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Practical classification of geotechnically complex formations with block-in-matrix fabrics

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Abstract

The terms "bimrocks", "bimsoils" and "soil-rock mixtures" indicate different and very common types of geological units with a block-in-matrix fabric that are also "geotechnically complex formations" and are characterized by an internal heterogeneity, and spatial variability of mechanical parameters and lithological compositions. Due to this internal complexity, the understanding of their geomechanical behavior presents a key challenge in geotechnical engineering. However, the lack of a standardized and clear terminology complicates the discrimination of different types of complex formations and their internal mechanical properties, which leads to inconsistency in the literature and research studies. This inconsistency causes misunderstandings, with possible practical implications for the characterization, analysis, design and construction of engineering works. By a combination of geological and geotechnical observations, we propose a new classification for geotechnically complex formations, with particular attention to those with a block-in-matrix internal fabric. Four properties are at the base of this new classification and have a primary role in controlling the geotechnical behavior of block-in-matrix units (bimunits): (i) the composition (i.e., lithology, degree of lithification/consolidation, nature, and rheology) of blocks and the matrix that affects the water sensitivity, (ii) the degree of internal anisotropy (DA) of the block-in-matrix fabric, (iii) the degree of stratal disruption and mixing, and (iv) the volumetric block proportion (VPB). As a result, we classified bimunits in those with "anisotropic", "isotropic", and "mixed" (i.e., different behavior depending on the DA of the matrix) textures and, each of these types, into block-in-matrix rocks and block-in-matrix soils (bimrocks and bimsoils in the following). According to the water sensitivity of the matrix, bimrocks are also differentiated into "hard" and "soft". The novelty of the classification is that it is not limited to few types of geotechnically complex formations (e.g., flysch) but it can be easily applied to all field-based investigations of the different types of complex formations, regardless of their internal degree of stratal disruption, composition, and mechanical response to water sensitivity.

Keywords

Complex formation; block-in-matrix fabric; classification; bimrock; bimsoil; mélange

1. Introduction

At the scale of engineering works, geotechnically complex formations are rock units or soils that have lithological and/or structurally discontinuities with contrasting geomechanical properties (Barla and Perello, 2014; Cancelli, 1986; D'Elia et al., 1986; Harrison, 2014). Complex formations include mélanges, "argille scagliose"/scaly clays, flysch deposits, etc., which together form significant component of geomaterials worldwide. The most difficult complex formations to geotechnically characterize and model are those with block-in-matrix internal arrangements ("fabrics") because of the presence of hard blocks, ranging in size from centimeters to kilometers, with differing geologic natures (e.g., sedimentary, crystalline, igneous intrusive, volcanic, metamorphic, etc.), lithology, orientation, shape and rheology, which are embedded in a softer matrix of different composition (e.g., clay, mud, sand, etc.; see, e.g., Afifipour and Moarefvand, 2014; Gokceoglu and Zorlu, 2004; Kalender et al., 2014; Medley, 2001, 1994; Napoli, 2021; Napoli et al., 2021a, 2021c, 2021b, 2018; Tsesarsky et al., 2016). The high internal heterogeneity and compositional variability of block-in-matrix units ("bimunits" in the following), which is mainly due to the strong rheological contrast between blocks and the matrix, extends the geotechnical complexity over a wide spectrum of complex formations, ranging from rocks to soils, with a significant engineering and societal impact (Medley and Zekkos, 2011). Technical difficulties, delays, economic repercussions and health and safety risks have occurred at many engineering projects developed on complex formations (Goodman and Ahlgren, 2000; Lunardi et al., 2014; Medley, 2007, 2001). These difficulties have encouraged both private and public institutions to develop and fund several research projects all over the world during the 40 years (e.g., the Italian Research Council (C.N.R.) (D'Elia et al., 1998), the California Department of Water Resource's Division of Safety of Dams – DSOD, see (Lindquist, 1994a; Medley, 1994), the National Natural Science Foundation of China, see (Huang et al., 2021; Wang, 2014; Yang et al., 2019; Zhou et al., 2014), and the Alexander von Humboldt Foundation, see (Kahraman and Alber, 2008), to better understand the geotechnical behavior of heterogeneous formations with a block-in-matrix fabric.

A significant problem results from the inappropriate or loose use of the term "complex formation" to indicate a broad range of lithological units or complexes (e.g., mélanges, weathered rocks, conglomerates, agglomerates, flysch deposits, pyroclastites, olistostromes, breccias, fault rocks, etc.), all having very dissimilar fabrics and structural organization, composition and, therefore, rheological and geotechnical characteristics. In addition, different technical fields use various terms to indicate complex formations with mixed strong/weak rocks. For example, "Mixed Face Conditions" and "Soft Rock-Hard Rock" are commonly used in tunneling and mining, respectively. To overcome this problem, geopractitioners have introduced and widely used terms such as "bimrock" (Medley, 1994), "bimsoil" (Medley and Goodman, 1994) and "soil-rock mixture" (SRM; Xu et al., 2011) to indicate such heterogeneous formations. "Bimrock" is the acronym of "block-in-matrix rock", an extension of the geological term "block-in-matrix" which was introduced by Raymond (1984) to indicate chaotic rock units with hard blocks embedded within a softer matrix (i.e., the fabrics of mélanges). Medley (1994) defined a bimrock as "*a mixture of rocks, composed of geotechnically significant blocks within a bonded matrix of finer texture*". In this definition, the expression *"geotechnically significant blocks"* indicates that a sufficient mechanical contrast between competent blocks and weaker matrix must exist, and that both the volume and dimension of the hard inclusions influence the rock mass properties at the scales of engineering interest (which range between centimeters and hundreds of meters). Medley (1994) introduced the acronym "bimsoil" (block-in-matrix soil) for geological units with rock blocks embedded in a soil-like matrix (Kalender et al., 2014; Medley and Goodman, 1994; Sonmez et al., 2016). Heterogeneous and loose deposits with hard blocks embedded in a fine-grained soil matrix, such as colluvial and debris flow deposits, have also been defined “soil-rock mixtures” (SRM) (Gong and Liu, 2015; Xu et al., 2011; Yang et al., 2019; Zhang et al., 2020) or “rock and soil aggregates” (RSA) (Li et al., 2004). “Bimrocks” have been subdivided into “welded” and “unwelded” (Kalender et al., 2014; Khorasani et al., 2019b; Sonmez et al., 2009), according to the strength of the blocks-matrix interface. Specifically, the strength of interfaces between blocks and matrix is approximately equal to that of the matrix for welded bimrocks, while the strength is lower than that of the matrix for unwelded bimrocks. However, it can be extremely difficult to estimate the strength of block-matrix interfaces of a bimunit before ascribing it to the welded or unwelded category.

Although very helpful, the different non-geological expressions mentioned above may indicate deposits with highly dissimilar geological, lithological and structural features and, therefore, different geotechnical behaviors. As a result, the use of those terms does not allow easy comparison with the terminology used by geologists in both research and geological maps/documents and confuses the interpretation of results from geotechnical research. Hence, the possibility of using and/or improving the approaches developed in previous studies of other authors is quite difficult. The main risk is that the research has an end in itself, resulting not useful for improving knowledge of geoscientists and engineers on this complex but fundamental issue.

