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1	Practical classification of geotechnically complex formations with block-in-matrix fabrics
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#### 13 Abstract

The terms "bimrocks", "bimsoils" and "soil-rock mixtures" indicate different and very common 14 types of geological units with a block-in-matrix fabric that are also "geotechnically complex 15 16 formations" and are characterized by an internal heterogeneity, and spatial variability of mechanical parameters and lithological compositions. Due to this internal complexity, the 17 understanding of their geomechanical behavior presents a key challenge in geotechnical 18 engineering. However, the lack of a standardized and clear terminology complicates the 19 discrimination of different types of complex formations and their internal mechanical properties, 20 which leads to inconsistency in the literature and research studies. This inconsistency causes 21 misunderstandings, with possible practical implications for the characterization, analysis, design 22 and construction of engineering works. By a combination of geological and geotechnical 23 observations, we propose a new classification for geotechnically complex formations, with 24 particular attention to those with a block-in-matrix internal fabric. Four properties are at the base 25 of this new classification and have a primary role in controlling the geotechnical behavior of block-26 in-matrix units (bimunits): (i) the composition (i.e., lithology, degree of lithification/consolidation, 27 28 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 29 mixing, and (iv) the volumetric block proportion (VPB). As a result, we classified bimunits in those 30

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.

#### 38 Keywords

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

#### 40 **1. Introduction**

At the scale of engineering works, geotechnically complex formations are rock units or soils that 41 have lithological and/or structurally discontinuities with contrasting geomechanical properties 42 (Barla and Perello, 2014; Cancelli, 1986; D'Elia et al., 1986; Harrison, 2014). Complex formations 43 include mélanges, "argille scagliose"/scaly clays, flysch deposits, etc., which together form 44 significant component of geomaterials worldwide. The most difficult complex formations to 45 46 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, 47 with differing geologic natures (e.g., sedimentary, crystalline, igneous intrusive, volcanic, 48 metamorphic, etc.), lithology, orientation, shape and rheology, which are embedded in a softer 49 matrix of different composition (e.g., clay, mud, sand, etc.; see, e.g., Afifipour and Moarefvand, 50 2014; Gokceoglu and Zorlu, 2004; Kalender et al., 2014; Medley, 2001, 1994; Napoli, 2021; Napoli 51 et al., 2021a, 2021c, 2021b, 2018; Tsesarsky et al., 2016). The high internal heterogeneity and 52 compositional variability of block-in-matrix units ("bimunits" in the following), which is mainly due 53 to the strong rheological contrast between blocks and the matrix, extends the geotechnical 54 complexity over a wide spectrum of complex formations, ranging from rocks to soils, with a 55 significant engineering and societal impact (Medley and Zekkos, 2011). Technical difficulties, 56

delays, economic repercussions and health and safety risks have occurred at many engineering 57 58 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 59 60 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 61 62 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., 63 2014), and the Alexander von Humboldt Foundation, see (Kahraman and Alber, 2008), to better 64 understand the geotechnical behavior of heterogeneous formations with a block-in-matrix fabric. 65

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A significant problem results from the inappropriate or loose use of the term "complex formation" 67 68 to indicate a broad range of lithological units or complexes (e.g., mélanges, weathered rocks, conglomerates, agglomerates, flysch deposits, pyroclastites, olistostromes, breccias, fault rocks, 69 etc.), all having very dissimilar fabrics and structural organization, composition and, therefore, 70 rheological and geotechnical characteristics. In addition, different technical fields use various terms 71 to indicate complex formations with mixed strong/weak rocks. For example, "Mixed Face 72Conditions" and "Soft Rock-Hard Rock" are commonly used in tunneling and mining, respectively. 73 To overcome this problem, geopractitioners have introduced and widely used terms such as 74 "bimrock" (Medley, 1994), "bimsoil" (Medley and Goodman, 1994) and "soil-rock mixture" (SRM; 75 Xu et al., 2011) to indicate such heterogeneous formations. "Bimrock" is the acronym of "block-in-76 matrix rock", an extension of the geological term "block-in-matrix" which was introduced by 77 Raymond (1984) to indicate chaotic rock units with hard blocks embedded within a softer matrix 78 (i.e., the fabrics of mélanges). Medley (1994) defined a bimrock as "a mixture of rocks, composed 79 80 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 81 between competent blocks and weaker matrix must exist, and that both the volume and dimension 82 of the hard inclusions influence the rock mass properties at the scales of engineering interest 83 (which range between centimeters and hundreds of meters). Medley (1994) introduced the 84 acronym "bimsoil" (block-in-matrix soil) for geological units with rock blocks embedded in a soil-85 like matrix (Kalender et al., 2014; Medley and Goodman, 1994; Sonmez et al., 2016). 86 87 Heterogeneous and loose deposits with hard blocks embedded in a fine-grained soil matrix, such

88 as colluvial and debris flow deposits, have also been defined "soil-rock mixtures" (SRM) (Gong and 89 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., 90 2014; Khorasani et al., 2019b; Sonmez et al., 2009), according to the strength of the blocks-matrix 91 interface. Specifically, the strength of interfaces between blocks and matrix is approximately equal 92 to that of the matrix for welded bimrocks, while the strength is lower than that of the matrix for 93 unwelded bimrocks. However, it can be extremely difficult to estimate the strength of block-matrix 94 interfaces of a bimunit before ascribing it to the welded or unwelded category. 95

Although very helpful, the different non-geological expressions mentioned above may indicate 96 deposits with highly dissimilar geological, lithological and structural features and, therefore, 97 different geotechnical behaviors. As a result, the use of those terms does not allow easy 98 comparison with the terminology used by geologists in both research and geological 99 maps/documents and confuses the interpretation of results from geotechnical research. Hence, 100 the possibility of using and/or improving the approaches developed in previous studies of other 101 authors is quite difficult. The main risk is that the research has an end in itself, resulting not useful 102 for improving knowledge of geoscientists and engineers on this complex but fundamental issue. 103

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 withblock-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.

#### **117 2.** Previous classifications of complex formations

Only a few classifications have been proposed to define and describe in a simple way the main 118 characteristics of geotechnically complex formations (Esu, 1977; Marinos and Hoek, 2001; Marinos, 119 2019; Nikolaidis and Saroglou, 2016). Esu (1977) proposed a descriptive classification (Fig. 1), 120 subdividing complex formations into three main groups, differing from each other by their degree 121 of internal heterogeneity and stratal disruption. The first group (group "A") includes coherent 122 sedimentary (rock) units, ranging from layered and well-bedded deposits to sheared ones. The 123 second group (group "B") includes sedimentary (rock) units with different degree of stratal 124 disruption, ranging from fissured ordered deposits (i.e., well-bedded; Sub-group "B1") to chaotic 125 rock units with a block-in-matrix fabric (Sub-group "B3"), in which blocks are embedded in a softer 126 and sheared matrix. The last group (group "C") includes highly heterogeneous sedimentary units, 127 consisting of fragments of weathered rocks embedded in a clayey matrix (e.g., residual and colluvial 128 soils; see Fig. 1). The different subdivisions of Group "B" appear to be organized to represent the 129 gradual disruption of an originally well-bedded lithostratigraphic unit, to an end condition of sub-130 group "B3" with blocks that represent fragmented beds resulting from the dismemberment of the 131 previously coherent stratigraphic unit. The label to "residual and colluvial soils" for the Group "C" 132 (Fig. 1) suggests that blocks formed by weathering of the parent rock and surficial gravity transport 133 (colluvium, landslides, etc.), respectively. Overall, the classification of Esu (1977) seems not to 134 consider the wider range of complex formations that have blocks whose source is not present in 135 the surrounding lithological units within a complex formation zone, and which are different from 136 any lithology found in surrounding country rocks (i.e., mélanges). Such blocks are "exotic" blocks 137 according to the current geological terminology (see also below Section 3.1). 138

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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. 147 Nikolaidis and Saroglou (2016) proposed an approach for the characterization of complex 148 formations with a block-in-matrix fabric, based on six parameters (i.e. linear block proportion, 149 bimrock strength, matrix complexity, block classification, bimrock complexity and orientation of 150 blocks) that can be straightforwardly assessed in the field. The authors also analyzed a case study, 151 outlining that an appropriate characterization of block-in-matrix materials requires a significant 152 appreciation of geology.

