thus, if the Corey Shape Factor is in some way a measure of the maximum projection area, it may be argued that CSF does present a reasonable index of particle shape to be used in settling-velocity equations. Inspection of Fig. 14B reveals that the isolines of the maximum projection area, when normalised to the nominal diameter $D_0$ (i.e., all particles in the diagram have equal volume), resembles the Corey Shape Factor reasonably well. Therefore, on the assumption that particle volume and maximum projection area are the main parameters controlling settling velocity, equancy ($D_0/D$) is the principal shape classification relevant to the prediction of settling velocity (Fig. 14C, F). An as yet unresolved issue, however, is whether diagrams that consider equal-volume particles are appropriate for the analysis of sieve-based grain-size intervals.

### 4.4. Transport of bioclastic carbonate grains

Knowledge about the hydrodynamic behaviour of carbonate sediment in terms of deposition and transport has wide applications. Some research is focused on carbonate sediment distribution (Kench and McLean, 1996; Kench, 1997; Cuttler et al., 2017), occasionally specified to a certain mode of transport including storm events (Li et al., 2020), currents and waves (Weill et al., 2016; Durafour et al., 2015; Flemming, 2017; Joshi et al., 2014; Rieux et al., 2019; Riazzi et al., 2020) and turbidity currents (Bornhold and Pilkey, 1971; Van Tassell, 1981; Herbig and Mamet, 1994; Hodson and Alexander, 2010; Le Goff et al., 2021). Other studies deal with specific organisms, in particular planktic...
Fig. 14. (A) Corey (1949) Shape Factor in the Zingg (1935) shape classification diagram. (B) Maximum projection area normalised to nominal diameter $D_n$ (equal-volume grains everywhere) in the Zingg diagram. (C) Equancy-based shape classification in the Zingg diagram. (D) Ternary shape diagram of Sneed and Folk (1958). (E) Corey Shape Factor in the Sneed and Folk diagram. Zingg shape classes are shown. (F) Equancy-based shape classification in the Sneed and Folk diagram. (G, H, I) 403 grains of sediment population FAV from De Boer et al. (2018) and De Kruijf et al. (2018) plotted in the (G) Sneed and Folk diagram, (H) Zingg diagram, and (I) grain size versus Corey Shape Factor plot. (A), (C), (D) and (F) modified from Blott and Pye (2008).
foraminifers (Berger and Piper, 1972; Fuk-Pun and Komar, 1983; Takahashi and Be, 1984; Oehmig, 1993; Caromel et al., 2014), biological processes such as the generation of fecal pellets (Wanless et al., 1981; Taghon et al., 1984) and sedimentation due to bioerosion (Perry et al., 2011a, 2015). The physical transport of specific bioclasts may result in the accumulation of sediment bodies, for example composed of bivalve shells (Allen, 1984; Olivera and Wood, 1997; Papithit et al., 2002; Weill et al., 2010; Rieux et al., 2019; Li et al., 2020), maerl (Joshi et al., 2014), fresh-water oncosoids (Verrecchia et al., 1997) and large benthic foraminifers (Jell et al., 1965; Jorry et al., 2006; Yordanova and Hohenegger, 2007; Briguglio and Hohenegger, 2009; Briguglio et al., 2017). Carbonate settling velocity is also an input parameter for local carbonate budget models (Land, 1979; Hubbard et al., 1990; Harney et al., 2000; De Falco et al., 2011; Trower et al., 2019) or for global-scale calcium carbonate dissolution studies (Jansen et al., 2002). In addition, the environmental durability and transport of carbonate particles provide insight into the stability and maintenance of coral reefs (Perry et al., 2011b). The suspension fallout pattern of carbonate sediment transported by tsunamis is another application of settling velocity (Ferguson and Church, 2004; Pyles et al., 2013; Stammer, 2011b). The suspension fallout pattern of carbonate sediment transport can be approximated by its vertical settling velocity in quiescent water (Kench, 1997; Flemming and Bartholomá, 1997; Flemming, 2002, 2007). Yet, sediment transport processes are more complex than the vertical settling of single grains. For example, there are several modes of sediment transport: bed load, suspended load and wash load (predicted by the Rouse number; Rouse, 1937), associated with distinct transport and sedimentation mechanisms (entrainment, saltation, and unidirectional and hindered settling; Einstein, 1942; Meyer-Peter and Müller, 1948; Brown, 1950; Bagnold, 1954; Engelund and Hansen, 1967; Van Rijn, 1984, 2007; Nielsen, 1992). Differences in settling velocity due to variation in particle shape and density lead to vertical sorting during suspension fallout and horizontal sorting in a decelerating flow (Ferguson and Church, 2004; Pyles et al., 2013; Stammer, 2014). Particle behaviour during longitudinal transport is subject to grain-to-grain interactions and flow conditions (Hodson and Alexander, 2010; Wang et al., 2018). The settling velocity, therefore, remains only an approximation of the hydrodynamic behaviour of carbonate grains. Yet, because of the underlying fundamental mechanics on which settling velocity depends, it remains an important and applicable parameter to provide insight into the transport and deposition characteristics of heterogeneous carbonate sands (Smith and Cheung, 2003; Hodson and Alexander, 2015; Cuttler et al., 2017).