To better and easily distinguish among different types of bimunits with dissimilar geotechnical characteristics, a new classification of complex formations, linking geological and geotechnical terminology, would provide a useful tool for easier and practical geotechnical evaluations of both field-observations and information synthetized in geological documents (i.e., maps, technical notes, etc.).

The aim of this paper is to propose such new and practical classification of complex formations with block-in-matrix fabrics.

After a short description of existing classifications of complex formations (Section 2), we overview the geological terminology for bimunits, comparing it with the geotechnical one (Section 3). We then present a new classification (Section 4) with the aim to reduce the gap between geotechnical/engineering and geological observations, and thus improving the existing geotechnical classifications and facilitating the link between information provided by geopractitioners with different backgrounds and experiences with geological complexity.

2. Previous classifications of complex formations

Only a few classifications have been proposed to define and describe in a simple way the main characteristics of geotechnically complex formations (Esu, 1977; Marinos and Hoek, 2001; Marinos, 2019; Nikolaidis and Saroglou, 2016). Esu (1977) proposed a descriptive classification (Fig. 1), subdividing complex formations into three main groups, differing from each other by their degree of internal heterogeneity and stratal disruption. The first group (group "A") includes coherent sedimentary (rock) units, ranging from layered and well-bedded deposits to sheared ones. The second group (group "B") includes sedimentary (rock) units with different degree of stratal disruption, ranging from fissured ordered deposits (i.e., well-bedded; Sub-group "B1") to chaotic rock units with a block-in-matrix fabric (Sub-group "B3"), in which blocks are embedded in a softer and sheared matrix. The last group (group "C") includes highly heterogeneous sedimentary units, consisting of fragments of weathered rocks embedded in a clayey matrix (e.g., residual and colluvial soils; see Fig. 1). The different subdivisions of Group "B" appear to be organized to represent the gradual disruption of an originally well-bedded lithostratigraphic unit, to an end condition of sub-group "B3" with blocks that represent fragmented beds resulting from the dismemberment of the previously coherent stratigraphic unit. The label to "residual and colluvial soils" for the Group "C" (Fig. 1) suggests that blocks formed by weathering of the parent rock and surficial gravity transport (colluvium, landslides, etc.), respectively. Overall, the classification of Esu (1977) seems not to consider the wider range of complex formations that have blocks whose source is not present in the surrounding lithological units within a complex formation zone, and which are different from any lithology found in surrounding country rocks (i.e., mélanges). Such blocks are "exotic" blocks according to the current geological terminology (see also below Section 3.1).

Marinos and Hoek (2001) proposed a quantitative classification of complex formations, later extended by Marinos (2019) (Fig. 1). The Geological Strength Index (GSI) of the Rock Mass Classification System was used with the Hoek-Brown failure criterion (Hoek, 1994) (with associated m, s, and a parameters), so that rock mass strength could be predicted for both "normal" and some types of heterogeneous "complex" formations (e.g., flysch deposits). Although this classification covers a wide range of complex geomaterials, most of those with a block-in-matrix internal arrangement (e.g., mélanges) are not taken into consideration.

Nikolaidis and Saroglou (2016) proposed an approach for the characterization of complex formations with a block-in-matrix fabric, based on six parameters (i.e. linear block proportion, bimrock strength, matrix complexity, block classification, bimrock complexity and orientation of blocks) that can be straightforwardly assessed in the field. The authors also analyzed a case study~~,~~ outlining that an appropriate characterization of block-in-matrix materials requires a significant appreciation of geology.

Hence, to date, a new classification system is necessary, that accounts for the engineering geological conditions and geotechnical behavior of complex formations with a block-in-matrix internal arrangement and facilitating their link with geological observations.

3. Linking geological and geotechnical terminology for bimunits

Geotechnical and engineering works on complex formations investigate, interpret and model geological units. Rock units like mélanges, weathered rocks, conglomerates, agglomerates, flysch deposits, pyroclastites, olistostromes, breccias, fault rocks, and several others, are generally categorized as "geotechnically" complex formations even if most of them are not considered complex formations from the geological point of view (Anagnostou et al., 2014; Barla and Perello, 2014). In addition, those rock units represent different geological deposits, with dissimilar internal organization, composition, rheology, size of blocks and, therefore, different mechanical/geotechnical characteristics. Hence, to avoid confusion and misunderstanding between geological units, in the following (see Section 3.1 for details) we clarify the geological terminology related to "complex formations" with a block-in-matrix fabric (i.e., the "chaotic rock units" of geologists), also providing information on their internal fabric, block size and distribution, which are significant for geotechnical characterization. We use the general term bimunits because it includes both bimrock and bimsoil complex formations.

3.1. Bimunits: mélanges and broken formations

Although the term "complex formation", not to be confused with the terms "complex" and "formation" used separately (see NACSN, 2005 for details), has not a specific identity in geology, it may be used, at least in part, as a synonym or alias for of a wide range of "chaotic rock units" whose complexity is due to their internal block-in-matrix fabric, which differs from that of coherent and/or well-bedded units (see, e.g., Berkland et al., 1972; Raymond, 1984; Silver and Beutner, 1980; for details). The general and non-genetic term "chaotic rock units" (Fig. 2) includes broken formations and mélanges (see below), which represent the product of stratal disruption and mixing of primary coherent lithostratigraphic units, acting by tectonic, sedimentary (gravitational) or diapiric processes and their interaction (see, e.g., Festa et al., 2010; Raymond, 1984; Silver and Beutner, 1980; for details). In geology, the term "mélange" (Greenly, 1919) is a descriptive and non-genetic term, defining a mappable (at 1:25,000 or smaller scale) body of internally disrupted and mixed rocks, with "exotic" lithologies (Figs. 2 and 3G-I) included as discrete masses (i.e., blocks) in a pervasively deformed finer matrix, without restriction to any particular lithological unit (e.g., Berkland et al., 1972; Cowan, 1985; Raymond, 1984; Silver and Beutner, 1980). The term "exotic" includes all types of blocks that are "foreign" with respect to the matrix of a mélange (see Hsü, 1968; Festa et al., 2012). Hence, their source is not present in the surrounding lithological units within a mélange zone, and they are different from any lithology found in country rocks (see Festa et al., 2019 for a complete discussion). Notable examples of "exotics" are, among several others, blocks recording different metamorphic degrees (i.e., different Pressure-Temperature, P-T, conditions) embedded in a non-metamorphosed matrix such as in the Franciscan Complex in California (e.g., Cloos, 1982; Raymond, 2019; Wakabayashi, 2021), mixed blocks of mantle rocks (serpentinite, gabbro and basalt), granitoids, chert and limestone embedded in a clay matrix such as in the Ligurian Units in Northern Apennines (e.g., Barbero et al., 2020; Bettelli and Panini, 1987; Elter and Raggi, 1965; Marroni et al., 2010;), in the Dinaric-Hellenic orogenic belt (e.g., Bortolotti et al., 2013 and references therein), and in the Valmala Shear Zone in the Western Alps (e.g., Balestro et al., 2020). On the other hand, the geological term "broken formation" (Hsu, 1968) is used to define a disrupted rock unit, with a block-in-matrix fabric, that contains no "exotic" blocks but only "native" ones (Figs. 2 and 3D-F). "Native" blocks are "intraformational" components originated only from the disruption of a primary lithostratigraphic unit (Figs. 3A-C). Therefore, a "broken formation" differs from a "mélange" because it preserves its lithological and chronological identity (e.g., Festa et al., 2020, 2022; Hsü, 1968; Pini, 1999; Raymond, 1984; and references therein). Broken formations commonly show a gradual transition from to the coherent, well-bedded, primary succession to the highly disrupted block-in-matrix fabric (Figs. 2 and 3A-F).