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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

158 Geotechnical and engineering works on complex formations investigate, interpret and model geological units. Rock units like mélanges, weathered rocks, conglomerates, agglomerates, flysch 159 160 deposits, pyroclastites, olistostromes, breccias, fault rocks, and several others, are generally categorized as "geotechnically" complex formations even if most of them are not considered 161 complex formations from the geological point of view (Anagnostou et al., 2014; Barla and Perello, 162 163 2014). In addition, those rock units represent different geological deposits, with dissimilar internal 164 organization, composition, rheology, size of blocks and, therefore, different mechanical/geotechnical characteristics. Hence, to avoid confusion and misunderstanding 165 166 between geological units, in the following (see Section 3.1 for details) we clarify the geological 167 terminology related to "complex formations" with a block-in-matrix fabric (i.e., the "chaotic rock 168 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 169 it includes both bimrock and bimsoil complex formations. 170

#### 171 **3.1.** Bimunits: mélanges and broken formations

172 Although the term "complex formation", not to be confused with the terms "complex" and 173 "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 174 complexity is due to their internal block-in-matrix fabric, which differs from that of coherent and/or 175 well-bedded units (see, e.g., Berkland et al., 1972; Raymond, 1984; Silver and Beutner, 1980; for 176 details). The general and non-genetic term "chaotic rock units" (Fig. 2) includes broken formations 177 and mélanges (see below), which represent the product of stratal disruption and mixing of primary 178 coherent lithostratigraphic units, acting by tectonic, sedimentary (gravitational) or diapiric 179 processes and their interaction (see, e.g., Festa et al., 2010; Raymond, 1984; Silver and Beutner, 180 1980; for details). In geology, the term "mélange" (Greenly, 1919) is a descriptive and non-genetic 181 182 term, defining a mappable (at 1:25,000 or smaller scale) body of internally disrupted and mixed 183 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., 184 Berkland et al., 1972; Cowan, 1985; Raymond, 1984; Silver and Beutner, 1980). The term "exotic" 185 includes all types of blocks that are "foreign" with respect to the matrix of a mélange (see Hsü, 186 187 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 188 et al., 2019 for a complete discussion). Notable examples of "exotics" are, among several others, 189 190 blocks recording different metamorphic degrees (i.e., different Pressure-Temperature, P-T, 191 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 192 (serpentinite, gabbro and basalt), granitoids, chert and limestone embedded in a clay matrix such 193 as in the Ligurian Units in Northern Apennines (e.g., Barbero et al., 2020; Bettelli and Panini, 1987; 194 Elter and Raggi, 1965; Marroni et al., 2010;), in the Dinaric-Hellenic orogenic belt (e.g., Bortolotti 195 et al., 2013 and references therein), and in the Valmala Shear Zone in the Western Alps (e.g., 196 Balestro et al., 2020). On the other hand, the geological term "broken formation" (Hsu, 1968) is 197 198 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 199 originated only from the disruption of a primary lithostratigraphic unit (Figs. 3A-C). Therefore, a 200 "broken formation" differs from a "mélange" because it preserves its lithological and chronological 201 identity (e.g., Festa et al., 2020, 2022; Hsü, 1968; Pini, 1999; Raymond, 1984; and references 202 therein). Broken formations commonly show a gradual transition from to the coherent, well-203 bedded, primary succession to the highly disrupted block-in-matrix fabric (Figs. 2 and 3A-F). 204

Notable examples are represented by the *Argille scagliose* or *Argille varicolori* (Varicolored scaly 205 206 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 207 flysch or Taconic mélange in the Northern Appalachians (e.g., Kidd et al., 1995), the chaotic rock 208 units in the Shimanto belt in Japan (e.g., Kimura et al., 2012), in the US-Western Cordillera (e.g., 209 Cowan, 1985; Hsü, 1968; Raymond, 1984, 2019), in the McHugh complex in Alaska (e.g., Fisher and 210 Byrne, 1987), and in the Torlesse accretionary wedge in New Zealand (e.g., Barnes and Korsh, 1991; 211 Sunesson, 1993) among several others. Importantly, disrupted, or dismembered flysch deposits 212 without "exotic" blocks included, correspond to "broken formations" and not to "mélanges" (see, 213 e.g., Ogata et al., 2021). The heterogeneous to block-in-matrix complex formations classified by 214 Esu (1977), Marinos and Hoek (2001), and Marinos (2019) represent, therefore, typical broken 215 formations (i.e., without "exotic" blocks), which are differentiated according to their degree of 216 stratal disruption. Those different degrees of stratal disruption (i.e., Groups "B1" to "B3" of Esu, 217 1977; and Types VIII to XI of Marinos, 2019) are well comparable, in fact, with those described in 218 geology (Fig. 2), ranging from stratigraphic units with locally broken internal stratal continuity to 219 rock bodies without internal stratal continuity or exotic blocks (see, e.g., Raymond, 1984). Hence, 220 221 those classifications do not consider mélanges, which represent the most complex type of bimunits 222 (Fig. 2), nor take in considerations that mélanges and broken formations have very different blockmatrix interface strength (e.g., Festa et al., 2019, 2022; Ogata et al., 2021 and references therein), 223 strongly affecting their sampling, characterization, mechanical behavior and modeling. 224

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 wellknown 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.

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Tectonic mélanges and tectonic broken formations are characterized by a scale-independent 241 repetition of a "structurally ordered" block-in-matrix fabric (Figs. 2 and 3), which defines a planar 242 anisotropic texture (e.g., Festa et al., 2019; Pini, 1999). Scale independence means that the 243 appearance of the rock mass is similar regardless of the scale of observations - for example: a few 244 large blocks and a multitude of smaller and smaller blocks. Although the shape and arrangement 245 of blocks may vary depending on physical factors acting in the original tectonic deformational 246 setting (e.g., fluid pressure, pressure, temperature, mineral transformation, etc.), rheological 247 proprieties, deformational mechanism (e.g., brittle versus plastic deformation), consolidation and 248 lithification degrees, and strain rate, they commonly range from lenticular (Figs. 3B and 3G) to 249 sigmoidal (Figs. 3E, 3F and 3H) or elongated (Fig. 3D) with a mean aspect ratio (i.e., long axis/short 250 axis) ranging from between 2.8 and 4.1 (tectonic mélanges) and 3.9-4.5 (tectonic broken 251formations) (Figs. 4A and 4D), and with their long axis aligned to the main shear zones (Figs. 3D-3I) 252in which they formed (see Festa et al., 2019 for details). 253

Tectonic mélanges and broken formations can be considered structurally equivalent to mappable 254fault or shear zones (e.g., Cowan, 1974). Broken formations roughly correspond to Types X and XI 255of Marinos (2019), and in part to group B2 of Esu (1977). Blocks may range in size from centimeters 256 to hundreds of meters (Fig. 3), depending on the thickness of the shear zone in which they formed 257258 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 259 polished surfaces (Fig. 3E), spaced millimeters to centimeters apart (e.g., Bettelli and Vannucchi, 260 261 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. 262 263 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; 264

265 Marroni et al., 2010;Pini, 1999; Remitti et al., 2007), the Shimanto belt in Japan (e.g., Kimura et al.,
266 2012).

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268 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 269 slumps (see, e.g., Ogata et al., 2019, 2020; Pini et al., 2012). The block-in-matrix fabric of 270 sedimentary mélanges and broken formations (or endolistostromes sensu Elter and Raggi, 1965), 271 strongly contrasts with that formed by tectonic processes (Fig. 2). Independent of the scale of 272 observation, they are characterized by a highly disordered block-in-matrix arrangement (Figs. 2 and 273 3) with blocks of different shape (e.g., irregular to equiangular, depending on their lithology), 274 lithology, age, size (e.g., from centimeters to hundreds of meters up to a few kilometers), floating 275 with a random distribution in a finer grained matrix (see Festa et al., 2016, 2019 for details). The 276 random distribution of blocks and the brecciated texture of the matrix define an isotropic texture 277at all scales (Figs. 2, 5A, 5B, 5F). The mean aspect ratio (long axis/short axis) of blocks ranges 278 between 1.4 and 2.5 (see Festa et al., 2019 for details; see Figs. 4B, 4D). The matrix is commonly 279 280 fine-grained, ranging from clay to shale, and includes angular-to rounded clasts, sub-millimeters to 281 millimeters in size (Figs. 2 and 5A, 5D). Sandstone matrix, as well as matrix composed of ultramafic-282 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 283 related to lithostatic or tectonic loading, or later tectonic reworking (i.e., polygenetic mélanges in 284 Fig. 2; see Festa et al., 2020 for details) of the block-in-matrix fabric (Figs. 5D, 5E, 5I). Therefore, 285 286 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, 287 288 which is commonly erosional, may be characterized by an anisotropic shear zone decimeters thick 289 (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). 290

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).

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Diapiric mélanges and broken formations are characterized by a distribution of the block-in-matrix 304 fabric which shows internal zoning from margins to the core of the diapir (e.g., Codegone et al., 305 2012; Dela Pierre et al., 2007; Orange, 1990; see Figs. 2 and 5J-5K). Close to the margins (i.e., close 306 to the intrusive contacts with the country rock), the fabric commonly shows a sub-vertical trending 307 with phacoidal to tabular blocks, embedded within a fine-grained (shaly or clay) matrix, pervasively 308 deformed by scaly fabric, and aligned to the intrusive contacts (Figs. 2 and 5K, 5L). The clustering 309 of blocks and the pervasiveness of the scaly fabric gradually decrease toward the center of the 310 diapiric body where blocks, which are larger in size (i.e., up to tens of meters), are commonly 311 angular, loosely clustered, and randomly distributed within a non-foliated, and irregularly folded, 312 313 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. 314 4C, 4D). The alignment of both blocks and the scaly fabric to the intrusive margins defines a planar 315 anisotropy, which gradually passes to a partially isotropic texture toward the center of the diapir 316 (Fig. 2). Although formed by a different process, part of the block-in-matrix fabric of diapiric 317 mélanges and broken formations resembles Types VII, VIII, X and XI (compare Figs. 1 and 2) of 318 Marinos (2019), and groups B2 and B3 of Esu (1977). Notable examples occur in the Olympic 319 320 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., 321 Codegone et al., 2012; Dela Pierre et al., 2007; Festa, 2011). 322

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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, 327 composition, rheological characteristics, degree of anisotropy and, therefore, with different shape
 328 of blocks, strength, stiffness, and permeability values. Therefore, they must be classified
 329 separately.

