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Original

Practical classification of geotechnically complex formations with block-in-matrix fabrics / Napoli, MARIA LIA; Festa, Andrea; Barbero, Monica. - In: ENGINEERING GEOLOGY. - ISSN 0013-7952. - ELETTRONICO. - 301:106595(2022). [10.1016/j.enggeo.2022.106595]

Availability:

This version is available at: 11583/2957930 since: 2022-03-24T18:22:10Z

Publisher:

Elsevier

Published

DOI:10.1016/j.enggeo.2022.106595

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

Maria Lia Napoli^{a*}, Andrea Festa^{b,c}, Monica Barbero^a

^a*Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, C.so Duca degli Abruzzi 24, 10124, Torino, Italy*

^b*Department of Earth Sciences, Università degli Studi di Torino, Via Valperga Caluso 35, Torino, Italy*

^c*CNR-IGG, National Research Council of Italy, Institute of Geosciences and Earth Resources, Via Valperga Caluso 35, Torino, Italy*

* Corresponding author: Maria Lia Napoli, maria.napoli@polito.it (ORCID: 0000-0002-3396-4370)

andrea.festa@unito.it (ORCID: 0000-0001-5325-0263)

monica.barbero@polito.it (ORCID: 0000-0002-7917-540)

Abstract

The terms “bimrocks”, “bimsoils” and “soil-rock mixtures” indicate different and very common types of geological units with a block-in-matrix fabric that are also “geotechnically complex formations” and are characterized by an internal heterogeneity, and spatial variability of mechanical parameters and lithological compositions. Due to this internal complexity, the understanding of their geomechanical behavior presents a key challenge in geotechnical engineering. However, the lack of a standardized and clear terminology complicates the discrimination of different types of complex formations and their internal mechanical properties, which leads to inconsistency in the literature and research studies. This inconsistency causes misunderstandings, with possible practical implications for the characterization, analysis, design and construction of engineering works. By a combination of geological and geotechnical observations, we propose a new classification for geotechnically complex formations, with particular attention to those with a block-in-matrix internal fabric. Four properties are at the base of this new classification and have a primary role in controlling the geotechnical behavior of block-in-matrix units (bimunits): (i) the composition (i.e., lithology, degree of lithification/consolidation, nature, and rheology) of blocks and the matrix that affects the water sensitivity, (ii) the degree of internal anisotropy (DA) of the block-in-matrix fabric, (iii) the degree of stratal disruption and mixing, and (iv) the volumetric block proportion (VPB). As a result, we classified bimunits in those

31 with “anisotropic”, “isotropic”, and “mixed” (i.e., different behavior depending on the DA of the
32 matrix) textures and, each of these types, into block-in-matrix rocks and block-in-matrix soils
33 (bimrocks and bimsoils in the following). According to the water sensitivity of the matrix, bimrocks
34 are also differentiated into “hard” and “soft”. The novelty of the classification is that it is not limited
35 to few types of geotechnically complex formations (e.g., flysch) but it can be easily applied to all
36 field-based investigations of the different types of complex formations, regardless of their internal
37 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**

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

57 delays, economic repercussions and health and safety risks have occurred at many engineering
58 projects developed on complex formations (Goodman and Ahlgren, 2000; Lunardi et al., 2014;
59 Medley, 2007, 2001). These difficulties have encouraged both private and public institutions to
60 develop and fund several research projects all over the world during the 40 years (e.g., the Italian
61 Research Council (C.N.R.) (D’Elia et al., 1998), the California Department of Water Resource’s
62 Division of Safety of Dams – DSOD, see (Lindquist, 1994a; Medley, 1994), the National Natural
63 Science Foundation of China, see (Huang et al., 2021; Wang, 2014; Yang et al., 2019; Zhou et al.,
64 2014), and the Alexander von Humboldt Foundation, see (Kahraman and Alber, 2008), to better
65 understand the geotechnical behavior of heterogeneous formations with a block-in-matrix fabric.
66

67 A significant problem results from the inappropriate or loose use of the term “complex formation”
68 to indicate a broad range of lithological units or complexes (e.g., mélanges, weathered rocks,
69 conglomerates, agglomerates, flysch deposits, pyroclastites, olistostromes, breccias, fault rocks,
70 etc.), all having very dissimilar fabrics and structural organization, composition and, therefore,
71 rheological and geotechnical characteristics. In addition, different technical fields use various terms
72 to indicate complex formations with mixed strong/weak rocks. For example, “Mixed Face
73 Conditions” and “Soft Rock-Hard Rock” are commonly used in tunneling and mining, respectively.
74 To overcome this problem, geopractitioners have introduced and widely used terms such as
75 “bimrock” (Medley, 1994), “bimsoil” (Medley and Goodman, 1994) and “soil-rock mixture” (SRM;
76 Xu et al., 2011) to indicate such heterogeneous formations. “Bimrock” is the acronym of “block-in-
77 matrix rock”, an extension of the geological term “block-in-matrix” which was introduced by
78 Raymond (1984) to indicate chaotic rock units with hard blocks embedded within a softer matrix
79 (i.e., the fabrics of mélanges). Medley (1994) defined a bimrock as *“a mixture of rocks, composed
80 of geotechnically significant blocks within a bonded matrix of finer texture”*. In this definition, the
81 expression *“geotechnically significant blocks”* indicates that a sufficient mechanical contrast
82 between competent blocks and weaker matrix must exist, and that both the volume and dimension
83 of the hard inclusions influence the rock mass properties at the scales of engineering interest
84 (which range between centimeters and hundreds of meters). Medley (1994) introduced the
85 acronym “bimsoil” (block-in-matrix soil) for geological units with rock blocks embedded in a soil-
86 like matrix (Kalender et al., 2014; Medley and Goodman, 1994; Sonmez et al., 2016).
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)
90 (Li et al., 2004). “Bimrocks” have been subdivided into “welded” and “unwelded” (Kalender et al.,
91 2014; Khorasani et al., 2019b; Sonmez et al., 2009), according to the strength of the blocks-matrix
92 interface. Specifically, the strength of interfaces between blocks and matrix is approximately equal
93 to that of the matrix for welded bimrocks, while the strength is lower than that of the matrix for
94 unwelded bimrocks. However, it can be extremely difficult to estimate the strength of block-matrix
95 interfaces of a bimunit before ascribing it to the welded or unwelded category.