Notable examples are represented by the *Argille scagliose* or *Argille varicolori* (Varicolored scaly clays) of the Ligurian Units in the Northern Apennines (e.g., Bettelli et al., 2004; Festa et al., 2013; Pini, 1999), the *Flysch Rosso* on the Southern Apennines (e.g., Vezzani et al., 2010), the Taconic flysch or Taconic mélange in the Northern Appalachians (e.g., Kidd et al., 1995), the chaotic rock units in the Shimanto belt in Japan (e.g., Kimura et al., 2012), in the US-Western Cordillera (e.g., Cowan, 1985; Hsü, 1968; Raymond, 1984, 2019), in the McHugh complex in Alaska (e.g., Fisher and Byrne, 1987), and in the Torlesse accretionary wedge in New Zealand (e.g., Barnes and Korsh, 1991; Sunesson, 1993) among several others. Importantly, disrupted, or dismembered flysch deposits without "exotic" blocks included, correspond to "broken formations" and not to "mélanges" (see, e.g., Ogata et al., 2021). The heterogeneous to block-in-matrix complex formations classified by Esu (1977), Marinos and Hoek (2001), and Marinos (2019) represent, therefore, typical broken formations (i.e., without "exotic" blocks), which are differentiated according to their degree of stratal disruption. Those different degrees of stratal disruption (i.e., Groups "B1" to "B3" of Esu, 1977; and Types VIII to XI of Marinos, 2019) are well comparable, in fact, with those described in geology (Fig. 2), ranging from stratigraphic units with locally broken internal stratal continuity to rock bodies without internal stratal continuity or exotic blocks (see, e.g., Raymond, 1984). Hence, those classifications do not consider mélanges, which represent the most complex type of bimunits (Fig. 2), nor take in considerations that mélanges and broken formations have very different block-matrix interface strength (e.g., Festa et al., 2019, 2022; Ogata et al., 2021 and references therein), strongly affecting their sampling, characterization, mechanical behavior and modeling.

From the geological point of view, other types of heterogeneous units (e.g., weathered rocks, conglomerates, agglomerates, pyroclastites, etc.), which could be regarded as geotechnically complex formations, exclude broken formations or mélanges in strict sense (see, e.g., Festa et al., 2012).

3.2. Internal organization of different types of bimunits

A significant aspect of complex formations (i.e., mélanges and broken formations), which is well-known in geology, is that their block-in-matrix fabric differs in relation to the process of their formation (i.e., tectonic, sedimentary or diapiric; e.g., Festa et al., 2010, 2019 and references therein, see Fig. 2). Those dissimilar internal fabrics (Fig. 2), with different shapes and distributions of blocks, have a significant control on the mechanical behavior of chaotic rock units and fluid migration, as documented for example for seismic rupture propagation (e.g., Bürgmann, 2018; Cerchiari et al., 2020; Fagereng and Sibson, 2010; Festa et al., 2018), and therefore significant geotechnical implications, such as different failure modes according to the shape and orientation of rock blocks (Huang et al., 2021; Khorasani et al., 2019a; Napoli et al., 2021b, 2019) and associated fabrics.

Tectonic mélanges and tectonic broken formations are characterized by a scale-independent repetition of a “structurally ordered” block-in-matrix fabric (Figs. 2 and 3), which defines a planar anisotropic texture (e.g., Festa et al., 2019; Pini, 1999). Scale independence means that the appearance of the rock mass is similar regardless of the scale of observations - for example: a few large blocks and a multitude of smaller and smaller blocks. Although the shape and arrangement of blocks may vary depending on physical factors acting in the original tectonic deformational setting (e.g., fluid pressure, pressure, temperature, mineral transformation, etc.), rheological proprieties, deformational mechanism (e.g., brittle versus plastic deformation), consolidation and lithification degrees, and strain rate, they commonly range from lenticular (Figs. 3B and 3G) to sigmoidal (Figs. 3E, 3F and 3H) or elongated (Fig. 3D) with a mean aspect ratio (i.e., long axis/short axis) ranging from between 2.8 and 4.1 (tectonic mélanges) and 3.9-4.5 (tectonic broken formations) (Figs. 4A and 4D), and with their long axis aligned to the main shear zones (Figs. 3D-3I) in which they formed (see Festa et al., 2019 for details).

Tectonic mélanges and broken formations can be considered structurally equivalent to mappable fault or shear zones (e.g., Cowan, 1974). Broken formations roughly correspond to Types X and XI of Marinos (2019), and in part to group B2 of Esu (1977). Blocks may range in size from centimeters to hundreds of meters (Fig. 3), depending on the thickness of the shear zone in which they formed and the magnitude of the tectonic strain during shearing. The matrix of both tectonic mélanges and broken formations is commonly deformed to a typical scaly fabric formed by anastomosing polished surfaces (Fig. 3E), spaced millimeters to centimeters apart (e.g., Bettelli and Vannucchi, 2003; Pini, 1999; Vannucchi and Bettelli, 2010). On the whole, the alignment of lenticular to sigmoidal blocks and the scaly fabric defines the planar anisotropy (i.e., transversal isotropy; Fig. 3). Notable examples occur in the Franciscan Complex in California (e.g., Cloos, 1982; Wakabayashi, 2012), the Ligurian Units in the Northern Apennines (e.g., Bettelli et al., 2004; Festa et al., 2013;

Marroni et al., 2010;Pini, 1999; Remitti et al., 2007), the Shimanto belt in Japan (e.g., Kimura et al., 2012).

Sedimentary (i.e., gravitational) mélanges (or olistostromes) correspond to different types of heterogeneous mass transport deposits, ranging from submarine debris flow, block flow, slide and slumps (see, e.g., Ogata et al., 2019, 2020; Pini et al., 2012). The block-in-matrix fabric of sedimentary mélanges and broken formations (or endolistostromes *sensu* Elter and Raggi, 1965), strongly contrasts with that formed by tectonic processes (Fig. 2). Independent of the scale of observation, they are characterized by a highly disordered block-in-matrix arrangement (Figs. 2 and 3) with blocks of different shape (e.g., irregular to equiangular, depending on their lithology), lithology, age, size (e.g., from centimeters to hundreds of meters up to a few kilometers), floating with a random distribution in a finer grained matrix (see Festa et al., 2016, 2019 for details). The random distribution of blocks and the brecciated texture of the matrix define an isotropic texture at all scales (Figs. 2, 5A, 5B, 5F). The mean aspect ratio (long axis/short axis) of blocks ranges between 1.4 and 2.5 (see Festa et al., 2019 for details; see Figs. 4B, 4D). The matrix is commonly fine-grained, ranging from clay to shale, and includes angular-to rounded clasts, sub-millimeters to millimeters in size (Figs. 2 and 5A, 5D). Sandstone matrix, as well as matrix composed of ultramafic-rich arenites and rudites, consisting of serpentinite clasts, may also occur (Fig. 5B). It is not uncommon that the matrix of ancient sedimentary mélanges is affected by a planar anisotropy related to lithostatic or tectonic loading, or later tectonic reworking (i.e., polygenetic mélanges in Fig. 2; see Festa et al., 2020 for details) of the block-in-matrix fabric (Figs. 5D, 5E, 5I). Therefore, depending on the degree of anisotropy of the matrix, they may have a mixed texture, ranging from isotropic to anisotropic. In addition, the base of sedimentary mélanges and broken formations, which is commonly erosional, may be characterized by an anisotropic shear zone decimeters thick (Figs. 2 and 5) closely resembling those formed by tectonic mélanges but with a brecciated matrix (see Festa et al., 2016, Ogata et al., 2019 for details).