#### **4.** Geological-constrained classification of geotechnically complex formations

Our overview of the geological terminology for complex formations (see Section 3.1) shows that 331 they consist of different types, differing in their internal block-in-matrix fabric (i.e., anisotropic vs. 332 isotropic texture), composition, rheology and, therefore, mechanical, and geotechnical behavior. 333 Although very useful, the general terms "bimrocks", "soil-rock mixtures", "bimsoils" and "rock and 334 soil aggregates" do not allow distinguishing among geomaterials with different geotechnical 335 characteristics, nor linking geological information/terminology used in geological maps and 336 documents to a geotechnical significance. Geological maps with their codified terminology 337 338 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 339 340 formations. The lack of a common vocabulary to describe those heterogeneous geomaterials complicates popularization of scientific results, strongly diminishing the benefit for all researchers 341 342 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 343 characterize bimunits with completely different characteristics, causing wrong interpretations with 344 possibly significant practical implications. For instance, the scale-independent properties of some 345 mélanges in the Franciscan Complex in California (Medley, 2004, 1994), although common to many 346 347 bimrocks, cannot be successfully applied to all block-in-matrix geomaterials (e.g., conglomerates, disrupted flysch deposits, diamicton deposits, etc.). 348

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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

358 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., 359 metamorphosed or non-metamorphosed), degree of lithification/recrystallization, and rheological 360 contrast between blocks and the matrix, complex formations have different mechanical contrast 361 362 between blocks and matrix (Kahraman and Alber, 2008; Medley, 2001) and different strength of 363 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 364 of additional factors, such as pressure, temperature, fluid pressure, strain rate, and fluid/water 365 content. Particularly, depending on the lithology and mineralogy, complex formations are 366 differently sensitive to water. This is quite evident in comparing, for example, a complex formation 367 consisting of serpentinite blocks embedded in a micaschist matrix and one of limestone blocks 368 embedded in a marly matrix. 369

370

The second parameter taken into consideration is the degree of anisotropy (DA). The internal block-371 in-matrix fabrics of complex formations show different DAs, depending on the processes of their 372 formation (tectonic, sedimentary or diapiric) and/or superposition and interaction of processes as 373 described in Section 3. The DA, which may range, for example, from the anisotropic texture of 374 tectonic mélanges and tectonic broken formations (Fig. 3), as well as that one of the marginal zone 375 of diapiric bodies (Figs. 5K and 5L), to the isotropic one of most of sedimentary mélanges (or 376 heterogeneous mass transport deposits) and the core zone of diapiric bodies (Figs. 5A, 5B, and 5J), 377 378 strongly influences the mechanical behavior of complex formations. It may control fractures propagation, fluid migration, fluid overpressure, seismic rupture propagation, etc., as documented 379 in both geological and geotechnical literature (e.g., Bürgmann, 2018; Fagereng and Sibson, 2010; 380 Festa et al., 2018; Khorasani et al., 2019a; Napoli et al., 2021b). Importantly, the development of a 381 planar anisotropy in the matrix of sedimentary mélanges (olistostromes or heterogeneous mass 382

transport deposits) may change the DA depending on the pervasiveness of planar surfaces (see
Sections 3.2 and 4.2; see Figs. 5C-5E).

385

386 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 387 388 (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 389 3B). Non- to poorly deformed (but not disrupted) flysch deposits, consisting of alternating of 390 layers/beds with different competence, represent the most common example of coherent complex 391 formations (Fig. 3B). Broken formations represent the progressive disruption and dismemberment 392 of a primary coherent complex formation or a lithostratigraphic unit characterized by beds/layers 393 with internal contrasting competence, such as, for example, flysch deposits. They can range from 394 slightly disrupted formations (Figs. 3B-D), in which a roughly continuity of primary layers/beds is 395 still present, to "native" blocks completely isolated within the matrix (i.e., without any 396 layering/bedding-continuity preserved; see Section 3.1; see Figs. 3E and 3F). On the other hand, 397 mélanges represent the mixing of "exotic" blocks (i.e., their source is not present in the surrounding 398 lithological units within a mélange zone (Figs. 3G-I), and they are different from any lithology found 399 400 in country rocks; see Section 3.1).

401

The last parameter is the "Volumetric Block Proportion" (VBP). As well documented in the 402 literature, the presence of rock blocks does not affect the overall behavior of geotechnically 403 complex formations if their VBP is lower than about 10%-25%. On the contrary, geomaterials with 404 block contents ranging between 25% and 75% show markedly greater strength and stiffness, higher 405 safety factors, and more tortuous failure surfaces than those of the matrix alone, depending on the 406 407 VBPs (Khorasani et al., 2019a; Lindquist, 1994a; Medley, 1994; Napoli, 2021; Napoli et al., 2019; 408 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 409 for in-site masses is a daunting task, depending on field measurements of point (PBP), linear (LBP) 410 or areal block proportions (ABP). These lower order measures will almost never equal the VBP. 411 Hence, they must be adjusted by uncertainty factors to estimate realistic VBP ranges (Medley, 412 1997; Napoli et al., 2020; Ramos-Cañón et al., 2020). 413

#### 414 **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. 420 6), because the qualitative degree of anisotropy (DA) is an observable property, common to both 421 geologists and engineers. Each of these three types of bimunits show different geotechnical 422 characteristics according to (i) the composition and nature of blocks and the matrix that affects the 423 water sensitivity over a short period (Hard bimrocks, Soft bimrocks and Bimsoils in Fig. 6), (ii) the 424 degree of stratal disruption and mixing (from 1 to 6, from the lowest to the highest, respectively, 425 in Fig. 6), and (iii) the VBP (high – H, or low – L, in Fig. 6). In Figure 6, the combination of 426 abbreviations used for those different parameters defines specific labels, each of which identifies 427 a different type of geotechnically complex formation in the new classification. The first capital letter 428 of each acronym is referred to the degree of anisotropy (e.g., A, I or M) of the bimunit; the number 429 corresponds to the degree of internal disruption (from 1 to 6, from the lowest to the highest, 430 respectively), and the last two lower case letters indicate the VPB (i.e., L or H) (see also the 431 "acronyms index" at the bottom of Fig. 6). 432
- 433 The classifications are described in detail below.
- 434

#### 435 4.2.1. Anisotropic complex formations (DA=A)

436 Complex formations with anisotropic textures (Fig. 6) are characterized by different 437 mechanical/geotechnical properties in different directions and are easily recognized by geological, 438 geotechnical and geophysical observations. Independently of the degree of stratal disruption (i.e., 439 from 1 to 6 in Fig. 6), the occurrence of a planar anisotropy characterizes different types of complex 440 formations, ranging from coherent ones to those with a block-in-matrix fabric (i.e., broken 441 formations and mélanges; compare Figs. 3A-I). In coherent complex formations, such as non- to 442 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 443 and rheology (e.g., alternating of sandstone and mudstone, limestone and claystone, etc.). With 444 the increase (from 1 to 6 in Fig. 6; see also Fig. 3B) of disruption and dismemberment (e.g., tectonic 445 faulting or diapiric rising along intrusive contacts), the planar anisotropy is defined by the alignment 446 of elongated (i.e., tabular, lenticular, sigmoidal, etc.) "native" bed fragments/blocks, grading to a 447 block-in-matrix fabric (e.g., Hard bimrocks from A1L to A6L in Fig. 6). The genetic deformational 448 mechanisms can range from brittle to plastic depending on the Pressure-Temperature (P-T) 449 conditions and consolidation/lithification degree of the rock unit, which were acquired during 450 burial (e.g., subduction processes). As explained above (see Section 3), the different degrees of 451 stratal disruption represented by broken formations is well documented in sheared or deformed 452 flysch deposits (see Figs. 3D-F), independently of the deformational process (i.e., tectonic, 453 gravitational or diapiric). Notable examples are the Flysch Rosso (Red beds) in the Southern 454 Apennines (e.g., Vezzani et al., 2010), the Argille scagliose or Argille varicolori (Varicolored scaly 455 clays) of the Northern Apennines (e.g., Bettelli et al., 2004; Coli and Tanzini, 2013; D'Elia et al., 456 1998; Festa et al., 2013; Pini 1999), the Taconic Flysch in the US-Appalachians (e.g., Kidd et al., 457 1995), as well as most of stratigraphic successions consisting of alternating beds with different 458 competence and rheology (e.g., sandstone and marls, limestone and claystone, etc.). 459

460

Although mélanges represent a common component of many geomaterials around the world, they 461 are not included in previous classifications (e.g., Esu, 1977, Marinos and Hoek, 2001, and Marinos, 462 2019), nor differentiated from those with a very different (isotropic) block-in-matrix fabric (see 463 below). Mélanges represent the highest degree of internal dismemberment of complex formations 464 with anisotropic textures, as well as related mixing processes which incorporate "exotic" blocks 465 466 into the matrix. They must be classified separately from broken formations (see Fig. 6) because the 467 "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 468 from that of the matrix may produce high strain and stress in tunnel linings, more rapid wear of 469 cutters, and damage to the cutting tools and/or mucking system. In a broken formation the range 470 of block/matrix interface strengths of a single block/matrix couple is likely to be within some range 471 of other block/matrix couples, at same alteration and deformation conditions. This is due to the 472 "native" nature of blocks (i.e., blocks and matrix derive from the dismemberment of the same 473

coherent unit, see Figs. 3B-D). On the contrary, the occurrence of "exotic" blocks (i.e., lithotypes 474 that are not present in the surrounding of the complex formation, see Fig. 3G-I), commonly 475 476 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 477 block/matrix interface strengths within a mélange, preventing their predictability (Fig. 3I). 478 However, it is important to outline that in some cases it is possible to unexpectedly encounter 479 exotic blocks (e.g., a huge block of crystalline or metamorphic rock) within a broken formation. This 480 481 may occur, for example, in cases in which broken formations are interfingered by mass transport 482 deposits (i.e., sedimentary mélanges or olistostromes), sourced from lithological units exposed 483 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 484 maps) are fundamental in correctly evaluating the geotechnical characteristics of each type of 485 complex formation and the possibility to encounter unexpected "exotic gifts". 486