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

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

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

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

117 2. Previous classifications of complex formations

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

139
140 Marinos and Hoek (2001) proposed a quantitative classification of complex formations, later
141 extended by Marinos (2019) (Fig. 1). The Geological Strength Index (GSI) of the Rock Mass
142 Classification System was used with the Hoek-Brown failure criterion (Hoek, 1994) (with associated
143 m , s , and a parameters), so that rock mass strength could be predicted for both “normal” and some
144 types of heterogeneous “complex” formations (e.g., flysch deposits). Although this classification
145 covers a wide range of complex geomaterials, most of those with a block-in-matrix internal
146 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.

153
154 Hence, to date, a new classification system is necessary, that accounts for the engineering
155 geological conditions and geotechnical behavior of complex formations with a block-in-matrix
156 internal arrangement and facilitating their link with geological observations.

157 **3. Linking geological and geotechnical terminology for bimunits**

158 Geotechnical and engineering works on complex formations investigate, interpret and model
159 geological units. Rock units like *mélanges*, weathered rocks, conglomerates, agglomerates, flysch
160 deposits, pyroclastites, olistostromes, breccias, fault rocks, and several others, are generally
161 categorized as “geotechnically” complex formations even if most of them are not considered
162 complex formations from the geological point of view (Anagnostou et al., 2014; Barla and Perello,
163 2014). In addition, those rock units represent different geological deposits, with dissimilar internal
164 organization, composition, rheology, size of blocks and, therefore, different
165 mechanical/geotechnical characteristics. Hence, to avoid confusion and misunderstanding
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,
169 which are significant for geotechnical characterization. We use the general term bimunits because
170 it includes both bimrock and bimsoil complex formations.

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

174 may be used, at least in part, as a synonym or alias for of a wide range of “chaotic rock units” whose
175 complexity is due to their internal block-in-matrix fabric, which differs from that of coherent and/or
176 well-bedded units (see, e.g., [Berkland et al., 1972](#); [Raymond, 1984](#); [Silver and Beutner, 1980](#); for
177 details). The general and non-genetic term “chaotic rock units” ([Fig. 2](#)) includes broken formations
178 and mélanges (see below), which represent the product of stratal disruption and mixing of primary
179 coherent lithostratigraphic units, acting by tectonic, sedimentary (gravitational) or diapiric
180 processes and their interaction (see, e.g., [Festa et al., 2010](#); [Raymond, 1984](#); [Silver and Beutner,](#)
181 [1980](#); for details). In geology, the term “mélange” ([Greenly, 1919](#)) is a descriptive and non-genetic
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
184 pervasively deformed finer matrix, without restriction to any particular lithological unit (e.g.,
185 [Berkland et al., 1972](#); [Cowan, 1985](#); [Raymond, 1984](#); [Silver and Beutner, 1980](#)). The term “exotic”
186 includes all types of blocks that are “foreign” with respect to the matrix of a mélange (see [Hsü,](#)
187 [1968](#); [Festa et al., 2012](#)). Hence, their source is not present in the surrounding lithological units
188 within a mélange zone, and they are different from any lithology found in country rocks (see [Festa](#)
189 [et al., 2019](#) for a complete discussion). Notable examples of “exotics” are, among several others,
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
192 California (e.g., [Cloos, 1982](#); [Raymond, 2019](#); [Wakabayashi, 2021](#)), mixed blocks of mantle rocks
193 (serpentinite, gabbro and basalt), granitoids, chert and limestone embedded in a clay matrix such
194 as in the Ligurian Units in Northern Apennines (e.g., [Barbero et al., 2020](#); [Bettelli and Panini, 1987](#);
195 [Elter and Raggi, 1965](#); [Marroni et al., 2010](#)); in the Dinaric-Hellenic orogenic belt (e.g., [Bortolotti](#)
196 [et al., 2013](#) and references therein), and in the Valmala Shear Zone in the Western Alps (e.g.,
197 [Balestro et al., 2020](#)). On the other hand, the geological term “broken formation” ([Hsu, 1968](#)) is
198 used to define a disrupted rock unit, with a block-in-matrix fabric, that contains no “exotic” blocks
199 but only “native” ones ([Figs. 2 and 3D-F](#)). “Native” blocks are “intraformational” components
200 originated only from the disruption of a primary lithostratigraphic unit ([Figs. 3A-C](#)). Therefore, a
201 “broken formation” differs from a “mélange” because it preserves its lithological and chronological
202 identity (e.g., [Festa et al., 2020, 2022](#); [Hsü, 1968](#); [Pini, 1999](#); [Raymond, 1984](#); and references
203 therein). Broken formations commonly show a gradual transition from to the coherent, well-
204 bedded, primary succession to the highly disrupted block-in-matrix fabric ([Figs. 2 and 3A-F](#)).