There is not a direct correspondence with the classifications of Esu (1977), Marinos and Hoek (2001) and Marinos (2019) as group “C” of Esu (1977) represents “residual and colluvial soils” rather than mass transport deposits. Notable examples of sedimentary mélanges and gravitational broken formations are the Makran olistostrome in Iran (e.g., Burg et al., 2008), the Val Tiepido-Canossa and the Baiso argillaceous breccias in the Northern Apennines (e.g., Bettelli et al., 2004; Festa et al., 2015, 2020; Pini, 1999; Remitti et al., 2011), the Specchio mass transport complex (e.g., Ogata et al., 2014a) and those in the Marnoso-Arenacea foredeep deposits (e.g., Lucente and Pini, 2008; Pini et al., 2020) in Northern Apennines, the mass transport deposits associated with the Hikurangi margin in New Zealand (e.g., Clausmman et al., 2021a, 2021b), the Lichi mélange in Taiwan (e.g., Lai et al., 2021), and the Porma mélange in Northern Spain (e.g., Alonso et al., 2015). Several of those examples may cover wide sectors up to several tens of thousands square kilometers (see Festa et al., 2016 and Ogata et al., 2020 for a complete review).

Diapiric mélanges and broken formations are characterized by a distribution of the block-in-matrix fabric which shows internal zoning from margins to the core of the diapir (e.g., Codegone et al., 2012; Dela Pierre et al., 2007; Orange, 1990; see Figs. 2 and 5J-5K). Close to the margins (i.e., close to the intrusive contacts with the country rock), the fabric commonly shows a sub-vertical trending with phacoidal to tabular blocks, embedded within a fine-grained (shaly or clay) matrix, pervasively deformed by scaly fabric, and aligned to the intrusive contacts (Figs. 2 and 5K, 5L). The clustering of blocks and the pervasiveness of the scaly fabric gradually decrease toward the center of the diapiric body where blocks, which are larger in size (i.e., up to tens of meters), are commonly angular, loosely clustered, and randomly distributed within a non-foliated, and irregularly folded, matrix (Figs. 2 and 5J). The main aspect ratio of blocks (long axis/short axes) decreases from 2.9 and 3.8 to 1.6 and 3.2 from the marginal zone to the center of the diapiric body, respectively (Figs. 4C, 4D). The alignment of both blocks and the scaly fabric to the intrusive margins defines a planar anisotropy, which gradually passes to a partially isotropic texture toward the center of the diapir (Fig. 2). Although formed by a different process, part of the block-in-matrix fabric of diapiric mélanges and broken formations resembles Types VII, VIII, X and XI (compare Figs. 1 and 2) of Marinos (2019), and groups B2 and B3 of Esu (1977). Notable examples occur in the Olympic Peninsula in the US-Cordillera (e.g., Orange, 1990), in the Myanmar (e.g., Moore et al., 2019), in East Timor in Indonesia (e.g., Brown, 2013 and reference therein), in the Northern Apennines (e.g., Codegone et al., 2012; Dela Pierre et al., 2007; Festa, 2011).

All the above examples show that the geological distinction between the different types of mélanges and broken formations, as well as between “exotic” and “native” blocks, are fundamental to distinguish geological units with very different internal block-in-matrix organization, composition, rheological characteristics, degree of anisotropy and, therefore, with different shape of blocks, strength, stiffness, and permeability values. Therefore, they must be classified separately.

4. Geological-constrained classification of geotechnically complex formations

Our overview of the geological terminology for complex formations (see Section 3.1) shows that they consist of different types, differing in their internal block-in-matrix fabric (i.e., anisotropic vs. isotropic texture), composition, rheology and, therefore, mechanical, and geotechnical behavior. Although very useful, the general terms “bimrocks”, “soil-rock mixtures”, “bimsoils” and “rock and soil aggregates” do not allow distinguishing among geomaterials with different geotechnical characteristics, nor linking geological information/terminology used in geological maps and documents to a geotechnical significance. Geological maps with their codified terminology represent, in fact, the main document consulted in planning engineering works, thus suggesting that a common terminology between geologists and engineers is necessary in describing complex formations. The lack of a common vocabulary to describe those heterogeneous geomaterials complicates popularization of scientific results, strongly diminishing the benefit for all researchers interested in this topic. Approaches and methodologies developed in the engineering literature for specific complex formations can be incorrectly applied by researchers and geopractitioners to characterize bimunits with completely different characteristics, causing wrong interpretations with possibly significant practical implications. For instance, the scale-independent properties of some mélanges in the Franciscan Complex in California (Medley, 2004, 1994), although common to many bimrocks, cannot be successfully applied to all block-in-matrix geomaterials (e.g., conglomerates, disrupted flysch deposits, diamicton deposits, etc.).

In order to address these issues, in the following we propose a new classification of geomaterials with a block-in-matrix fabric (see Section 4.2), with the aim of reducing the terminological and practical gap between geologists and engineers and provide a useful tool for all geopractitioners and researchers working in the broad field of geotechnically complex formations. The novelty of this classification is that the close relation with geological observations (and terminology) requires the evaluation of four main properties (see Sections 4.1) that play a significant role in distinguishing bimunits with different geotechnical characteristics.

4.1. Properties controlling geotechnical behavior of complex formations

The first property taken into consideration is the composition of blocks and the matrix. Depending on their lithology (e.g., quartzite, limestone, marlstone, claystone, volcanic rocks, etc.), nature (e.g., metamorphosed or non-metamorphosed), degree of lithification/recrystallization, and rheological contrast between blocks and the matrix, complex formations have different mechanical contrast between blocks and matrix (Kahraman and Alber, 2008; Medley, 2001) and different strength of the block/matrix interface (e.g., welded vs unwelded *sensu* Sonmez et al., 2009), which strongly influence the geotechnical characteristics. Their mechanical behavior also changes in the presence of additional factors, such as pressure, temperature, fluid pressure, strain rate, and fluid/water content. Particularly, depending on the lithology and mineralogy, complex formations are differently sensitive to water. This is quite evident in comparing, for example, a complex formation consisting of serpentinite blocks embedded in a micaschist matrix and one of limestone blocks embedded in a marly matrix.