487

A wide range of complex formations with anisotropic texture may also show different geotechnical 488 behaviors depending on their composition, degree of lithification/consolidation, and change of 489 physical conditions and external factors (e.g., pressure, temperature, water content, etc.), resulting 490 491 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 492 outline this important aspect. Hard bimrocks include both metamorphic and non-metamorphic 493 complex formations, which are well lithified/consolidated, with blocks bonded with the matrix 494 (e.g., "welded bimrocks", see Avşar, 2021; Afifipour and Moarefvand, 2014; Kalender et al., 2014; 495 Mahdevari and Maarefvand, 2017; Sonmez et al., 2009). They are relatively insensitive to changes 496 of physical conditions and external factors over a short period (i.e., from hours to months) such as, 497 498 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 499 of the matrix, nor the strength of the block and matrix interface. 500

501

502 Soft bimrocks mainly consist of poorly consolidated/lithified sedimentary units (e.g., marl, clay, 503 sand, etc.). Although blocks are bonded with the matrix, they become unbonded when subjected 504 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. 505 For example, dissolution and slaking processes due to the presence of water can weaken the matrix 506 depending on its mineralogical composition (e.g., carbonate content), chemical bonding state in 507 the grain boundaries, and internal structure (e.g., occurrence of foliation, layering, cleavages, 508 fractures, etc.). This water-sensitive weakening behavior greatly affects the choice of the site 509 exploration and sampling techniques, preparation of intact specimen processes, laboratory testing 510 equipment to be used, testing procedures and, of course, test results. Under these conditions, soft 511 bimrocks have a mechanical behavior which is transitional between hard bimrocks and bimsoils 512 (Fig. 6). 513

514

515 Bimsoils are not classified within complex formations with anisotropic texture because they are 516 commonly characterized by a primary isotropic fabric (Figs. 6 and 5G, 5H). However, considering 517 that an anisotropic texture may occur in particular cases (e.g., translation of some glacial deposits, 518 lithostatic or tectonic loading), overprinting the isotropic one (Figs. 6 and 5I), we classified this type 519 of bimsoils as those with mixed texture (see below Section 4.2.3).

520

Considering that the VPB may strongly influence the mechanical behavior of all complex formations 521 522 (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 523VBPs are lower than about 15%-25% and the influence of the blocks is negligible in controlling the 524 geotechnical behavior of the bimunits. Therefore, from a geotechnical point of view, the low-VBP 525block-in-matrix geomaterials can be considered to be homogeneous by neglecting the blocks 526 during characterization and modeling (they must be remembered for the benefit of excavators and 527 tunnelers, though). On the contrary, when the bimunits have VBPs ranging from about 25% to 75% 528 (when the VBP is higher than 75% the geomaterial can be treated as blocky rock mass and, 529 therefore, cannot be considered a complex formation) the blocks significantly to markedly affect 530 their strength and failure mode (Lindquist, 1994b; Medley and Sanz Rehermann, 2004; Napoli, 531 2021; Napoli et al., 2019, 2021b). Therefore, these latter formations should be analyzed and 532 modelled by means of heterogeneous-stochastic approaches, to take into account the inherent 533 variability of bimunits. This is true also for complex formations with both isotropic and mixed 534 (anisotropic/isotropic) textures, described below in Sections 4.2.2. and 4.2.3, respectively. 535

#### 536 4.2.2. Isotropic complex formations (DA=I)

Complex formations with an isotropic block-in-matrix texture have the same 537 mechanical/geotechnical behavior in all directions. Unlike anisotropic formations, they do not 538 include coherent complex formations (Fig. 6) because their internal arrangement is always 539 540 characterized by a block-in-matrix fabric (i.e., sedimentary broken formations and mélanges, conglomerates, diamicton deposits, etc.), which commonly formed through mass wasting 541 processes or weathering of rock masses with a primary isotropic texture (Figs. 5A, 5B and 5G, 5H). 542 However, isotropic bimrocks may also form in the central part of diapiric bodies (see Section 3.2). 543 The isotropic texture is governed by the random distribution of blocks (see, e.g., Hard bimrock I5H 544 in Fig. 6), ranging from irregular to equiangular depending on their lithology (e.g., Festa et al., 2016 545 546 and references therein), within a softer matrix (Figs. 5A, 5B and 5G, 5H).

547

As explained above (see Section 4.2.1), the occurrences of "native" vs. "exotic" blocks also have 548 significant geotechnical and practical implications for the evaluation of the internal geomechanical 549 characteristics of isotropic bimunits. Unlike for "native" blocks of broken formations, the 550 mechanical characteristics of "exotic" blocks are difficult to be predicted because they were 551 wrenched from rock masses that are no longer present in the surrounding country rock of the 552 complex formation (see, e.g., Hard bimrock I6L in Fig. 6). In addition, the size of "exotic" blocks may 553 be highly variable, ranging from centimeters to hundreds of meters (Fig. 5F). This implies that huge 554 blocks (i.e., olistoliths) may be scattered distributed within a complex formation (see, e.g., Hard 555 bimrock I6L in Fig. 6), which mainly consists of smaller (centimeters to decimeters) blocks 556 embedded in a matrix. This is the case of many sedimentary mélanges (e.g., heterogeneous mass 557 transport deposits, see Festa et al., 2016; Ogata et al., 2019, 2020; Pini et al., 2012;) throughout 558 the world. Notable examples are the Casanova Complex in the External Ligurian Units of Northern 559 Apennines (e.g., Elter et al., 1991; Marroni et al., 2010), the Val Tiepido – Canossa and Baiso 560 561 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 562 Northern Spain (e.g., Alonso et al., 2015), the Makran olistostrome in Iran (e.g., Burg et al., 2008), 563 the carbonate mass transport deposits of the Paleogene Julian-Slovenian basin (e.g., Ogata et al., 564

2014b), the chaotic sedimentary unit of Chikura Group in Central Japan (e.g., Yamamoto et al., 565 566 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 567 568 theoretically they cannot be larger than that of the thickest bed observed in the coherent 569 (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 570 blocks in Hard bimrock I6H in Fig. 6). "Native" blocks of an isotropic broken formation actually 571 indicate the disruption and fragmentation of competent beds within a previously coherent 572lithostratigraphic unit (e.g., flysch deposits) whose average thickness can be observed and 573 measured. This means that before reaching the final characteristic isotropic texture with blocks 574 isolated within the matrix (e.g., Hard bimrock I5HL in Fig. 6), a broken formation (e.g., a flysch 575 deposit) may show different degrees of anisotropy which are comparable with those classified from 576 1 to 4 in Figure 6 (e.g., from Hard bimrock A1L to A4L in Fig. 6; see also Fig. 3C), independently of 577 the process of formation. For example, the progressive disruption of a flysch deposit during 578 slumping (Fig. 3C) may form anisotropic textures well-comparable in both block-in-matrix fabric 579 and geotechnical behavior with those formed by tectonic dismemberment (e.g., compare Fig. 3C 580 581 and Hard bimrock A4L in Fig. 6), even if the process of dismemberment is different (gravitational 582 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 583 and dismemberment. 584

585

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.

593

594 Bimsoils are included in isotropic complex formations (Fig. 6; see, e.g., bimsoil I5L) because they 595 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 596 because to geologists "soil" refers to the unconsolidated mineral and organic material on the 597 surface of Earth. But, from the point of view of an engineer, "soil" is defined as a natural aggregate 598 of mineral grains, with or without organic constituents, that can be separated by gentle mechanical 599 means such as agitation in water (Murthy, 2003). To many geotechnical engineers, "soil" can be 600 excavated using conventional earthmoving equipment, from shovel to bulldozer. Hence, the term 601 "bimsoil" refers to the geotechnical definition of soil, and identifies deposits with blocks not 602 bonded with the matrix. 603

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).

#### 610 4.2.3. Complex formations with a mixed (anisotropic/isotropic) texture (DA=M)

611 Complex formations with a mixed (anisotropic/isotropic) block-in-matrix texture include a wide 612 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 613 the primary isotropic block-in-matrix fabric is overprinted with different DA by planar surfaces (i.e., 614 foliation, bedding, etc.; see, e.g., Soft bimrock M5L and Soft bimrock M6L in Fig. 6; see also Figs. 615 5C-E and 5I). The DA may have been caused by both lithostatic and/or tectonic loading (and 616 617 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 618 619 their translations. Depending on the pervasiveness of those planar surfaces, mixed bimunits may 620 maintain an isotropic mechanical behavior or acquire an anisotropic one (see Fig. 6). In the latter 621 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 622 preferential horizons (e.g., Bimsoil M5H and Soft bimrock M5H in Fig. 6). These horizons are, in 623 turn, aligned to planar surfaces in the matrix: the resulting complex discontinuity fabrics present 624 625 geotechnical disadvantages.