205 Notable examples are represented by the *Argille scagliose* or *Argille varicolori* (Varicolored scaly
206 clays) of the Ligurian Units in the Northern Apennines (e.g., Bettelli et al., 2004; Festa et al., 2013;
207 Pini, 1999), the *Flysch Rosso* on the Southern Apennines (e.g., Vezzani et al., 2010), the Taconic
208 flysch or Taconic mélange in the Northern Appalachians (e.g., Kidd et al., 1995), the chaotic rock
209 units in the Shimanto belt in Japan (e.g., Kimura et al., 2012), in the US-Western Cordillera (e.g.,
210 Cowan, 1985; Hsü, 1968; Raymond, 1984, 2019), in the McHugh complex in Alaska (e.g., Fisher and
211 Byrne, 1987), and in the Torlesse accretionary wedge in New Zealand (e.g., Barnes and Korsh, 1991;
212 Sunesson, 1993) among several others. Importantly, disrupted, or dismembered flysch deposits
213 without “exotic” blocks included, correspond to “broken formations” and not to “mélanges” (see,
214 e.g., Ogata et al., 2021). The heterogeneous to block-in-matrix complex formations classified by
215 Esu (1977), Marinós and Hoek (2001), and Marinós (2019) represent, therefore, typical broken
216 formations (i.e., without “exotic” blocks), which are differentiated according to their degree of
217 stratal disruption. Those different degrees of stratal disruption (i.e., Groups “B1” to “B3” of Esu,
218 1977; and Types VIII to XI of Marinós, 2019) are well comparable, in fact, with those described in
219 geology (Fig. 2), ranging from stratigraphic units with locally broken internal stratal continuity to
220 rock bodies without internal stratal continuity or exotic blocks (see, e.g., Raymond, 1984). Hence,
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 block-
223 matrix interface strength (e.g., Festa et al., 2019, 2022; Ogata et al., 2021 and references therein),
224 strongly affecting their sampling, characterization, mechanical behavior and modeling.

225 From the geological point of view, other types of heterogeneous units (e.g., weathered rocks,
226 conglomerates, agglomerates, pyroclastites, etc.), which could be regarded as geotechnically
227 complex formations, exclude broken formations or mélanges in strict sense (see, e.g., Festa et al.,
228 2012).

229 3.2. Internal organization of different types of bimunits

230 A significant aspect of complex formations (i.e., mélanges and broken formations), which is well-
231 known in geology, is that their block-in-matrix fabric differs in relation to the process of their
232 formation (i.e., tectonic, sedimentary or diapiric; e.g., Festa et al., 2010, 2019 and references
233 therein, see Fig. 2). Those dissimilar internal fabrics (Fig. 2), with different shapes and distributions

234 of blocks, have a significant control on the mechanical behavior of chaotic rock units and fluid
235 migration, as documented for example for seismic rupture propagation (e.g., [Bürgmann, 2018](#);
236 [Cerchiari et al., 2020](#); [Fagereng and Sibson, 2010](#); [Festa et al., 2018](#)), and therefore significant
237 geotechnical implications, such as different failure modes according to the shape and orientation
238 of rock blocks ([Huang et al., 2021](#); [Khorasani et al., 2019a](#); [Napoli et al., 2021b, 2019](#)) and associated
239 fabrics.

240

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

254 Tectonic mélanges and broken formations can be considered structurally equivalent to mappable
255 fault or shear zones (e.g., [Cowan, 1974](#)). Broken formations roughly correspond to Types X and XI
256 of [Marinos \(2019\)](#), and in part to group B2 of [Esu \(1977\)](#). Blocks may range in size from centimeters
257 to hundreds of meters ([Fig. 3](#)), depending on the thickness of the shear zone in which they formed
258 and the magnitude of the tectonic strain during shearing. The matrix of both tectonic mélanges and
259 broken formations is commonly deformed to a typical scaly fabric formed by anastomosing
260 polished surfaces ([Fig. 3E](#)), spaced millimeters to centimeters apart (e.g., [Bettelli and Vannucchi,](#)
261 [2003](#); [Pini, 1999](#); [Vannucchi and Bettelli, 2010](#)). On the whole, the alignment of lenticular to
262 sigmoidal blocks and the scaly fabric defines the planar anisotropy (i.e., transversal isotropy; [Fig.](#)
263 [3](#)). Notable examples occur in the Franciscan Complex in California (e.g., [Cloos, 1982](#); [Wakabayashi,](#)
264 [2012](#)), the Ligurian Units in the Northern Apennines (e.g., [Bettelli et al., 2004](#); [Festa et al., 2013](#);

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

267
268 Sedimentary (i.e., gravitational) mélanges (or olistostromes) correspond to different types of
269 heterogeneous mass transport deposits, ranging from submarine debris flow, block flow, slide and
270 slumps (see, e.g., [Ogata et al., 2019, 2020](#); [Pini et al., 2012](#)). The block-in-matrix fabric of
271 sedimentary mélanges and broken formations (or endolistostromes *sensu* [Elter and Raggi, 1965](#)),
272 strongly contrasts with that formed by tectonic processes ([Fig. 2](#)). Independent of the scale of
273 observation, they are characterized by a highly disordered block-in-matrix arrangement ([Figs. 2 and](#)
274 [3](#)) with blocks of different shape (e.g., irregular to equiangular, depending on their lithology),
275 lithology, age, size (e.g., from centimeters to hundreds of meters up to a few kilometers), floating
276 with a random distribution in a finer grained matrix (see [Festa et al., 2016, 2019](#) for details). The
277 random distribution of blocks and the brecciated texture of the matrix define an isotropic texture
278 at all scales ([Figs. 2, 5A, 5B, 5F](#)). The mean aspect ratio (long axis/short axis) of blocks ranges
279 between 1.4 and 2.5 (see [Festa et al., 2019](#) for details; see [Figs. 4B, 4D](#)). The matrix is commonly
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
283 uncommon that the matrix of ancient sedimentary mélanges is affected by a planar anisotropy
284 related to lithostatic or tectonic loading, or later tectonic reworking (i.e., polygenetic mélanges in
285 [Fig. 2](#); see [Festa et al., 2020](#) for details) of the block-in-matrix fabric ([Figs. 5D, 5E, 5I](#)). Therefore,
286 depending on the degree of anisotropy of the matrix, they may have a mixed texture, ranging from
287 isotropic to anisotropic. In addition, the base of sedimentary mélanges and broken formations,
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
290 (see [Festa et al., 2016, Ogata et al., 2019](#) for details).