The second parameter taken into consideration is the degree of anisotropy (DA). The internal block-in-matrix fabrics of complex formations show different DAs, depending on the processes of their formation (tectonic, sedimentary or diapiric) and/or superposition and interaction of processes as described in Section 3. The DA, which may range, for example, from the anisotropic texture of tectonic mélanges and tectonic broken formations (Fig. 3), as well as that one of the marginal zone of diapiric bodies (Figs. 5K and 5L), to the isotropic one of most of sedimentary mélanges (or heterogeneous mass transport deposits) and the core zone of diapiric bodies (Figs. 5A, 5B, and 5J), strongly influences the mechanical behavior of complex formations. It may control fractures propagation, fluid migration, fluid overpressure, seismic rupture propagation, etc., as documented in both geological and geotechnical literature (e.g., Bürgmann, 2018; Fagereng and Sibson, 2010; Festa et al., 2018; Khorasani et al., 2019a; Napoli et al., 2021b). Importantly, the development of a planar anisotropy in the matrix of sedimentary mélanges (olistostromes or heterogeneous mass transport deposits) may change the DA depending on the pervasiveness of planar surfaces (see Sections 3.2 and 4.2; see Figs. 5C-5E).

The third parameter taken into consideration is the degree of internal disruption and dismemberment of complex formations, ranging from coherent units to different types of bimunits (i.e., broken formations, and mélanges). Coherent units represent lithostratigraphic or lithological units in which their primary internal organization (e.g., beds, layers) is well preserved (Figs. 2 and 3B). Non- to poorly deformed (but not disrupted) flysch deposits, consisting of alternating of layers/beds with different competence, represent the most common example of coherent complex formations (Fig. 3B). Broken formations represent the progressive disruption and dismemberment of a primary coherent complex formation or a lithostratigraphic unit characterized by beds/layers with internal contrasting competence, such as, for example, flysch deposits. They can range from slightly disrupted formations (Figs. 3B-D), in which a roughly continuity of primary layers/beds is still present, to "native" blocks completely isolated within the matrix (i.e., without any layering/bedding-continuity preserved; see Section 3.1; see Figs. 3E and 3F). On the other hand, mélanges represent the mixing of "exotic" blocks (i.e., their source is not present in the surrounding lithological units within a mélange zone (Figs. 3G-I), and they are different from any lithology found in country rocks; see Section 3.1).

The last parameter is the "Volumetric Block Proportion" (VBP). As well documented in the literature, the presence of rock blocks does not affect the overall behavior of geotechnically complex formations if their VBP is lower than about 10%-25%. On the contrary, geomaterials with block contents ranging between 25% and 75% show markedly greater strength and stiffness, higher safety factors, and more tortuous failure surfaces than those of the matrix alone, depending on the VBPs (Khorasani et al., 2019a; Lindquist, 1994a; Medley, 1994; Napoli, 2021; Napoli et al., 2019; Wang et al., 2020). When the VBP is greater than about 75% the geomaterial can be treated as blocky rock mass (Medley, 2001; Sonmez et al., 2009). As a practical matter, the estimation of VBP for in-site masses is a daunting task, depending on field measurements of point (PBP), linear (LBP) or areal block proportions (ABP). These lower order measures will almost never equal the VBP. Hence, they must be adjusted by uncertainty factors to estimate realistic VBP ranges (Medley, 1997; Napoli et al., 2020; Ramos-Cañón et al., 2020).

4.2. Classification of complex formations

The introduction of the above-described properties allow modifications of previous classifications of bimunits. We here propose a new scheme (Fig. 6), which is intended to (i) better discriminate complex formations with different geotechnical characteristics, (ii) link them with geological observations and terminology, and (iii) provide an easy and practical field-application guide based on objective descriptive observations.

We subdivide complex formations into anisotropic (A), isotropic (I), and mixed (M) bimunits (Fig. 6), because the qualitative degree of anisotropy (DA) is an observable property, common to both geologists and engineers. Each of these three types of bimunits show different geotechnical characteristics according to (i) the composition and nature of blocks and the matrix that affects the water sensitivity over a short period (Hard bimrocks, Soft bimrocks and Bimsoils in Fig. 6), (ii) the degree of stratal disruption and mixing (from 1 to 6, from the lowest to the highest, respectively, in Fig. 6), and (iii) the VBP (high – H, or low – L, in Fig. 6). In Figure 6, the combination of abbreviations used for those different parameters defines specific labels, each of which identifies a different type of geotechnically complex formation in the new classification. The first capital letter of each acronym is referred to the degree of anisotropy (e.g., A, I or M) of the bimunit; the number corresponds to the degree of internal disruption (from 1 to 6, from the lowest to the highest, respectively), and the last two lower case letters indicate the VPB (i.e., L or H) (see also the "acronyms index" at the bottom of Fig. 6).

The classifications are described in detail below.

4.2.1. Anisotropic complex formations (DA=A)

Complex formations with anisotropic textures (Fig. 6) are characterized by different mechanical/geotechnical properties in different directions and are easily recognized by geological, geotechnical and geophysical observations. Independently of the degree of stratal disruption (i.e., from 1 to 6 in Fig. 6), the occurrence of a planar anisotropy characterizes different types of complex formations, ranging from coherent ones to those with a block-in-matrix fabric (i.e., broken formations and mélanges; compare Figs. 3A-I). In coherent complex formations, such as non- to poorly deformed flysch deposits, the anisotropy is defined by alternating layers and/or beds (e.g., Hard bimrocks A1L and A1H, and Soft bimrocks A1L and A1H in Fig. 6) with different competence and rheology (e.g., alternating of sandstone and mudstone, limestone and claystone, etc.). With the increase (from 1 to 6 in Fig. 6; see also Fig. 3B) of disruption and dismemberment (e.g., tectonic faulting or diapiric rising along intrusive contacts), the planar anisotropy is defined by the alignment of elongated (i.e., tabular, lenticular, sigmoidal, etc.) "native" bed fragments/blocks, grading to a block-in-matrix fabric (e.g., Hard bimrocks from A1L to A6L in Fig. 6). The genetic deformational mechanisms can range from brittle to plastic depending on the Pressure-Temperature (P-T) conditions and consolidation/lithification degree of the rock unit, which were acquired during burial (e.g., subduction processes). As explained above (see Section 3), the different degrees of stratal disruption represented by broken formations is well documented in sheared or deformed flysch deposits (see Figs. 3D-F), independently of the deformational process (i.e., tectonic, gravitational or diapiric). Notable examples are the *Flysch Rosso* (Red beds) in the Southern Apennines (e.g., Vezzani et al., 2010), the *Argille scagliose* or *Argille varicolori* (Varicolored scaly clays) of the Northern Apennines (e.g., Bettelli et al., 2004; Coli and Tanzini, 2013; D'Elia et al., 1998; Festa et al., 2013; Pini 1999), the Taconic Flysch in the US-Appalachians (e.g., Kidd et al., 1995), as well as most of stratigraphic successions consisting of alternating beds with different competence and rheology (e.g., sandstone and marls, limestone and claystone, etc.).