#### 626 **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 639 formations, with particular reference to those with a block-in-matrix internal arrangement. 640 641 Particularly important for this classification are the composition and the degree of 642 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 643 and test results. Bimrocks are subdivided into "soft" and "hard", according to their matrix 644 characteristics and water sensitivity. The new classification, which is also based on several other 645 646 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) 647 648 but it can be easily applied to all field-based investigations of the different types of complex 649 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 650 is recommended that practitioners always match definitions with photographs of the geological 651 652 mass studied.

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#### 656 **References**

- 657Afifipour, M., Moarefvand, P., 2014. Mechanical behavior of bimrocks having high rock block658proportion.Int.J.RockMech.Min.Sci.65,40–48.659https://doi.org/10.1016/j.ijrmms.2013.11.008
- Alonso, J.L., Marcos, A., Villa, E., Suarez, A., Merino-Tomé, O.A., Fernandez, L.P., 2015. Mélanges
   and other types of block-in-matrix formations in the Cantabrian Zone (Variscan Orogen,
   northwest Spain): origin and significance. Int. Geol. Rev. 57 (5–8), 563–580.
- Amerman, R., Trudgill, B., Nelson, E.P., Pyles, D.R., 2009. 4-D distribution of deepwater mass transport deposits (Late Cretaceous Gosau Subgroup, Muttekopg Area, Northern Calcareous
   Alps, Austria): implications for syndepositional structural reconstruction. AAPG Datapages.
   Search and Discovery Article #30108.
- Anagnostou, G., Schuerch, R., Ramoni, M., 2014. TBM tunnelling in complex rock formations, in:
  Chapter 15, In: XV MIR Conference "Interventi e Opere Nelle Formazioni Complesse", 19-20
  November, Torino. pp. 307–330.
- Avşar, E., 2021. An experimental investigation of shear strength behavior of a welded bimrock by
   meso-scale direct shear tests. Eng. Geol. 294. https://doi.org/10.1016/j.enggeo.2021.106321
- Barla, G., Perello, P., 2014. Introduzione alla caratterizzazione geologica e geotecnica delle
  formazioni complesse, in: Ed, C. (Ed.), MIR 2014 XV Ciclo Di Conferenze Di Meccanica e
  Ingegneria Delle Rocce. Torino, 19-20 novembre 2014, pp. 11–38.
- Balestro,G., Nosenzo, F., Cadoppi, P., Fioraso, G., Groppo, C., Festa, A., 2020. Geology of the
  southern Dora-Maira Massif: insights from a sector with mixed ophiolitic and continental rocks
  (Valmala Tectonic Unit, Western Alps). J. Maps 16(2), 736–744.
- Barbero, E., Festa, A., Saccani, E., Catanzariti, R., D'Onofrio, R., 2020. Redefinition of the Ligurian
  Units at the Alps-Apennines junction (NW Italy) and their role in the evolution of the Ligurian
  accretionary wedge: constraints from mélanges and broken formations. J. Geol. Soc. London
  177, 562-574. https://doi.org/10.1144/jgs2019-022
- Barnes, P.M., Korsch, R.J., 1991. Mélange and related structures in Torlesse accretionary wedge,
  Wairarapa, New Zealand. N. Z. J. Geol. Geophys. 34, 517–532.
- Berkland, J.O., Raymond, L.A., Kramer, J.C., Moores, E.M., O'Day, M., 1972. What is Franciscan?
  AAPG Bull. 56, 2295–2302
- Bettelli, G., Conti, S., Panini, F., Vannucchi, P., Fioroni, C., Fregni, P., Bonacci, M., Gibellini, R.,
  Mondani, C., 2004. The mapping of chaotic rocks in Abruzzo (Central Italy): comparison with
  selected examples from Northern Apennines. In: Pasquarè, G., Venturini, C., Groppelli, G. (Eds),
  Mapping geology in Italy. Firenze, APAT SELCA, 199–206

- Bettelli, G., Panini, F. 1985. Il mélange sedimentario della Val Tiepido (Appennino modenese)—
  composizione litologica, distribuzione areale e posizione stratigrafica. Atti Soc. Nat. Mat.
  Modena 115, 91–106.
- Bettelli, G., Panini, F., 1987. I mélanges dell'Appenino settentrionale dal T. Tresinaro al T. Sillaro.
  Mem. Soc. Geol. It. 39, 187–214.
- Bettelli, G., Vannucchi, P., 2003. Structural style of the offscraped Ligurian oceanic sequences of
   the Northern Apennines: new hypothesis concerning the development of mélange block-in matrix fabric. J. Struct. Geol. 25, 371–388.
- Bortolotti, V., Chiari,M., Marroni,M., Pandolfi, L., Principi, G., Saccani, E., 2013. Geodynamic
  evolution of ophiolites from Albania and Greece (Dinaric–Hellenic belt): one, two, or more
  oceanic basins? Int. J. Earth Sci. 102, 783–811.
- Burg, J.P., Bernoulli, D., Smit, J., Dolati, A., Bahroudi, A., 2008. A giant catastrophic mud and debris
   flow in the Miocene Makran. Terra Nova 20, 181–193.
- Bürgmann, R., 2018. The geophysics, geology and mechanics of slow fault slip. Earth Planet. Sci.
  Lett. 195, 112–134.
- Cancelli, A., 1986. The determination of shear strength parameters for sheared clay shales, in:
   Proceedings of the International Symposium on Engineering in Complex Rock Formations.
   Beijing, China, pp. 297–304.
- Cerchiari, A., Remitti, F., Mittempergher, S., Festa, A., Lugli, F. & Cipriani, A. 2020. Cyclical variations
   of fluid sources and stress state in a shallow megathrust zone mélange. J. Geol. Soc. London 177,
   647-659. https://doi.org/10.1144/jgs2019-072.
- Clausmman, B., Bailleaul, J., Chanier, F., Mahieux, G., Caron, V., McArthur, A.D., Chaptal, C.,
   Morgans, H.E.G., Vendeville, B.C., 2021a. Shelf-derived mass-transport deposits: origin and
   significance in the stratigraphic development of trench-slope basins. N. Z. J. Geol. Geophys.,
   Published online: 27 May 2021, https://doi.org/10.1080/00288306.2021.1918729
- Clausmman, B., Bailleaul, J., Chanier, F., Mahieux, G., Caron, V., McArthur, A.D., Mahieux, G.,
  Chaptal, Vendeville, B.C., 2021b. Contrasting mixed siliciclastic-carbornate shelf-derived gravitydriven systems in compressional intra-slope basins (southern Hikurangi margin, New Zealand).
  Mar. Pet. Geol. 134, 105252. https://doi.org/10.1016/j.marpetgeo.2021.105252
- Cloos, M., 1982. Flow melanges: numerical modeling and geologic constraints on their origin in the
   Franciscan subduction complex, California. Geological Society of America Bulletin 93, 330–345.
- Codegone, G., Festa, A., Dilek, Y., Pini, G.A., 2012. Small-scale polygenetic mélanges in the Ligurian
   accretionary complex, Northern Apennines, Italy, and the role of shale diapirism in superposed
   mélange evolution in orogenic belts. Tectonophysics 568–569, 170–184.
- Coli, N., Tanzini, M., 2013. Characterization of the "Chaotic Complex" (Northern Apennines, Italy),
  in: Taylor & Francis Group (Ed.), Rock Mechanics for Resources, Energy and Environment.
  London, pp. 111–116.
- Cowan, D.S., 1985. Structural styles in Mesozoic and Cenozoic mélanges in the western Cordillera
  of North America. Geol. Soc. Am. Bull. 96, 451–462. https://doi.org/10.1130/00167606(1985)96<451</li>