Several studies have investigated the link between settling velocity and entrainment properties of carbonate grains. For example, taphonomic features, such as symmetry and concavo-convexity, control the settling mode and entrainment thresholds of single bivalve shells (Allen, 1984; Olivera and Wood, 1997; Rieux et al., 2019; Li et al., 2020; Fick et al., 2020). Weill et al. (2010) emphasised the dual nature of shell fragments, which exhibit low settling velocities in combination with a high resistance to flow friction once deposited (bed roughness). This combination explains the high transport rates of shell fragments (see also Miedema and Ramsdell, 2011). Similarly, the relative ease of transport, once entrained, has been recognized for large benthic foraminifers, which display organism-dependent behaviour as a function of test shape (Jorry et al., 2006; Yordanova and Hohenegger, 2007; Briguglio and Hohenegger, 2009; Briguglio et al., 2017). Contrastingly, fecal pellets become entrained at much lower shear velocities, compared to discoidal shell and test fragments due to their spherical shape (Wanless et al., 1981; Trower et al., 2017).

In effect, differences in sediment transport mode determine whether bioclastic grains diffuse over large areas (e.g., carbonate platforms and shelves; Andresen et al., 2003; Jorry et al., 2020) or whether they form highly concentrated accumulations (e.g., Nummulite banks; Jorry et al., 2006; Briguglio et al., 2017). Such diffusion parameters, which can be estimated through settling and flume experiments (Flemming, 1992; Frager et al., 1996) are required for realistic carbonate platform models (e.g., Droxler and Schlager, 1985; Schlager et al., 1994) and stratigraphic forward models (e.g., Dionisios; Granjean, 1997; Granjean and Joseph, 1999; Busson et al., 2019; Bortromano et al., 2020).

Another aspect yet to be included in studies on the dispersion of carbonate sediment is the hiding-exposure effect (Einstein, 1950; Wilcock, 1993), i.e., the modification of critical shear stress by the shielding of small grains by larger ones and lowering the entrainment threshold of large grains by finer particles, which influences the mobility of bimodal sediment mixtures (McCarron et al., 2019), such as present in many carbonate environments. Bimodal sediment mixtures also affect tidal subaqueous dunes in mixed environments. Bioclasts may remain in suspension under high flow-energy during low tide, generating dominantly silicilastic dune foresets, whereas in low-energy high-tide flow, deposition also includes the bioclastic fraction (Longhitano, 2011).

Once in suspended transport, the sediment concentration of carbonate grains becomes an important variable (Hodson and Alexander, 2010; Wang et al., 2018). Experiments with silicilastic sand-mud mixtures demonstrate that depositional texture varies as a function of bulk concentration and the proportion of sand and mud in the sediment suspension (Amy et al., 2006). In mud-free suspensions, depositional texture is largely controlled by sediment concentration, which determines the degree of particle-particle interaction, from free settling at low concentrations to hindered settling above a threshold of 9% sediment concentration for silicilastics (Bagnold, 1954). Hindered settling leads to retarding effects and suppresses vertical and lateral sorting mechanisms. Additionally, hindered settling may invoke flow stratification and the formation of a high-density flow layer (Lowe, 1982, 1988; Postma et al., 1988; Sohn, 1997; Cartigny et al., 2013). Two main particle interactions are relevant here: interparticle collisions and wake-related turbulence.