291 There is not a direct correspondence with the classifications of [Esu \(1977\)](#), [Marinos and Hoek](#)
292 [\(2001\)](#) and [Marinos \(2019\)](#) as group “C” of [Esu \(1977\)](#) represents “residual and colluvial soils” rather
293 than mass transport deposits. Notable examples of sedimentary mélanges and gravitational broken
294 formations are the Makran olistostrome in Iran (e.g., [Burg et al., 2008](#)), the Val Tiepido-Canossa
295 and the Baiso argillaceous breccias in the Northern Apennines (e.g., [Bettelli et al., 2004](#); [Festa et](#)

296 al., 2015, 2020; Pini, 1999; Remitti et al., 2011), the Specchio mass transport complex (e.g., Ogata
297 et al., 2014a) and those in the Marnoso-Arenacea foredeep deposits (e.g., Lucente and Pini, 2008;
298 Pini et al., 2020) in Northern Apennines, the mass transport deposits associated with the Hikurangi
299 margin in New Zealand (e.g., Clausmman et al., 2021a, 2021b), the Lichi mélange in Taiwan (e.g.,
300 Lai et al., 2021), and the Porma mélange in Northern Spain (e.g., Alonso et al., 2015). Several of
301 those examples may cover wide sectors up to several tens of thousands square kilometers (see
302 Festa et al., 2016 and Ogata et al., 2020 for a complete review).

303

304 Diapiric mélanges and broken formations are characterized by a distribution of the block-in-matrix
305 fabric which shows internal zoning from margins to the core of the diapir (e.g., Codegone et al.,
306 2012; Dela Pierre et al., 2007; Orange, 1990; see Figs. 2 and 5J-5K). Close to the margins (i.e., close
307 to the intrusive contacts with the country rock), the fabric commonly shows a sub-vertical trending
308 with phacoidal to tabular blocks, embedded within a fine-grained (shaly or clay) matrix, pervasively
309 deformed by scaly fabric, and aligned to the intrusive contacts (Figs. 2 and 5K, 5L). The clustering
310 of blocks and the pervasiveness of the scaly fabric gradually decrease toward the center of the
311 diapiric body where blocks, which are larger in size (i.e., up to tens of meters), are commonly
312 angular, loosely clustered, and randomly distributed within a non-foliated, and irregularly folded,
313 matrix (Figs. 2 and 5J). The main aspect ratio of blocks (long axis/short axes) decreases from 2.9
314 and 3.8 to 1.6 and 3.2 from the marginal zone to the center of the diapiric body, respectively (Figs.
315 4C, 4D). The alignment of both blocks and the scaly fabric to the intrusive margins defines a planar
316 anisotropy, which gradually passes to a partially isotropic texture toward the center of the diapir
317 (Fig. 2). Although formed by a different process, part of the block-in-matrix fabric of diapiric
318 mélanges and broken formations resembles Types VII, VIII, X and XI (compare Figs. 1 and 2) of
319 Marinos (2019), and groups B2 and B3 of Esu (1977). Notable examples occur in the Olympic
320 Peninsula in the US-Cordillera (e.g., Orange, 1990), in the Myanmar (e.g., Moore et al., 2019), in
321 East Timor in Indonesia (e.g., Brown, 2013 and reference therein), in the Northern Apennines (e.g.,
322 Codegone et al., 2012; Dela Pierre et al., 2007; Festa, 2011).

323

324 All the above examples show that the geological distinction between the different types of
325 mélanges and broken formations, as well as between “exotic” and “native” blocks, are fundamental
326 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.

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

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

349

350 In order to address these issues, in the following we propose a new classification of geomaterials
351 with a block-in-matrix fabric (see [Section 4.2](#)), with the aim of reducing the terminological and
352 practical gap between geologists and engineers and provide a useful tool for all geopractitioners
353 and researchers working in the broad field of geotechnically complex formations. The novelty of
354 this classification is that the close relation with geological observations (and terminology) requires

355 the evaluation of four main properties (see [Sections 4.1](#)) that play a significant role in distinguishing
356 bimunits with different geotechnical characteristics.

357 **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
359 on their lithology (e.g., quartzite, limestone, marlstone, claystone, volcanic rocks, etc.), nature (e.g.,
360 metamorphosed or non-metamorphosed), degree of lithification/recrystallization, and rheological
361 contrast between blocks and the matrix, complex formations have different mechanical contrast
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
364 influence the geotechnical characteristics. Their mechanical behavior also changes in the presence
365 of additional factors, such as pressure, temperature, fluid pressure, strain rate, and fluid/water
366 content. Particularly, depending on the lithology and mineralogy, complex formations are
367 differently sensitive to water. This is quite evident in comparing, for example, a complex formation
368 consisting of serpentinite blocks embedded in a micaschist matrix and one of limestone blocks
369 embedded in a marly matrix.