- Dela Pierre, F., Festa, A., Irace, A., 2007. Interaction of tectonic, sedimentary and diapiric processes
  in the origin of chaotic sediments: an example from the Messinian of the Torino Hill (Tertiary
  Piedmont Basin, NW Italy). Geol. Soc. Am. Bull. 119, 1107–1119.
- D'Elia, B., Distefano, D., Esu, F., Federico, G., 1986. Slope movements in structurally complex
   formations, in: Proceedings of the International Symposium on Engineering in Complex Rock
   Formations, 3-7 November, 1986, Beijing, China. pp. 430–436.
- D'Elia, B., Picarelli, L., Leroueil, S., Vaunant, J., 1998. Geotechnical characterisation of slope
   movements in structurally complex clay soil and stiff jointed clays. Riv. Ital. di Geotec. 3, 5–32.
- Filter, P., Raggi, G., 1965. Contributo alla conoscenza dell'Apennino ligure: 1. Osservazioni
  preliminari sulla posizione delle ofioliti nella zona di Zignago (La Spezia); 2. Considerazioni sul
  problema degli olistostromi. Boll. della Soc. Geol. Ital. 84, 303–322.
- Elter, P., Marroni, M., Molli, G., Pandolfi, L., 1991. Le caratteristiche stratigrafiche del Complesso di
   M. Penna/Casanova (Alta Val di Trebbia, Appennino Settentrionale). Atti Tic. Sc. Terra 34, 97–
   106.
- Esu, F., 1977. Behaviour of Slopes in Structurally Complex Formations, in: General Report, Session
   IV. Proc. Int. Symp. The Geotechnics of Structurally Complex Formations, Capri, Italy. pp. 292–
   304.
- 747 Fagereng, Å., Sibson, R.H., 2010. Mélange rheology and seismic style. Geology 38, 751–754.
- Festa, A., 2011. Tectonic, sedimentary, and diapiric formation of the Messinian melange: Tertiary
  Piedmont Basin (northwestern Italy). In: Wakabayashi, J., Dilek, Y. (Eds.), Melanges: Processes
  of formation and societal significance. Geol. Soc. Am. Spe. Pap. 480, 215–232,
  http://dx.doi.org/10.1130/2011.2480(10).
- Festa, A., Dilek, Y., Codegone, G., Cavagna, S., Pini, G.A., 2013. Structural anatomy of the Ligurian
  accretionary wedge (Monferrato, NW Italy), and evolution of superposed mélanges. Geol. Soc.
  Am. Bull. 125 (9–10), 1580–1598. http://dx.doi.org/10.1130/B30847.1.
- Festa, A., Dilek, Y., Pini, G.A., Codegone, G., Ogata, K., 2012. Mechanisms and processes of stratal disruption and mixing in the development of mélanges and broken formations : Redefining and classifying mélanges. Tectonophysics 568–569, 7–24. https://doi.org/10.1016/j.tecto.2012.05.021
- Festa, A., Dilek, Y., Mittempergher, S., Ogata, K., Pini, G.A., Remitti, F., 2018. Does subduction of
   mass transport deposits (MTDs) control seismic behavior of shallow-level megathrusts at
   convergent margins? Gondwana Res. 60, 186-193.
- Festa, A.; Ogata, K.; and Pini, G. A., 2020. Polygenetic mélanges: a glimpse on tectonic, sedimentary
   and diapiric recycling in convergent margins. J. Geol. Soc. London 177, 551–561.
- Festa, A., Ogata, K., Pini, G.A., Dilek, Y., Alonso, J.L., 2016. Origin and significance of olistostromes
   in the evolution of orogenic belts: a global synthesis. Gondwana Res. 39, 180–203.
- Festa, A., Ogata, K., Pini, G.A., Dilek, Y., Codegone, G., 2015. Late Oligocene–early Miocene
  olistostromes (sedimentary mélanges) as tectono-stratigraphic constraints to the geodynamic
  evolution of the exhumed Ligurian accretionary complex (Northern Apennines, NW Italy). Int.
  Geol. Rev. 57 (5–8), 540–562.

- Festa, A., Pini, G.A., Dilek, Y., Codegone, G., 2010. Mélanges and mélange-forming processes: a
  historical overview and new concepts. Int. Geol. Rev. 52, 1040–1105.
  https://doi.org/10.1080/00206810903557704
- Festa, A., Pini, G.A., Ogata, K., Dilek, Y., 2019. Diagnostic features and field-criteria in recognition
   of tectonic, sedimentary and diapiric mélanges in orogenic belts and exhumed subduction accretion complexes. Gondwana Res. 74, 11–34.
- Festa, A., Barbero, E., Remitti, F., Ogata, K., Pini G.A., 2022. Mélanges and chaotic rock units:
   Implications for exhumed subduction complexes and orogenic belts. Geosystems and
   Geoenvironment 1(2), 100030. https://doi.org/10.1016/j.geogeo.2022.100030.
- Fisher, D., Byrne, T., 1987. Structural evolution of underthrusted sediments, Kodiak Islands, Alaska.
   Tectonics 6, 775–793.
- Gokceoglu, C., Zorlu, K., 2004. A fuzzy model to predict the uniaxial compressive strength and the
  modulus of elasticity of a problematic rock. Eng. Appl. Artif. Intell. 17, 61–72.
  https://doi.org/10.1016/j.engappai.2003.11.006
- 784Gong, J., Liu, J., 2015. Analysis on the mechanical behaviors of soil-rock mixtures using Discrete785Element Method. Procedia Eng. 102, 1783–1792. https://doi.org/10.1016/j.proeng.2015.01.315
- Goodman, R.E., Ahlgren, C.S., 2000. Evaluating Safety of Concrete Gravity Dam on Weak Rock: Scott
  Dam. J. Geotech. Geoenvironmental Eng. 126, 429–442. https://doi.org/10.1061/(ASCE)10900241(2000)126:5(429)
- Greenly, E., 1919. The geology of Anglesey, vols I and II. Mem. Geol. Survey. HM Stationary Office,
   London, pp. 1–388, 390–980.
- Harrison, J.P., 2014. What do we mean about complexity?, in: Chapter 2, In:XV MIR Conference
  "Interventi e Opere Nelle Formazioni Complesse", Torino. pp. 39–48.
- Hoek, E., 1994. Strength of rock and rock masses. ISRM News J. 2, 4–16.
- Hsu, K.J., 1968. Principles of Melanges and Their Bearing on the Franciscan-Knoxville Paradox. Geol.
   Soc. Am. Bull. 79, 1063–1074.
- Huang, X., Wei, Y., Ai, W., Jiang, P., 2021. Stability analysis of soil rock slope (SRS) with an
  improved stochastic method and physical models. Environ. Earth Sci. 80, 1–21.
  https://doi.org/10.1007/s12665-021-09939-2
- Kahraman, S., Alber, M., 2008. Triaxial strength of a fault breccia of weak rocks in a strong matrix.
  Bull. Eng. Geol. Environ. 67, 435–441. https://doi.org/10.1007/s10064-008-0152-3
- Kalender, A., Sonmez, H., Medley, E., Tunusluoglu, C., Kasapoglu, K.E., 2014. An approach to
  predicting the overall strengths of unwelded bimrocks and bimsoils. Eng. Geol. 183, 65–79.
  https://doi.org/10.1016/j.enggeo.2014.10.007
- Khorasani, E., Amini, M., Hossaini, M., Medley, E., 2019a. Evaluating the effects of the inclinations
  of rock blocks on the stability of Bimrock slopes. Geomech. Eng. 17, 281–287.
  https://doi.org/10.12989/gae.2019.17.3.281
- Khorasani, E., Amini, M., Hossaini, M.F., Medley, E.W., 2019b. Statistical analysis of bimslope
  stability using physical and numerical models. Eng. Geol. 254, 13–24.
  https://doi.org/10.1016/j.enggeo.2019.03.023

Kidd, W.S.F., Plesch, A., Vollmer, F.W., 1995. Lithofacies and structure of the Taconic Flysch,
Melange, & Allochthon in New York Capital District. In: Garver, J.I., Smith, J.A. (Eds.), Field Trip
Guide for the 67th Annual Meeting of the New York State Geological Association. Union College,
Schenectady, NY, 57–80.

- Kimura, G., Yamaguchi, A., Hojo, M., Kitamura, Y., Kameda, J., Ujiie, K., Hamada, Y., Hamahasi, M.,
  Hina, S., 2012. Tectonic mélange as fault rock of subduction plate boundary. Tectonophysics
  568-569, 25–38
- Lai, L.S-H., Doresy, R.J., Horng. C-S., Chi, W-R-, Shea, K-S., Yen, J-Y., 2021. Polygenetic mélange in
  the retrowedge foredeep of an active arc-continent collision, Coastal Range of eastern Taiwan.
  Sed. Geol. 418, 105901. https://doi.org/10.1016/j.sedgeo.2021.105901
- Li, X., Liao, Q.L., He, J.M., 2004. In situ tests and a stochastic structural model of rock and soil
  aggregate in the Three Gorges reservoir area, China. Int. J. Rock Mech. Min. Sci. 41, 6.
  https://doi.org/10.1016/j.ijrmms.2003.12.030
- Lindquist, E.S., 1994a. The Strength and Deformation Properties of Melange. Ph.D. Thesis.
  University of California, Berkeley.
- Lindquist, E.S., 1994b. The mechanical properties of a physical model melange., in: 7th International IAEG Congress. Austin, Texs; 1-3 June, pp. 819–826.
- Lucente, C.C., Pini, G.A., 2008. Basin-wide mass-wasting complexes as markers of the Oligo Miocene foredeep-accretionary wedge evolution in the Northern Apennines, Italy. Basin Res.
   20, 49 71.
- Lunardi, P., Cassani, F., Pennino, F., 2014. Lo scavo a piena sezione di gallerie in formazioni
  complesse, in: Chapter 14, In:XV MIR Conference: Interventi e Opere Nelle Formazioni
  Complesse, Torino. pp. 277–305.
- Mahdevari, S., Maarefvand, P., 2017. Applying ultrasonic waves to evaluate the volumetric block
  proportion of bimrocks. Arab J Geosci 10, 204. https://doi.org/10.1007/s12517-017-2999-8
- Marinos, P., Hoek, E., 2001. Estimating the geotechnical properties of rock masses such as flysch.
  Bull. Eng. Geol. Environ. 60, 85–92.
- Marinos, V., 2019. A revised, geotechnical classification GSI system for tectonically disturbed
  heterogeneous rock masses, such as flysch. Bull. Eng. Geol. Environ. 78, 899–912.
  https://doi.org/10.1007/s10064-017-1151-z
- Marroni, M., Meneghini, F., Pandolfi, L., 2010, Anatomy of the Ligure-Piemontese subduction
  system: evidence from Late Cretaceous–Middle Eocene convergent margin deposits in the
  Northern Apennines, Italy. Int. Geol. Rev. 52, 1160–1192. doi:10.1080/00206810903545493
- Medley, E.W., 2007. Bimrocks Part 1: Introduction. Newsl. Hell. Soc. Soil Mech. Geotech. Eng.
  Athens, Greece 17–21.
- 845 Medley, E.W., 2004. Observations on Tortuous Failure Surfaces in Bimrocks. Felsbau 22, 35–43.
- 846 Medley, E.W., 2001. Orderly Characterization of Chaotic Franciscan Melanges. Felsbau 19, 20–33.