Although mélanges represent a common component of many geomaterials around the world, they are not included in previous classifications (e.g., Esu, 1977, Marinos and Hoek, 2001, and Marinos, 2019), nor differentiated from those with a very different (isotropic) block-in-matrix fabric (see below). Mélanges represent the highest degree of internal dismemberment of complex formations with anisotropic textures, as well as related mixing processes which incorporate "exotic" blocks into the matrix. They must be classified separately from broken formations (see Fig. 6) because the "exotic" nature of blocks has a significant practical implication on the geotechnical behavior of mélanges. For example, when excavating in heterogeneous ground, blocks of lithologies different from that of the matrix may produce high strain and stress in tunnel linings, more rapid wear of cutters, and damage to the cutting tools and/or mucking system. In a broken formation the range of block/matrix interface strengths of a single block/matrix couple is likely to be within some range of other block/matrix couples, at same alteration and deformation conditions. This is due to the "native" nature of blocks (i.e., blocks and matrix derive from the dismemberment of the same coherent unit, see Figs. 3B-D). On the contrary, the occurrence of “exotic” blocks (i.e., lithotypes that are not present in the surrounding of the complex formation, see Fig. 3G-I), commonly differing one to each other in composition, rheology, nature (e.g., metamorphic vs sedimentary rocks) and size (from decimeters to tens or hundreds of meters), suggests different ranges of block/matrix interface strengths within a mélange, preventing their predictability (Fig. 3I). However, it is important to outline that in some cases it is possible to unexpectedly encounter exotic blocks (e.g., a huge block of crystalline or metamorphic rock) within a broken formation. This may occur, for example, in cases in which broken formations are interfingered by mass transport deposits (i.e., sedimentary mélanges or olistostromes), sourced from lithological units exposed outside of the depositional basin (e.g., the wildflysch Auct., see Festa et al., 2016 and references therein). Therefore, geological observations (i.e., field mapping and information from geological maps) are fundamental in correctly evaluating the geotechnical characteristics of each type of complex formation and the possibility to encounter unexpected “exotic gifts”.

A wide range of complex formations with anisotropic texture may also show different geotechnical behaviors depending on their composition, degree of lithification/consolidation, and change of physical conditions and external factors (e.g., pressure, temperature, water content, etc.), resulting in a transitional condition between bimrocks and bimsoils. Therefore, we differentiate bimrocks into “hard” and “soft” types (compare, e.g., Hard bimrock A5L and Soft bimrock A5L in Fig. 6) to outline this important aspect. Hard bimrocks include both metamorphic and non-metamorphic complex formations, which are well lithified/consolidated, with blocks bonded with the matrix (e.g., “welded bimrocks”, see Avşar, 2021; Afifipour and Moarefvand, 2014; Kalender et al., 2014; Mahdevari and Maarefvand, 2017; Sonmez et al., 2009). They are relatively insensitive to changes of physical conditions and external factors over a short period (i.e., from hours to months) such as, for example, those induced by the abrupt increase of water content due to rain, flooding or water accumulation during excavations. These changes do not significantly change the volume and state of the matrix, nor the strength of the block and matrix interface.

Soft bimrocks mainly consist of poorly consolidated/lithified sedimentary units (e.g., marl, clay, sand, etc.). Although blocks are bonded with the matrix, they become unbonded when subjected to changes of physical conditions and external factors over a short period (i.e., from hours to months), because of the decreased strengths of both the matrix and the block/matrix interfaces. For example, dissolution and slaking processes due to the presence of water can weaken the matrix depending on its mineralogical composition (e.g., carbonate content), chemical bonding state in the grain boundaries, and internal structure (e.g., occurrence of foliation, layering, cleavages, fractures, etc.). This water-sensitive weakening behavior greatly affects the choice of the site exploration and sampling techniques, preparation of intact specimen processes, laboratory testing equipment to be used, testing procedures and, of course, test results. Under these conditions, soft bimrocks have a mechanical behavior which is transitional between hard bimrocks and bimsoils (Fig. 6).

Bimsoils are not classified within complex formations with anisotropic texture because they are commonly characterized by a primary isotropic fabric (Figs. 6 and 5G, 5H). However, considering that an anisotropic texture may occur in particular cases (e.g., translation of some glacial deposits, lithostatic or tectonic loading), overprinting the isotropic one (Figs. 6 and 5I), we classified this type of bimsoils as those with mixed texture (see below Section 4.2.3).

Considering that the VPB may strongly influence the mechanical behavior of all complex formations (see Section 4.1), including those with anisotropic texture, they are also differentiated in those with low (L) and high (H) VPBs (e.g., compare Hard bimrocks A5L and A5H in Fig. 6). In the former, the VBPs are lower than about 15%-25% and the influence of the blocks is negligible in controlling the geotechnical behavior of the bimunits. Therefore, from a geotechnical point of view, the low-VBP block-in-matrix geomaterials can be considered to be homogeneous by neglecting the blocks during characterization and modeling (they must be remembered for the benefit of excavators and tunnelers, though). On the contrary, when the bimunits have VBPs ranging from about 25% to 75% (when the VBP is higher than 75% the geomaterial can be treated as blocky rock mass and, therefore, cannot be considered a complex formation) the blocks significantly to markedly affect their strength and failure mode (Lindquist, 1994b; Medley and Sanz Rehermann, 2004; Napoli, 2021; Napoli et al., 2019, 2021b). Therefore, these latter formations should be analyzed and modelled by means of heterogeneous-stochastic approaches, to take into account the inherent variability of bimunits. This is true also for complex formations with both isotropic and mixed (anisotropic/isotropic) textures, described below in Sections 4.2.2. and 4.2.3, respectively.

4.2.2. Isotropic complex formations (DA=I)

Complex formations with an isotropic block-in-matrix texture have the same mechanical/geotechnical behavior in all directions. Unlike anisotropic formations, they do not include coherent complex formations (Fig. 6) because their internal arrangement is always characterized by a block-in-matrix fabric (i.e., sedimentary broken formations and mélanges, conglomerates, diamicton deposits, etc.), which commonly formed through mass wasting processes or weathering of rock masses with a primary isotropic texture (Figs. 5A, 5B and 5G, 5H). However, isotropic bimrocks may also form in the central part of diapiric bodies (see Section 3.2). The isotropic texture is governed by the random distribution of blocks (see, e.g., Hard bimrock I5H in Fig. 6), ranging from irregular to equiangular depending on their lithology (e.g., Festa et al., 2016 and references therein), within a softer matrix (Figs. 5A, 5B and 5G, 5H).