370

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

383 transport deposits) may change the DA depending on the pervasiveness of planar surfaces (see
384 [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
387 dismemberment of complex formations, ranging from coherent units to different types of bimunits
388 (i.e., broken formations, and *mélanges*). Coherent units represent lithostratigraphic or lithological
389 units in which their primary internal organization (e.g., beds, layers) is well preserved ([Figs. 2 and](#)
390 [3B](#)). Non- to poorly deformed (but not disrupted) flysch deposits, consisting of alternating of
391 layers/beds with different competence, represent the most common example of coherent complex
392 formations ([Fig. 3B](#)). Broken formations represent the progressive disruption and dismemberment
393 of a primary coherent complex formation or a lithostratigraphic unit characterized by beds/layers
394 with internal contrasting competence, such as, for example, flysch deposits. They can range from
395 slightly disrupted formations ([Figs. 3B-D](#)), in which a roughly continuity of primary layers/beds is
396 still present, to “native” blocks completely isolated within the matrix (i.e., without any
397 layering/bedding-continuity preserved; see [Section 3.1](#); see [Figs. 3E and 3F](#)). On the other hand,
398 *mélanges* represent the mixing of “exotic” blocks (i.e., their source is not present in the surrounding
399 lithological units within a *mélange* zone ([Figs. 3G-I](#)), and they are different from any lithology found
400 in country rocks; see [Section 3.1](#)).

401

402 The last parameter is the “Volumetric Block Proportion” (VBP). As well documented in the
403 literature, the presence of rock blocks does not affect the overall behavior of geotechnically
404 complex formations if their VBP is lower than about 10%-25%. On the contrary, geomaterials with
405 block contents ranging between 25% and 75% show markedly greater strength and stiffness, higher
406 safety factors, and more tortuous failure surfaces than those of the matrix alone, depending on the
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
409 blocky rock mass ([Medley, 2001](#); [Sonmez et al., 2009](#)). As a practical matter, the estimation of VBP
410 for in-site masses is a daunting task, depending on field measurements of point (PBP), linear (LBP)
411 or areal block proportions (ABP). These lower order measures will almost never equal the VBP.
412 Hence, they must be adjusted by uncertainty factors to estimate realistic VBP ranges ([Medley,](#)
413 [1997](#); [Napoli et al., 2020](#); [Ramos-Cañón et al., 2020](#)).

414 4.2. Classification of complex formations

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

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

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.,

443 [Hard bimrocks A1L and A1H](#), and [Soft bimrocks A1L and A1H](#) in [Fig. 6](#)) with different competence
444 and rheology (e.g., alternating of sandstone and mudstone, limestone and claystone, etc.). With
445 the increase (from [1](#) to [6](#) in [Fig. 6](#); see also [Fig. 3B](#)) of disruption and dismemberment (e.g., tectonic
446 faulting or diapiric rising along intrusive contacts), the planar anisotropy is defined by the alignment
447 of elongated (i.e., tabular, lenticular, sigmoidal, etc.) “native” bed fragments/blocks, grading to a
448 block-in-matrix fabric (e.g., [Hard bimrocks from A1L to A6L](#) in [Fig. 6](#)). The genetic deformational
449 mechanisms can range from brittle to plastic depending on the Pressure-Temperature (P-T)
450 conditions and consolidation/lithification degree of the rock unit, which were acquired during
451 burial (e.g., subduction processes). As explained above (see [Section 3](#)), the different degrees of
452 stratal disruption represented by broken formations is well documented in sheared or deformed
453 flysch deposits (see [Figs. 3D-F](#)), independently of the deformational process (i.e., tectonic,
454 gravitational or diapiric). Notable examples are the *Flysch Rosso* (Red beds) in the Southern
455 Apennines (e.g., [Vezzani et al., 2010](#)), the *Argille scagliose* or *Argille varicolori* (Varicolored scaly
456 clays) of the Northern Apennines (e.g., [Bettelli et al., 2004](#); [Coli and Tanzini, 2013](#); [D’Elia et al.,](#)
457 [1998](#); [Festa et al., 2013](#); [Pini 1999](#)), the Taconic Flysch in the US-Appalachians (e.g., [Kidd et al.,](#)
458 [1995](#)), as well as most of stratigraphic successions consisting of alternating beds with different
459 competence and rheology (e.g., sandstone and marls, limestone and claystone, etc.).

460
461 Although mélanges represent a common component of many geomaterials around the world, they
462 are not included in previous classifications (e.g., [Esu, 1977](#), [Marinos and Hoek, 2001](#), and [Marinos,](#)
463 [2019](#)), nor differentiated from those with a very different (isotropic) block-in-matrix fabric (see
464 below). Mélanges represent the highest degree of internal dismemberment of complex formations
465 with anisotropic textures, as well as related mixing processes which incorporate “exotic” blocks
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
468 mélanges. For example, when excavating in heterogeneous ground, blocks of lithologies different
469 from that of the matrix may produce high strain and stress in tunnel linings, more rapid wear of
470 cutters, and damage to the cutting tools and/or mucking system. In a broken formation the range
471 of block/matrix interface strengths of a single block/matrix couple is likely to be within some range
472 of other block/matrix couples, at same alteration and deformation conditions. This is due to the
473 “native” nature of blocks (i.e., blocks and matrix derive from the dismemberment of the same

474 coherent unit, see [Figs. 3B-D](#)). On the contrary, the occurrence of “exotic” blocks (i.e., lithotypes
475 that are not present in the surrounding of the complex formation, see [Fig. 3G-I](#)), commonly
476 differing one to each other in composition, rheology, nature (e.g., metamorphic vs sedimentary
477 rocks) and size (from decimeters to tens or hundreds of meters), suggests different ranges of
478 block/matrix interface strengths within a mélange, preventing their predictability ([Fig. 3I](#)).
479 However, it is important to outline that in some cases it is possible to unexpectedly encounter
480 exotic blocks (e.g., a huge block of crystalline or metamorphic rock) within a broken formation. This
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
484 therein). Therefore, geological observations (i.e., field mapping and information from geological
485 maps) are fundamental in correctly evaluating the geotechnical characteristics of each type of
486 complex formation and the possibility to encounter unexpected “exotic gifts”.