# Medley, E.W., 1997. Uncertainty in estimates of block volumetric proportions in melange bimrocks. Int. Symp. Eng. Geol. Environ. 267–272.

- Medley, E.W., 1994. The engineering characterization of melanges and similar Block-in-matrix rocks
   (Bimrocks). Ph.D. thesis. University of California, Berkeley.
- Medley, E.W., Goodman, R.E., 1994. Estimating the Block Volumetric Proportions of Melanges and
  Similar Block-in-Matrix Rocks (Bimrocks), in: Proceedings of the 1st North American Rock
  Mechanics Symposium. Austin, Texas; 1-3 June, pp. 851–858.
- Medley, E.W., Sanz Rehermann, P.F., 2004. Characterization of Bimrocks (Rock/Soil Mixtures) With
   Application to Slope Stability Problems, in: Eurock 2004 & 53rd Geomechanics Colloquium.
   Salzburg, Austria.
- Medley, E.W., Zekkos, D., 2011. Geopractitioner approaches to working with antisocial mélanges,
  in: Wakabayashi, J., Dilek, Y. (Eds.), Mélanges: Processes of Formation and Societal Significance
  Geological Society of America Special Paper 480. pp. 261–277. https://doi.org/10.1016/S00652156(09)70001-8
- Moore, G.F., Aung, Lin Thu, Fukuchi, R., Sample, J.C., Hellebrand, E., Kopf, A. et al., 2019, Tectonic,
  diapiric and sedimentary chaotic rocks of the Rakhine coast, western Myanmar. Gondwana Res.
  74, 130–147.
- Murthy, V.N.S., 2003. Geotechnical Engineering: Principles and Practices of Soil Mechanics and
   Foundation Engineering, 1st Editio. ed. CRC Press.
   https://doi.org/https://doi.org/10.1201/9781482275858
- NACSN North American Commission on Stratigraphic Nomenclature, 2005. Amendments to the
   American stratigraphic code. AAPG Bull. 89 (11), 1459–1464.
- Napoli, M.L., 2021. 3D slope stability analyses of a complex formation with a block-in-matrix fabric,
   in: Challenges and Innovations in Geomechanics. IACMAG 2021. Lecture Notes in Civil
   Engineering, Vol. 126. Springer, Turin, p. 7. https://doi.org/10.1007/978-3-030-64518-2\_88
- Napoli, M.L., Barbero, M., Scavia, C., 2021a. Geomechanical characterization of an Italian complex
  formation with a block-in-matrix fabric, in: Mechanics and Rock Engineering, from Theory to
  Practice (EUROCK 2021). Torino, Italy; 20-25 September, p. 8.
- Napoli, M.L., Barbero, M., Scavia, C., 2021b. Effects of block shape and inclination on the stability
   of melange bimrocks. Bull. Eng. Geol. Environ. https://doi.org/10.1007/s10064-021-02419-8
- Napoli, M.L., Barbero, M., Scavia, C., 2021c. Tunneling in heterogeneous rock masses with a blockin-matrix fabric. Int. J. Rock Mech. Min. Sci. 138, 11.
  https://doi.org/10.1016/j.ijrmms.2021.104655
- Napoli, M.L., Barbero, M., Scavia, C., 2019. Slope stability in heterogeneous rock masses with a
   block-in-matrix fabric, in: Rock Mechanics for Natural Resources and Infrastructure
   Development- Proceedings of the 14th International Congress on Rock Mechanics and Rock
   Engineering, ISRM. Foz do Iguassu, Brazil, pp. 3482–3489.
- Napoli, M.L., Barbero, M., Scavia, C., 2018. Analyzing slope stability in bimrocks by means of a
   stochastic approach, in: Litvinenko, V. (Ed.), European Rock Mechanics Symposium, EUROCK
   2018. Saint Petersburg; 22-26 May 2018.

- Napoli, M.L., Milan, L., Barbero, M., Scavia, C., 2020. Identifying uncertainty in estimates of
  bimrocks volumetric proportions from 2D measurements. Eng. Geol. 278.
  https://doi.org/10.1016/j.enggeo.2020.105831.
- Nikolaidis, G., Saroglou, C., 2016. Engineering geological characterization of block-in-matrix rocks.
  Bull. Geol. Soc. Greece 50, 874–884.
- Ogata, K., Mountjoy, J.J., Pini, G.A., Festa, A., Tinterri, E., 2014a. Shear zone liquefaction in mass
   transport deposit emplacement: a multi-scale integration of seismic reflection and outcrop data.
   Mar. Geol. 356 (Special Issue), 50–64.
- Ogata, K., Festa, A., Pini, G.A., Alonso, J.L., 2020, Submarine landslide deposits in orogenic belts:
  olistostromes and sedimentary mélanges. In: Ogata, K., Festa, A., Pini, G.A. (Eds.), Submarine
  Landslides: subaqueous mass transport deposits from outcrop to seismic profiles. Geophysical
  Monograph 247, First Edition, American Geophysical Union, John Wiley & Sons Inc., USA, 3-26,
  https://doi.org/10.1002/9781119500513.ch1
- Ogata, K., Festa, A., Pini, G.A., Pogačnik, Ž., 2021. Mélanges in flysch-type formations: Reviewing
   geological constraints for a better understanding of complex formations with block-in-matrix
   fabric. Eng. Geol. 293, 106289, https://doi.org/10.1016/j.enggeo.2021.106289
- Ogata, K., Festa, A., Pini, G.A., Pogačnik, Ž., Lucente, C.C., 2019, Substrate deformation and
   incorporation in sedimentary mélanges (olistostromes): Examples from the northern Apennines
   (Italy) and northwestern Dinarides (Slovenia). Gondwana Res. 74, 105–129.
- Ogata, K., Pogačnik, Ž., Pini, G.A., Tunis, G., Festa, A., Camerlenghi, A., Rebesco, M., 2014b. The
   carbonate mass transport deposits of the Paleogene Julian-Slovenian Basin (Italy/Slovenia):
   internal anatomy and inferred genetic processes. Mar. Geol. 356, 88–110.
- Orange, D.L., 1990. Criteria helpful in recognizing shear-zone and diapiric mélanges: examples from
   the Hoh accretionary complex, Olympic Peninsula, Washington. Geol. Soc. Am. Bull. 102, 935–
   911 951.
- Ortner, H., 2001. Growing folds and sedimentation of the Gosau Group, Muttekopf, Northern
  Calcareous Alps, Austria. Int. J. Earth Sci. 90, 727–739.
- Panini, F., Fioroni, C., Fregni, P., Bonacci, M., 2002. Le rocce caotiche dell'Oltrepo Pavese: note
  illustrative della Carta Geologica dell'Appennino vogherese tra Borgo Priolo e Ruino. Atti Tic. Sc.
  Terra 43, 83–109.
- 917 Pini, G.A., 1999. Tectonosomes and olistostromes in the Argille Scagliose of the Northern
  918 Apennines, Italy. Geol. Soc. Am. Spe. Pap. 335, 73 pp.
- Pini, G.A., Lucente, C.C., Venturi, S., Ogata, K., 2020, Mass-Transport Complexes of the Marnosoarenacea foredeep turbidite system (Northern Apennines, Italy): a reappraisal after twentyyears. In: Ogata, K., Festa, A., Pini, G.A. (Eds.), Submarine Landslides: subaqueous mass transport deposits from outcrop to seismic profiles. Geophysical Monograph 247, First Edition, American Geophysical Union, John Wiley & Sons Inc., https://doi.org/10.1002/9781119500513.ch8
- Pini, G.A., Ogata, K., Camerlenghi, A., Festa, A., Lucente, C.C., Codegone, G., 2012. Sedimentary
   mélanges and fossil mass-transport complexes: a key for better understanding submarine mass
   movements? In: Yamada, Y., et al. (Eds.), Submarine Mass Movements and Their Consequences