Particle collisions are obviously more frequent at higher concentrations of suspended sediment, but also depend on the degree of lateral movement of particles during falling. Settling trajectories therefore partly control the threshold at which hindered settling starts to occur. Although already hinted at by Braithwaite (1973), this concept remains virtually unexplored in the literature (but see Wang et al., 2018). Maiklem (1968) and Braithwaite (1973) identified several settling modes, i.e., the fall path and superimposed grain motion, including straight, spinning, spiral (oscillating) and unstable trajectories. Settling paths were further studied by Stringham et al. (1969) for discs and by Verrecchia et al. (1997) for oncocids. Maiklem (1968) linked settling trajectory to shape, whereas Braithwaite (1973) suggested that all grains go through a certain order of falling mode as the particle Reynolds number increases. Several studies already explored organism-dependent settling properties of carbonate sand (Figs. 12 and 13, compilation in Table S2 in Supplementary Data), yet the relation between composition and settling motion of the prevalent shapes produced by specific organisms awaits to be established.

A second important mode of particle interaction is related to turbulence generated by the return flow and wake behind settling grains (Stringham et al., 1969), which may retard the descent of other grains or
even displace lighter particles upward (Middleton and Southard, 1984). Such reduced settling velocity of the lighter fraction enhances particle segregation (Druitt, 1995; Winterwerp, 2002). Additional disturbance of nearby grains results from complex flow separation induced at angular particle edges (Wilson and Huang, 1979). Murray (1970) observed that nearby grains results from complex flow separation induced at angular architecture of skeletal carbonate grains is controlled by the growth habit of however, are arguably biogenic carbonate grains. The intricate architecture of skeletal carbonate grains is controlled by the growth habit of CaCO₃-secreting animals, plants, protists and microbial life forms, generating a wide range of particle shapes, densities and abrasion products, which become even more variable when extended into carbonate settings of the Earth’s distant past occupied by organisms now extinct. Deep understanding of the dynamics of particle settling is fundamental to make progress in solving more complicated problems such as sediment transport. The present contribution provided a historical overview of how settling equations for carbonate grains have evolved from modifications of formulae for siliciclastic particles, which themselves are adapted from more general derivations of regular geometric shapes falling through a fluid. The strategy adopted by hundreds of publications involves equating particle weight with the drag force created due to the resistance of deformation by the ambient fluid. The weight of the particle is a direct function of its volume and density. The drag force, on the other hand, often takes the dimensionless form of the drag coefficient, whose magnitude increases with settling velocity and the size of the downward-facing surface area. Particles have the tendency to settle with their maximum projection area perpendicular to the fall direction. Particle volume and maximum projection area, therefore, are the main input parameters in settling velocity equations. These parameters are straightforward to determine for spheres; needing only the spherical diameter. For most natural siliciclastic sands, however, an ellipsoidal approximation of grain shape seems to work well, culminating in the universal settling equation of Ferguson and Church (2004). Yet, carbonate grains may exhibit such irregular and asymmetric forms that more sophisticated measures of maximum projection area and particle volume are required. Bioclasts typically lack end-member shapes as identified for mature siliciclastic sediments, such that large divergence may exist between grains from different carbonate settings and even within single depositional environments.