As explained above (see Section 4.2.1), the occurrences of "native" vs. "exotic" blocks also have significant geotechnical and practical implications for the evaluation of the internal geomechanical characteristics of isotropic bimunits. Unlike for "native" blocks of broken formations, the mechanical characteristics of "exotic" blocks are difficult to be predicted because they were wrenched from rock masses that are no longer present in the surrounding country rock of the complex formation (see, e.g., Hard bimrock I6L in Fig. 6). In addition, the size of "exotic" blocks may be highly variable, ranging from centimeters to hundreds of meters (Fig. 5F). This implies that huge blocks (i.e., olistoliths) may be scattered distributed within a complex formation (see, e.g., Hard bimrock I6L in Fig. 6), which mainly consists of smaller (centimeters to decimeters) blocks embedded in a matrix. This is the case of many sedimentary mélanges (e.g., heterogeneous mass transport deposits, see Festa et al., 2016; Ogata et al., 2019, 2020; Pini et al., 2012;) throughout the world. Notable examples are the Casanova Complex in the External Ligurian Units of Northern Apennines (e.g., Elter et al., 1991; Marroni et al., 2010), the Val Tiepido – Canossa and Baiso argillaceous breccias in the Northern Apennines (e.g., Bettelli and Panini, 1985; Festa et al., 2015, 2020; Panini et al., 2002; Remitti et al., 2011;), the Porma mélange in the Cantabrian Region in Northern Spain (e.g., Alonso et al., 2015), the Makran olistostrome in Iran (e.g., Burg et al., 2008), the carbonate mass transport deposits of the Paleogene Julian-Slovenian basin (e.g., Ogata et al., 2014b), the chaotic sedimentary unit of Chikura Group in Central Japan (e.g., Yamamoto et al., 2007), and many others (see, e.g., Festa et al., 2016; Ogata et al., 2020 for additional examples). The sizes of "native" blocks within an isotropic broken formation is easier to evaluate because theoretically they cannot be larger than that of the thickest bed observed in the coherent (undeformed) succession in the surroundings of the complex formation (e.g., compare the maximum thickness of beds of the coherent unit of Hard bimrock I5H with the maximum size of blocks in Hard bimrock I6H in Fig. 6). "Native" blocks of an isotropic broken formation actually indicate the disruption and fragmentation of competent beds within a previously coherent lithostratigraphic unit (e.g., flysch deposits) whose average thickness can be observed and measured. This means that before reaching the final characteristic isotropic texture with blocks isolated within the matrix (e.g., Hard bimrock I5HL in Fig. 6), a broken formation (e.g., a flysch deposit) may show different degrees of anisotropy which are comparable with those classified from 1 to 4 in Figure 6 (e.g., from Hard bimrock A1L to A4L in Fig. 6; see also Fig. 3C), independently of the process of formation. For example, the progressive disruption of a flysch deposit during slumping (Fig. 3C) may form anisotropic textures well-comparable in both block-in-matrix fabric and geotechnical behavior with those formed by tectonic dismemberment (e.g., compare Fig. 3C and Hard bimrock A4L in Fig. 6), even if the process of dismemberment is different (gravitational vs tectonic). For these reasons, the distinction of complex formations with isotropic texture starts with the highest degrees (n. 5 in Fig. 6; e.g., Hard bimrock I5L, Soft bimrock I5L, etc.) of disruption and dismemberment.

According to their lithification/consolidation degree, composition, and water sensitivity, complex formations with isotropic block-in-matrix texture can be subdivided into "hard" and "soft" bimrocks (compare, e.g., Hard bimrock I5L and Soft bimrock I5L in Fig. 6), as also categorized for anisotropic ones (see Section 4.2.1). We remand to Section 4.2.1 for details on the different geotechnical characteristics of "hard" and "soft" bimrocks. Isotropic complex formations also include breccias, agglomerates and conglomerates as they have similar geotechnical characteristics of broken formations and mélanges, although not geologically classified as such.

Bimsoils are included in isotropic complex formations (Fig. 6; see, e.g., bimsoil I5L) because they consist of unsorted to poorly sorted terrigenous sediments, which contain clasts and blocks suspended in a fine-grained matrix (i.e., diamicton; see Figs. 5G-H). The term “soil” is misleading because to geologists “soil” refers to the unconsolidated mineral and organic material on the surface of Earth. But, from the point of view of an engineer, “soil” is defined as a natural aggregate of mineral grains, with or without organic constituents, that can be separated by gentle mechanical means such as agitation in water (Murthy, 2003). To many geotechnical engineers, “soil” can be excavated using conventional earthmoving equipment, from shovel to bulldozer. Hence, the term “bimsoil” refers to the geotechnical definition of soil, and identifies deposits with blocks not bonded with the matrix.

Bimsoils with isotropic texture are represented, for example, by several surficial deposits (i.e., diamicton), ranging from glacial till to colluvial deposits, up to weathered rock units and loose volcanic agglomerates. They correspond to “unwelded bimrocks” (Afifipour and Moarefvand, 2014; Kalender et al., 2014; Mahdevari and Maarefvand, 2017; Sonmez et al., 2009), “soil- rock mixtures” (SRM) (Gong and Liu, 2015; Xu et al., 2011; Yang et al., 2019; Zhang et al., 2020) and “rock and soil aggregates” (RSA) (Li et al., 2004).

4.2.3. Complex formations with a mixed (anisotropic/isotropic) texture (DA=M)

Complex formations with a mixed (anisotropic/isotropic) block-in-matrix texture include a wide range of units (e.g., sedimentary mélanges and broken formations or heterogeneous mass transport deposits, diamicton deposits and soils, the core zone of diapiric mélanges, etc.) in which the primary isotropic block-in-matrix fabric is overprinted with different DA by planar surfaces (i.e., foliation, bedding, etc.; see, e.g., Soft bimrock M5L and Soft bimrock M6L in Fig. 6; see also Figs. 5C-E and 5I). The DA may have been caused by both lithostatic and/or tectonic loading (and unloading), and tectonic reworking of the primary block-in-matrix fabric. Some heterogeneous and cohesive mass transport deposits (and/or glacial deposits) may also develop planar surfaces during their translations. Depending on the pervasiveness of those planar surfaces, mixed bimunits may maintain an isotropic mechanical behavior or acquire an anisotropic one (see Fig. 6). In the latter case, the planar anisotropy may affect solely the matrix (e.g., Bimsoil M5L and Soft bimrock M5L in Fig. 6) or rework and reorganize the primary block-in-matrix fabric with distribution of blocks along preferential horizons (e.g., Bimsoil M5H and Soft bimrock M5H in Fig. 6). These horizons are, in turn, aligned to planar surfaces in the matrix: the resulting complex discontinuity fabrics present geotechnical disadvantages.

5. Concluding Remarks

Scientific research has been performed on complex formations with a block-in-matrix fabric in the last few decades with the aim of contributing to a deeper and now mature understanding of their geomechanical behavior.

The findings and methodologies developed need now to be applied to other complex formations with similar characteristics. So, it is appropriate that complex geomaterials be correctly identified and described using appropriate terminology, which links geological and geotechnical terms and concepts.

However, to date no classification systems using terminology familiar to engineers and geologists has been developed that account for the engineering geological conditions and geotechnical behavior of complex formations with a block-in-matrix fabric. Consequently, there is little partnership or integration between disparate research streams, despite the vast literature available.

This paper proposes a novel, simple and practical classification for geotechnically complex formations, with particular reference to those with a block-in-matrix internal arrangement. Particularly important for this classification are the composition and the degree of lithification/consolidation of the matrix of bimunits, since they greatly influence the collection and preparation of regular specimens, the laboratory testing equipment to be used, testing procedures and test results. Bimrocks are subdivided into "soft" and "hard", according to their matrix characteristics and water sensitivity. The new classification, which is also based on several other properties (i.e., degree of internal anisotropy, stratal disruption and mixing, and volumetric block proportion - VPB), is not limited to a few types of geotechnically complex formations (e.g., flysch) but it can be easily applied to all field-based investigations of the different types of complex formations, regardless of their internal degree of stratal disruption, composition, and mechanical response to water sensitivity. To avoid possible subjectivity in using the proposed classification, it is recommended that practitioners always match definitions with photographs of the geological mass studied.

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Figure captions

Figure 1 – Classifications of complex formations by (**A**) Esu (1977) and (**B**) Marinos (2019).

Figure 2 – Schematic illustration showing the transition from a coherent lithostratigraphic unit (or sequence) to a chaotic rock unit (modified from Festa et al., 2019, 2020). Different mechanisms (stratal disruption vs. mixing) and nature of blocks (native vs. exotic) combine to form different

types of broken formation and mélange according to different forming processes (tectonic, sedimentary, and diapiric). Polygenetic mélanges represent the product of the interplay and superimposition of different processes. In contrast to mélanges, broken formations preserve their stratigraphic identity, representing formal or informal lithostratigraphic units.