- Advances in Natural and Technological Hazards Research 31. Springer Science+Business MediaB.V., pp. 585–594
- Ramos-Cañón, A.M., Castro-Malaver, L.C., Padilla-Bello, N. V., Vega-Posada, C.A., 2020. 929 Incertidumbre en la determinación del Porcentaje Volumétrico de Blogues de BIMrocks/BIMsoil 930 partir de información unidimensional. Rev. Boletín Geol. 42. 69-80. 931 а https://doi.org/10.18273/revbol.v42n1-2020004 932
- Raymond, L.A., 1984. Classification of melanges. In: Raymond, L.A., Boulder, L.A. (Eds.), Melanges:
   Their Nature, Origin and Significance, in: Geological Society of America Special Paper 198. pp. 7–
   20.
- Raymond, L.A., 2019, Perspectives on the roles of mélanges in subduction accretionary complexes:
   A review. Gondwana Res. 74, 72–93.
- Remitti, F., Bettelli, G., Vannucchi, P., 2007. Internal structure and tectonic evolution of an
  underthrusted tectonic mélange: the Sestola-Vidiciatico tectonic unit of the Northern
  Apennines, Italy. Geodin. Acta 20(1-2), 37-51.
- Remitti, F., Vannucchi, P., Bettelli, G., Fantoni, L., Panini, F., Vescovi, P., 2011. Tectonic and
  sedimentary evolution of the frontal part of an ancient subduction complex at the transition
  from accretion to erosion: the case of the Ligurian wedge of the northern Apennines, Italy.
  Geolo. Soc. Am. Bull. 123, 51–70.
- 945 Silver, E.A., Beutner, E.C., 1980. Melanges. Geology 8, 32–34.
- Sonmez, H., Ercanoglu, M., Kalender, A., Dagdelenler, G., Tunusluoglu, C., 2016. Predicting uniaxial 946 compressive strength and deformation modulus of volcanic bimrock considering engineering 947 dimension. Int. J. Rock Mech. Min. Sci. 86, 91–103. 948 https://doi.org/10.1016/j.ijrmms.2016.03.022 949
- Sonmez, H., Kasapoglu, K., Coskun, A., Tunusluglu, C., Medley, E.W., Zimmerman, R.W., 2009. A
  conceptual empirical approach for the overall strength of unwelded bimrocks, in: ISRM Regional
  Symposium, Rock Engineering in Difficult Ground Condition, Soft Rock and Karst, Dubrovnik,
  Croatia, 29-31 October.
- Sunesson, N.H., 1993. The geology of the Torlesse Complex along the Wellington area coast, North
  Island, New Zealand. N. Z. J. Geol. Geophys. 36, 369-384
- Tsesarsky, M., Hazan, M., Gal, E., 2016. Estimating the elastic moduli and isotropy of block in matrix
  (bim) rocks by computational homogenization. Eng. Geol. 200, 58–65.
  https://doi.org/10.1016/j.enggeo.2015.12.003
- Vannucchi, P., Bettelli, G., 2010. Myths and recent progress regarding the Argille Scagliose,
  Northern Apennines, Italy. In: Dilek, Y. (Ed.), Alpine Concept in Geology. Int. Geol. Rev. 52 (10–
  12), 1106–1137.
- Vezzani, L., Festa, A., Ghisetti, F., 2010. Geology and Tectonic evolution of the Central-Southern
  Apennines, Italy. Geol. Soc. Am. Spe. Pap. 469, 58 pp., accompanying by a CD-ROM including the
  "Geological-Structural Map of the Central-Southern Apennines (Italy)" at 1:250.000 scale,
  Sheets 1 and 2, doi: http://dx.doi.org/10.1130/2010.2469

966 Wakabayashi, J., 2012. Subducted sedimentary serpentinite mélanges: record of multiple burial-967 exhumation cycles and subduction erosion. Tectonophysics 568–569, 230–247.

Wakabayashi, J., 2021. Field and petrographic reconnaissance of Franciscan complex rocks of
Mount Diablo, California: Imbricated ocean floor stratigraphy with a roof exhumation fault
system. In: Sullivan, R., Sloan, D., Unruh, J.R., Schwartz, D.P. (eds.), Regional Geology of Mount
Diablo, California: Its Tectonic Evolution on the North America Plate Boundary. Geol. Soc. Am.
Mem. 217, 155–178, https://doi.org/10.1130/2021.1217(09).

- Wang, H., 2014. Numerical direct shear tests for outwash deposits with random structure and
   composition. https://doi.org/10.1007/s10035-014-0504-6
- Wang, S., Li, Y., Gao, X., Xue, Q., Zhang, P., Wu, Z., 2020. Influence of volumetric block proportion
  on mechanical properties of virtual soil-rock mixtures. Eng. Geol. 278.
  https://doi.org/10.1016/j.enggeo.2020.105850
- Xu, W., Xu, Q., Hu, R., 2011. Study on the shear strength of soil-rock mixture by large scale direct
  shear test. Int. J. Rock Mech. Min. Sci. 48, 1235–1247.
  https://doi.org/10.1016/j.ijrmms.2011.09.018

Yang, Y., Sun, G., Zheng, H., Qi, Y., 2019. Investigation of the sequential excavation of a soil-rockmixture slope using the numerical manifold method. Eng. Geol. 256, 93–109.
https://doi.org/10.1016/j.enggeo.2019.05.005

- Zhang, Z., Sheng, Q., Fu, X., Zhou, Y., Huang, J., Du, Y., 2020. An approach to predicting the shear
  strength of soil-rock mixture based on rock block proportion. Bull. Eng. Geol. Environ. 79, 2423–
  2437. https://doi.org/10.1007/s10064-019-01658-0
- Zhou, H., Zhang, C., Li, Z., Hu, D., Hou, J., 2014. Analysis of mechanical behavior of soft rocks and
  stability control in deep tunnels. J. Rock Mech. Geotech. Eng. 6, 219–226.
  https://doi.org/10.1016/j.jrmge.2014.03.003
- Yamamoto, Y., Ogawa, Y., Uchino, T., Muraoka, S., Chiba, T., 2007. Large-scale chaotically mixed
   sedimentary body within the Late Pliocene to Pleistocene Chikura Group, Central Japan., Island
   Arc 16, 505-507.
- 993
- 994 Figure captions
- 995
- 996 **Figure 1** Classifications of complex formations by (**A**) Esu (1977) and (**B**) Marinos (2019).
- 997
- 998 **Figure 2** Schematic illustration showing the transition from a coherent lithostratigraphic unit (or
- 999 sequence) to a chaotic rock unit (modified from Festa et al., 2019, 2020). Different mechanisms
- 1000 (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.

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1006 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 1007 1008 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 1009 1010 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 1011 1012 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 1013 coherent unit (top) to the early stage of development of a broken formation (bottom) trough 1014 slumping and related boudinage in the Miocene flysch deposits of the Marnoso arenacea Fm. 1015 (Passo dei Mandrioli) in Northern Apennines of Italy. (D) Progressive stratal disruption of a well 1016 1017 bedded unit (Flysch Rosso) forming a broken formation with lozenge-shaped blocks of mudstone 1018 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 1019 within a mudstone matrix displaying a pervasive scaly fabric (broken formation), due to tectonic 1020 deformation within a shear zone (Waimarama Beach, South Hawke's Bay, East Coast of North 1021 Island, New Zealand; Courtesy of G.A. Pini). Note that blocks long axes are aligned to the main shear 1022 zone. (F) Field-detail of a broken formation characterized by a high degree of stratal disruption with 1023 isolated hard sigmoidal blocks embedded in softer (clayey) matrix (Bobbio Tectonic Window, 1024 1025 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 1026 Upper Triassic pelagic limestone blocks in a heterogeneous and variously deformed matrix 1027 composed of shale, mudstone, and sandstone in the Jurassic-Cretaceous Avdella mélange (Pindos 1028 Mountains, Northern Greece). (I) Huge exotic ultramafic and limestone blocks, lenticular in shape, 1029 embedded in a fine grained green reddish ophiolitic matrix of the Cretaceous Ankara Ophiolitic 1030 Mélange (Central Anatolia, Turkey). Geoscientists for scale. 1031

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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).

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Figure 5 – Field examples showing different types of sedimentary (A-I) and diapiric (J-L) mélanges. 1039 1040 (A) Internal arrangement of a sedimentary mélange, showing the random distribution (isotropic 1041 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 1042 angular clasts of ultramafic rocks in a fine- to medium grained matrix of the same composition 1043 (Ligurian Units, Northern Apennines, Italy); note the block-in-matrix isotropic texture (hammer for 1044 scale). (C) Detail of sedimentary mélange consisting of highly disordered block-in-matrix fabric of 1045 trench-related debris flow with variably shaped blocks (equidimensional, tabular, phacoidal, and 1046 irregular) of metavolcanic and metagraywacke rocks (Panoche Road, Franciscan Complex, 1047 1048 California; see Wakabayashi, 2012 for details). (D) Outcrop view showing the block-in-matrix fabric 1049 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 1050 (Berceto, Parma area of the Northern Apennines of Italy). (E) Close-up view of a tectonically 1051 reworked sedimentary mélange (debris flow deposit) with blocks of an oceanic cover succession in 1052 a sheared, shaly matrix (Casanova Complex, Northern Apennines, Italy). Note that both the matrix 1053 and the block-in-matrix fabric define an isotropic texture (camera cap for scale). (F) Panoramic view 1054 of a sedimentary mélange showing the random distribution of huge Upper Cretaceous blocks 1055 1056 (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 1057 300m high. (G) Close-up view of a bimsoil (diamicton, i.e., glacial till) showing the random 1058 distribution (i.e., isotropic texture) of angular blocks and clasts, which are suspended in a fine-1059 1060 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 1061 1062 fabric defines a weak anisotropic texture acquired during depositional emplacement (Ivrea

1063 Morainic Amphitheatre, Northwestern Alps of Italy). Hammer for scale. (I) Close-up view of a 1064 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 1065 1066 (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 1067 1068 arrangement (Northern Apennines, Italy). Note that in the center of the diapiric body (core zone), 1069 blocks, which are larger in size (i.e., up to tens of meters), are commonly angular, loosely clustered, 1070 and randomly distributed the irregularly folded matrix. Close to the margins (J and K), the block-in-1071 matrix fabric shows a sub-vertical trending with phacoidal to tabular blocks, embedded within a 1072 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 1073 1074 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 1075 1076 Festa et al. 2013 for details).

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Figure 6 – Proposed classification of geotechnically complex formations with block-in-matrix fabric, 1078 1079 showing the transition from a coherent unit to different types of chaotic rock units. Different 1080 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, 1081 sedimentary, and diapiric). Four parameters, which have a primary role in controlling the 1082 geotechnical behavior of bimunits, are at the base of this new classification: (i) the composition 1083 and nature of blocks and the matrix that affects the water sensitivity over a short period (Hard 1084 bimrocks, Soft bimrocks and Bimsoils); (ii) the degree of anisotropy (anisotropic - A, isotropic - I, 1085 1086 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 1087 1088 text for explanation.