487
488 A wide range of complex formations with anisotropic texture may also show different geotechnical
489 behaviors depending on their composition, degree of lithification/consolidation, and change of
490 physical conditions and external factors (e.g., pressure, temperature, water content, etc.), resulting
491 in a transitional condition between bimrocks and bimsoils. Therefore, we differentiate bimrocks
492 into “hard” and “soft” types (compare, e.g., [Hard bimrock A5L](#) and [Soft bimrock A5L](#) in [Fig. 6](#)) to
493 outline this important aspect. Hard bimrocks include both metamorphic and non-metamorphic
494 complex formations, which are well lithified/consolidated, with blocks bonded with the matrix
495 (e.g., “welded bimrocks”, see [Avşar, 2021](#); [Afifipour and Moarefvand, 2014](#); [Kalender et al., 2014](#);
496 [Mahdevari and Maarefvand, 2017](#); [Sonmez et al., 2009](#)). They are relatively insensitive to changes
497 of physical conditions and external factors over a short period (i.e., from hours to months) such as,
498 for example, those induced by the abrupt increase of water content due to rain, flooding or water
499 accumulation during excavations. These changes do not significantly change the volume and state
500 of the matrix, nor the strength of the block and matrix interface.

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

505 months), because of the decreased strengths of both the matrix and the block/matrix interfaces.
506 For example, dissolution and slaking processes due to the presence of water can weaken the matrix
507 depending on its mineralogical composition (e.g., carbonate content), chemical bonding state in
508 the grain boundaries, and internal structure (e.g., occurrence of foliation, layering, cleavages,
509 fractures, etc.). This water-sensitive weakening behavior greatly affects the choice of the site
510 exploration and sampling techniques, preparation of intact specimen processes, laboratory testing
511 equipment to be used, testing procedures and, of course, test results. Under these conditions, soft
512 bimrocks have a mechanical behavior which is transitional between hard bimrocks and bimsoils
513 (Fig. 6).

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

521 Considering that the VPB may strongly influence the mechanical behavior of all complex formations
522 (see Section 4.1), including those with anisotropic texture, they are also differentiated in those with
523 low (L) and high (H) VPBs (e.g., compare Hard bimrocks A5L and A5H in Fig. 6). In the former, the
524 VBPs are lower than about 15%-25% and the influence of the blocks is negligible in controlling the
525 geotechnical behavior of the bimunits. Therefore, from a geotechnical point of view, the low-VBP
526 block-in-matrix geomaterials can be considered to be homogeneous by neglecting the blocks
527 during characterization and modeling (they must be remembered for the benefit of excavators and
528 tunnelers, though). On the contrary, when the bimunits have VBPs ranging from about 25% to 75%
529 (when the VBP is higher than 75% the geomaterial can be treated as blocky rock mass and,
530 therefore, cannot be considered a complex formation) the blocks significantly to markedly affect
531 their strength and failure mode (Lindquist, 1994b; Medley and Sanz Rehermann, 2004; Napoli,
532 2021; Napoli et al., 2019, 2021b). Therefore, these latter formations should be analyzed and
533 modelled by means of heterogeneous-stochastic approaches, to take into account the inherent
534 variability of bimunits. This is true also for complex formations with both isotropic and mixed
535 (anisotropic/isotropic) textures, described below in Sections 4.2.2. and 4.2.3, respectively.

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

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

547
548 As explained above (see Section 4.2.1), the occurrences of “native” vs. “exotic” blocks also have
549 significant geotechnical and practical implications for the evaluation of the internal geomechanical
550 characteristics of isotropic bimunits. Unlike for “native” blocks of broken formations, the
551 mechanical characteristics of “exotic” blocks are difficult to be predicted because they were
552 wrenched from rock masses that are no longer present in the surrounding country rock of the
553 complex formation (see, e.g., [Hard bimrock I6L](#) in Fig. 6). In addition, the size of “exotic” blocks may
554 be highly variable, ranging from centimeters to hundreds of meters (Fig. 5F). This implies that huge
555 blocks (i.e., olistoliths) may be scattered distributed within a complex formation (see, e.g., [Hard](#)
556 [bimrock I6L](#) in Fig. 6), which mainly consists of smaller (centimeters to decimeters) blocks
557 embedded in a matrix. This is the case of many sedimentary mélanges (e.g., heterogeneous mass
558 transport deposits, see [Festa et al., 2016](#); [Ogata et al., 2019, 2020](#); [Pini et al., 2012](#);) throughout
559 the world. Notable examples are the Casanova Complex in the External Ligurian Units of Northern
560 Apennines (e.g., [Elter et al., 1991](#); [Marroni et al., 2010](#)), the Val Tiepido – Canossa and Baiso
561 argillaceous breccias in the Northern Apennines (e.g., [Bettelli and Panini, 1985](#); [Festa et al., 2015,](#)
562 [2020](#); [Panini et al., 2002](#); [Remitti et al., 2011](#);), the Porma mélange in the Cantabrian Region in
563 Northern Spain (e.g., [Alonso et al., 2015](#)), the Makran olistostrome in Iran (e.g., [Burg et al., 2008](#)),
564 the carbonate mass transport deposits of the Paleogene Julian-Slovenian basin (e.g., [Ogata et al.,](#)