In this review, a small but significant body of settling tube data obtained from experiments using carbonate particles has been compiled (Figs. 12 and 13, compilation in Table S2 in Supplementary Data). These experiments provide some insights into the settling behaviour of specific organisms and components and/or sediment populations, yet the extent to which these specific settling data lay the basis for general inferences is limited. It is demonstrated that there is a need for a broad and systematic approach in documenting the hydrodynamic behaviour of carbonate sediments. This is hampered, however, by the general non-availability of commercially produced settling tubes, as most research groups rely on in-house constructions without inter-laboratory benchmarking (see recommendations listed in Syvitsky et al., 1999). Settling studies should be performed under standardised conditions including settling tube water properties, such as temperature and salinity, as suggested by Syvitski et al. (1991) and Fleming (2007). The integration of single-grain organism-specific behaviour with that of heterogeneous bulk sediment populations is required. Additional settling tube investigations should benefit from a thorough description of grain properties such as size, shape and density. A key question, however, is whether the hydrodynamic behaviour of a bulk sediment population is the sum of its subpopulations, each characterised by component- or organism-specific grains, potentially with discriminatory settling velocities and trajectories. If so, the hydrodynamic behaviour of a carbonate sediment can be predicted from a set of standard values (to be determined) multiplied by the measured volumetric proportions of those subpopulations. Recent developments are promising with regard to the application of carbonate-specific settling equations (Alcerreca et al., 2013; Cuttler et al., 2017; Wang et al., 2018; Li et al., 2020), yet grain shape and volume parameters in these equations still rely on some kind of approximation of spherical or tri-axial geometries. Innovative techniques are required for the accurate determination of irregular particle shape and volume, and in cases also for anisotropic skeletal density (Fig. 6, compilation in Table S1 in Supplementary Data). Creative solutions have been proposed, for example the application of classic two-dimensional image analysis on a particle that is stepwise rotated along its vertical axis to reconstruct its three-dimensional volume (Riaz and Türker, 2019). Alternatively, three-dimensional microtomography (CT-scanning) is a promising tool for the high-resolution determination of particle size and shape and the effects of grain alteration (Leiönen et al., 2020; Maroof et al., 2020). This technique allows to constrain grain size, orthogonal ratios, surface area and volume, which together can elucidate the three orders of grain shape: form, roundness and surface texture, up to a resolution of 1-10 μm with conventional setups (Cnudde and Boone, 2013). A drawback of microtomography, however, is the current labour-intensive procedure and the consequent inability to image large amounts of sediment. Upscaling of the results of single-grain analysis, therefore, is necessary to derive bulk sediment composition. Dynamic image analysis enables the measurement of the size and two-dimensional shape distribution of large quantities of particles (see for example Van Hateren et al., 2020), however, for complex carbonate grain morphologies a two-dimensional description may be insufficient. Su and Yan (2019) explore the possibilities of predicting three-dimensional size and shape parameters of siliciclastic particles from two-dimensional images (obtained with dynamic image analysis using Sympatec QICPIC), through linear relations established using three-dimensional microtomography. This approach likely requires a deep-learning component to account for the inherent heterogeneity of carbonate sediments. Machine-learning techniques offer an automated method of two-dimensional image analysis, such as the tool SedinNet which recently became available (Buscombe, 2020). The non-linear and complex interactions between particles and the fluid, which are responsible for much of the scatter in settling data, are being studied using data-driven machine learning approaches, including artificial neural networks (Goldstein and Coco, 2014) and random forest machine learning (Cao et al., 2020), which perform well provided that large datasets are available. Extensive datasets should not only focus on the averaged vertical vector of the settling velocity, i.e. the time needed to pass a certain vertical distance in an experimental apparatus, but ought to investigate the entire settling trajectory. Thus, incorporation of the movement of the grain and superimposed motions in the x-y-plane perpendicular to the vertical are required to gain insights into the non-linear settling behaviour of carbonate particles. Hydrodynamic grain behaviour is not restricted to be reported in terms of average terminal settling velocity, average Reynolds number or average drag coefficient, but rather should
be documented as evolving parameters, continuously changing as the particle descents. The description of the falling trajectory may be described qualitatively (Maiklem, 1968; Braithwaite, 1973; Smith and Cheung, 2003), but more importantly also quantitatively, for example by means of Strouhal numbers (i.e., vortex shedding, see Allen, 1984) and vector velocity fields (Mercier et al., 2020). Computational fluid dynamics of irregular grains using ever-stronger processors have already been demonstrated for non-carbonate particles (Zhao et al., 2014; Kumbhakar et al., 2017; Xu et al., 2018) and present promising future avenues for carbonate sediment investigations. Such models, however, require validation with real datasets like Krueger et al. (2015) presented for industrial waste, with three-dimensional velocimetry and continuous tracking of particles with complicated settling paths and superimposed grain motions and for which the drag coefficient is continuously fluctuating.