Figure 3 – Field examples showing the transition from a coherent unit (**A**) to broken formations (**B-F**) and tectonic mélanges (**G-I**). (**A**) Coherent, well-bedded, Ordovician flysch deposits consisting of alternating of sandstone and claystone from the Argentina Precordillera. Hammer for scale. Note early stages of stratal disruption through extensional boudinage in both the left and right side of the photograph. (**B**) Transition (white arrow) from a coherent unit, consisting of a normal bedded Late Ordovician succession of alternating graywacke and mudstone, to broken formation with elongated to lenticular graywacke blocks embedded in a mudstone matrix (Albany Berks County, Hamburg Klippe, Central Appalachians, USA). (**C**) Close-up view showing the transition from a coherent unit (top) to the early stage of development of a broken formation (bottom) trough slumping and related boudinage in the Miocene flysch deposits of the Marnoso arenacea Fm. (Passo dei Mandrioli) in Northern Apennines of Italy. (**D**) Progressive stratal disruption of a well bedded unit (Flysch Rosso) forming a broken formation with lozenge-shaped blocks of mudstone in a clayey marl matrix (Aventino valley, Abruzzi region, Central Apennines of Italy). Note that the matrix is deformed by a pervasive scaly fabric. (**E**) Sigmoidal to lozenge-shaped blocks of sandstone within a mudstone matrix displaying a pervasive scaly fabric (broken formation), due to tectonic deformation within a shear zone (Waimarama Beach, South Hawke's Bay, East Coast of North Island, New Zealand; Courtesy of G.A. Pini). Note that blocks long axes are aligned to the main shear zone. (**F**) Field-detail of a broken formation characterized by a high degree of stratal disruption with isolated hard sigmoidal blocks embedded in softer (clayey) matrix (Bobbio Tectonic Window, Northern Apennines of Italy). (**G**) Close-up view of tectonic mélange with lenticular exotic blocks in a sheared matrix (Franciscan Complex, CA-USA). Hammer for scale. (**H**) Sigmoidal to phacoidal Upper Triassic pelagic limestone blocks in a heterogeneous and variously deformed matrix composed of shale, mudstone, and sandstone in the Jurassic-Cretaceous Avdella mélange (Pindos Mountains, Northern Greece). (**I**) Huge exotic ultramafic and limestone blocks, lenticular in shape, embedded in a fine grained green reddish ophiolitic matrix of the Cretaceous Ankara Ophiolitic Mélange (Central Anatolia, Turkey). Geoscientists for scale.

Figure 4 – Diagrams showing different (meso-scale) organizational types of the block-in-matrix fabrics in tectonic mélanges and broken formations (**A**), sedimentary (**B**), and diapiric (**C**) mélanges, and their comparison (**D**), in terms of aspect ratio (block long axis/short axis) vs. block long axis. Data are plotted as means with 95% error bars indicated. Data from updated after Festa et al. (2019).

Figure 5 – Field examples showing different types of sedimentary (**A-I**) and diapiric (**J-L**) mélanges. (**A**) Internal arrangement of a sedimentary mélange, showing the random distribution (isotropic texture) of hard blocks (limestone, marlstone and sandstone) with a brecciated clayey matrix (Northern Apennines, Italy, modified from Festa et al., 2015). (**B**) Close-up view of rounded to angular clasts of ultramafic rocks in a fine- to medium grained matrix of the same composition (Ligurian Units, Northern Apennines, Italy); note the block-in-matrix isotropic texture (hammer for scale). (**C**) Detail of sedimentary mélange consisting of highly disordered block-in-matrix fabric of trench-related debris flow with variably shaped blocks (equidimensional, tabular, phacoidal, and irregular) of metavolcanic and metagraywacke rocks (Panoche Road, Franciscan Complex, California; see Wakabayashi, 2012 for details). (**D**) Outcrop view showing the block-in-matrix fabric of a sedimentary mélange, flattened and slightly deformed by compaction and tectonics, which reorganize the primary isotropic texture of the block-in-matrix fabric to an anisotropic one (Berceto, Parma area of the Northern Apennines of Italy). (**E**) Close-up view of a tectonically reworked sedimentary mélange (debris flow deposit) with blocks of an oceanic cover succession in a sheared, shaly matrix (Casanova Complex, Northern Apennines, Italy). Note that both the matrix and the block-in-matrix fabric define an isotropic texture (camera cap for scale). (**F**) Panoramic view of a sedimentary mélange showing the random distribution of huge Upper Cretaceous blocks (megabreccias or olistoliths) of calcareous limestone within a limestone matrix (Muttekopf, Calcareous Alps, Austria; see Amerman et al., 2009; Ortner, 2001). The mountain side is about 300m high. (**G**) Close-up view of a bimsoil (diamicton, i.e., glacial till) showing the random distribution (i.e., isotropic texture) of angular blocks and clasts, which are suspended in a fine-grained (clay) matrix (Aosta Valley, Italy). (**H**) Bimsoil detail, consisting of unsorted to poorly sorted terrigenous sediments embedding rounded hard clasts (diamicton). Note that the block-in-matrix fabric defines a weak anisotropic texture acquired during depositional emplacement (Ivrea

Morainic Amphitheatre, Northwestern Alps of Italy). Hammer for scale. (**I**) Close-up view of a bimsoil, showing a planar anisotropy defined by the occurrence of a pervasive scaly fabric in the clayey matrix, which overprints and rework the primary block-in-matrix fabric of the diamicton (Ivrea Morainic Amphitheatre, Northwestern Alps of Italy). Hammer for scale. (**J**) Panoramic view of the diapiric mélange, showing the internal zoning of deformation and the block-in-matrix arrangement (Northern Apennines, Italy). Note that in the center of the diapiric body (core zone), blocks, which are larger in size (i.e., up to tens of meters), are commonly angular, loosely clustered, and randomly distributed the irregularly folded matrix. Close to the margins (**J** and **K**), the block-in-matrix fabric shows a sub-vertical trending with phacoidal to tabular blocks, embedded within a fine-grained (shaly or clay) matrix, pervasively deformed by scaly fabric, and aligned to the intrusive contacts (red lines). Hammer for scale. (**L**) Close-up view of the marginal zone of a diapiric mélange showing phacoidal (rarely tabular) limestone and sandstone blocks aligned parallel to the subvertical fluidal fabric (dashed white lines) of the shaly matrix (Northern Apennines, Italy; see Festa et al. 2013 for details).

Figure 6 – Proposed classification of geotechnically complex formations with block-in-matrix fabric, showing the transition from a coherent unit to different types of chaotic rock units. Different mechanisms (stratal disruption vs. mixing) and nature of blocks (native vs. exotic) concur to form different types of broken formation and mélange independently of the forming process (tectonic, sedimentary, and diapiric). Four parameters, which have a primary role in controlling the geotechnical behavior of bimunits, are at the base of this new classification: (i) the composition and nature of blocks and the matrix that affects the water sensitivity over a short period (Hard bimrocks, Soft bimrocks and Bimsoils); (ii) the degree of anisotropy (anisotropic - A, isotropic - I, and mixed - M) of the block-in-matrix fabric; (iii) the degree of stratal disruption and mixing (from 1 – lower - to 6 - higher); and (iv) the volumetric block proportion - VBP (high – H, or low - L). See text for explanation.