565 [2014b](#)), the chaotic sedimentary unit of Chikura Group in Central Japan (e.g., [Yamamoto et al.,](#)
566 [2007](#)), and many others (see, e.g., [Festa et al., 2016](#); [Ogata et al., 2020](#) for additional examples).
567 The sizes of “native” blocks within an isotropic broken formation is easier to evaluate because
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
570 maximum thickness of beds of the coherent unit of Hard [bimrock I5H](#) with the maximum size of
571 blocks in [Hard bimrock I6H](#) in [Fig. 6](#)). “Native” blocks of an isotropic broken formation actually
572 indicate the disruption and fragmentation of competent beds within a previously coherent
573 lithostratigraphic unit (e.g., flysch deposits) whose average thickness can be observed and
574 measured. This means that before reaching the final characteristic isotropic texture with blocks
575 isolated within the matrix (e.g., [Hard bimrock I5HL](#) in [Fig. 6](#)), a broken formation (e.g., a flysch
576 deposit) may show different degrees of anisotropy which are comparable with those classified from
577 1 to 4 in [Figure 6](#) (e.g., from [Hard bimrock A1L](#) to [A4L](#) in [Fig. 6](#); see also [Fig. 3C](#)), independently of
578 the process of formation. For example, the progressive disruption of a flysch deposit during
579 slumping ([Fig. 3C](#)) may form anisotropic textures well-comparable in both block-in-matrix fabric
580 and geotechnical behavior with those formed by tectonic dismemberment (e.g., compare [Fig. 3C](#)
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
583 with the highest degrees (n. 5 in [Fig. 6](#); e.g., [Hard bimrock I5L](#), [Soft bimrock I5L](#), etc.) of disruption
584 and dismemberment.

585
586 According to their lithification/consolidation degree, composition, and water sensitivity, complex
587 formations with isotropic block-in-matrix texture can be subdivided into “hard” and “soft” bimrocks
588 (compare, e.g., [Hard bimrock I5L](#) and [Soft bimrock I5L](#) in [Fig. 6](#)), as also categorized for anisotropic
589 ones (see [Section 4.2.1](#)). We remand to [Section 4.2.1](#) for details on the different geotechnical
590 characteristics of “hard” and “soft” bimrocks. Isotropic complex formations also include breccias,
591 agglomerates and conglomerates as they have similar geotechnical characteristics of broken
592 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

596 suspended in a fine-grained matrix (i.e., diamicton; see [Figs. 5G-H](#)). The term “soil” is misleading
597 because to geologists “soil” refers to the unconsolidated mineral and organic material on the
598 surface of Earth. But, from the point of view of an engineer, “soil” is defined as a natural aggregate
599 of mineral grains, with or without organic constituents, that can be separated by gentle mechanical
600 means such as agitation in water ([Murthy, 2003](#)). To many geotechnical engineers, “soil” can be
601 excavated using conventional earthmoving equipment, from shovel to bulldozer. Hence, the term
602 “bimsoil” refers to the geotechnical definition of soil, and identifies deposits with blocks not
603 bonded with the matrix.

604 Bimsoils with isotropic texture are represented, for example, by several surficial deposits (i.e.,
605 diamicton), ranging from glacial till to colluvial deposits, up to weathered rock units and loose
606 volcanic agglomerates. They correspond to “unwelded bimrocks” ([Afifipour and Moarefvand, 2014](#);
607 [Kalender et al., 2014](#); [Mahdevari and Maarefvand, 2017](#); [Sonmez et al., 2009](#)), “soil- rock mixtures”
608 (SRM) ([Gong and Liu, 2015](#); [Xu et al., 2011](#); [Yang et al., 2019](#); [Zhang et al., 2020](#)) and “rock and soil
609 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
613 transport deposits, diamicton deposits and soils, the core zone of diapiric mélanges, etc.) in which
614 the primary isotropic block-in-matrix fabric is overprinted with different DA by planar surfaces (i.e.,
615 foliation, bedding, etc.; see, e.g., [Soft bimrock M5L](#) and [Soft bimrock M6L](#) in [Fig. 6](#); see also [Figs.](#)
616 [5C-E](#) and [5I](#)). The DA may have been caused by both lithostatic and/or tectonic loading (and
617 unloading), and tectonic reworking of the primary block-in-matrix fabric. Some heterogeneous and
618 cohesive mass transport deposits (and/or glacial deposits) may also develop planar surfaces during
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
622 [Fig. 6](#)) or rework and reorganize the primary block-in-matrix fabric with distribution of blocks along
623 preferential horizons (e.g., [Bimsoil M5H](#) and [Soft bimrock M5H](#) in [Fig. 6](#)). These horizons are, in
624 turn, aligned to planar surfaces in the matrix: the resulting complex discontinuity fabrics present
625 geotechnical disadvantages.