These recent techniques (micromotography, machine learning, automated particle velocimetry, computational fluid dynamics) are becoming commonplace in theoretical and applied studies of particle dynamics and engineering problems, however they await application on carbonate sediments. Once the simplified case of the settling of single carbonate grains in quiescent water is adequately understood, multiphase settling problems can be studied with numerous bioclastic particles falling together while interacting with one another (Wang et al., 2018). These issues are requirements for the ultimate future prospect of solving particle transportability problems of carbonate sediments, clarifying the relationship between settling velocity and shear velocity (Briguglio et al., 2017), suspension and saltation mechanisms (Fick et al., 2020), and the hydrodynamic behaviour of carbonate sediment concentrations in suspension (Hodson and Alexander, 2010).

In conclusion, the matter of the broad topic of carbonate-particle hydrodynamics, with settling behaviour at its showpiece, needs further integrated collaborations to be settled.

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Declaration of Competing Interest

The authors declare that there is no conflict of interest.

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Appendix A

Table 3

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<th>Symbol</th>
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<tr>
<td>A</td>
<td>Unspecified surface area.</td>
<td>m²</td>
</tr>
<tr>
<td>Aₐₑₐₜ</td>
<td>Surface area of the ellipsoid with axes equal to the three orthogonal axes of the particle Eq. (5).</td>
<td>m²</td>
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Table 3 (continued)

<table>
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<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
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<tr>
<td>$V_{\text{solid}}$</td>
<td>Volume of the solid fraction of the particle, thus excluding porosity.</td>
<td>m$^3$</td>
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<td>$\rho_{\text{porosity}}$</td>
<td>Volume of the porosity.</td>
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<td>$w$</td>
<td>General terminal settling velocity of particles.</td>
<td>m/s</td>
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<td>$\nu$</td>
<td>Dietrich (1982) settling velocity Eq. (23).</td>
<td>m/s</td>
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<td>$\nu_f$</td>
<td>Ferguson and Church (2004) settling velocity Eq. (23).</td>
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<td>$\nu_g$</td>
<td>Gibbs et al. (1971) settling velocity Eq. (20).</td>
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<td>$\nu_r$</td>
<td>Rubey (1933) settling velocity Eq. (19).</td>
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<td>$\nu_{\text{t}}$</td>
<td>Terminal settling velocity of spheres.</td>
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<td>$\nu_{\text{B}}$</td>
<td>Stokes (1851) settling velocity Eq. (17).</td>
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<td>$\nu_{\text{D}}$</td>
<td>Dimensional settling velocity Eq. (15).</td>
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<td>$\nu_{\text{Li}}$</td>
<td>Li et al. (2020) settling velocity Eq. (28).</td>
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<td>$\nu_{\text{Rai}}$</td>
<td>Raiiz et al. (2020) settling velocity Eq. (30).</td>
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<td>$\kappa$</td>
<td>Parameter for the calculation of the surface area of an ellipsoid Eq. (5).</td>
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<td>$\varphi$</td>
<td>Dynamic viscosity of the fluid.</td>
<td>Pa s</td>
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<td>$\nu_f$</td>
<td>Kinematic viscosity of the fluid.</td>
<td>m$^2$/s</td>
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<td>$\rho_f$</td>
<td>Density of the fluid medium, which is typically water.</td>
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<td>$\rho_{\text{particle}}$</td>
<td>Density of the particle. Definitions differ in the literature (Section 2.3).</td>
<td>kg/m$^3$</td>
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<tr>
<td>$\rho_{\text{solid}}$</td>
<td>Density of the solid fraction of the particle.</td>
<td>kg/m$^3$</td>
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<tr>
<td>$\rho_{\text{water}}$</td>
<td>Water density.</td>
<td>kg/m$^3$</td>
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References