626 **5. Concluding Remarks**

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

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

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

639 This paper proposes a novel, simple and practical classification for geotechnically complex
640 formations, with particular reference to those with a block-in-matrix internal arrangement.
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
643 preparation of regular specimens, the laboratory testing equipment to be used, testing procedures
644 and test results. Bimrocks are subdivided into “soft” and “hard”, according to their matrix
645 characteristics and water sensitivity. The new classification, which is also based on several other
646 properties (i.e., degree of internal anisotropy, stratal disruption and mixing, and volumetric block
647 proportion - VPB), is not limited to a few types of geotechnically complex formations (e.g., flysch)
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
650 response to water sensitivity. To avoid possible subjectivity in using the proposed classification, it
651 is recommended that practitioners always match definitions with photographs of the geological
652 mass studied.

653 **Acknowledgments**

654 The authors would like to express their sincere thanks to the two anonymous reviewers for their
 655 helpful and constructive comments, from which this paper has benefited greatly.

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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

1001 types of broken formation and *mélange* according to different forming processes (tectonic,
 1002 sedimentary, and diapiric). Polygenetic *mélanges* represent the product of the interplay and
 1003 superimposition of different processes. In contrast to *mélanges*, broken formations preserve their
 1004 stratigraphic identity, representing formal or informal lithostratigraphic units.

1005

1006 **Figure 3** – Field examples showing the transition from a coherent unit **(A)** to broken formations **(B-**
 1007 **F)** and tectonic *mélanges* **(G-I)**. **(A)** Coherent, well-bedded, Ordovician flysch deposits consisting of
 1008 alternating of sandstone and claystone from the Argentina Precordillera. Hammer for scale. Note
 1009 early stages of stratal disruption through extensional boudinage in both the left and right side of
 1010 the photograph. **(B)** Transition (white arrow) from a coherent unit, consisting of a normal bedded
 1011 Late Ordovician succession of alternating graywacke and mudstone, to broken formation with
 1012 elongated to lenticular graywacke blocks embedded in a mudstone matrix (Albany Berks County,
 1013 Hamburg Klippe, Central Appalachians, USA). **(C)** Close-up view showing the transition from a
 1014 coherent unit (top) to the early stage of development of a broken formation (bottom) trough
 1015 slumping and related boudinage in the Miocene flysch deposits of the Marnoso arenacea Fm.
 1016 (Passo dei Mandrioli) in Northern Apennines of Italy. **(D)** Progressive stratal disruption of a well
 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
 1019 matrix is deformed by a pervasive scaly fabric. **(E)** Sigmoidal to lozenge-shaped blocks of sandstone
 1020 within a mudstone matrix displaying a pervasive scaly fabric (broken formation), due to tectonic
 1021 deformation within a shear zone (Waimarama Beach, South Hawke's Bay, East Coast of North
 1022 Island, New Zealand; Courtesy of G.A. Pini). Note that blocks long axes are aligned to the main shear
 1023 zone. **(F)** Field-detail of a broken formation characterized by a high degree of stratal disruption with
 1024 isolated hard sigmoidal blocks embedded in softer (clayey) matrix (Bobbio Tectonic Window,
 1025 Northern Apennines of Italy). **(G)** Close-up view of tectonic *mélange* with lenticular exotic blocks in
 1026 a sheared matrix (Franciscan Complex, CA-USA). Hammer for scale. **(H)** Sigmoidal to phacoidal
 1027 Upper Triassic pelagic limestone blocks in a heterogeneous and variously deformed matrix
 1028 composed of shale, mudstone, and sandstone in the Jurassic-Cretaceous Avdella *mélange* (Pindos
 1029 Mountains, Northern Greece). **(I)** Huge exotic ultramafic and limestone blocks, lenticular in shape,
 1030 embedded in a fine grained green reddish ophiolitic matrix of the Cretaceous Ankara Ophiolitic
 1031 *Mélange* (Central Anatolia, Turkey). Geoscientists for scale.

1032

1033 **Figure 4** – Diagrams showing different (meso-scale) organizational types of the block-in-matrix
 1034 fabrics in tectonic mélanges and broken formations (**A**), sedimentary (**B**), and diapiric (**C**) mélanges,
 1035 and their comparison (**D**), in terms of aspect ratio (block long axis/short axis) vs. block long axis.
 1036 Data are plotted as means with 95% error bars indicated. Data from updated after [Festa et al.](#)
 1037 ([2019](#)).

1038

1039 **Figure 5** – Field examples showing different types of sedimentary (**A-I**) and diapiric (**J-L**) mélanges.
 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
 1042 (Northern Apennines, Italy, modified from [Festa et al., 2015](#)). (**B**) Close-up view of rounded to
 1043 angular clasts of ultramafic rocks in a fine- to medium grained matrix of the same composition
 1044 (Ligurian Units, Northern Apennines, Italy); note the block-in-matrix isotropic texture (hammer for
 1045 scale). (**C**) Detail of sedimentary mélange consisting of highly disordered block-in-matrix fabric of
 1046 trench-related debris flow with variably shaped blocks (equidimensional, tabular, phacoidal, and
 1047 irregular) of metavolcanic and metagraywacke rocks (Panoche Road, Franciscan Complex,
 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
 1050 reorganize the primary isotropic texture of the block-in-matrix fabric to an anisotropic one
 1051 (Berceto, Parma area of the Northern Apennines of Italy). (**E**) Close-up view of a tectonically
 1052 reworked sedimentary mélange (debris flow deposit) with blocks of an oceanic cover succession in
 1053 a sheared, shaly matrix (Casanova Complex, Northern Apennines, Italy). Note that both the matrix
 1054 and the block-in-matrix fabric define an isotropic texture (camera cap for scale). (**F**) Panoramic view
 1055 of a sedimentary mélange showing the random distribution of huge Upper Cretaceous blocks
 1056 (megabreccias or olistoliths) of calcareous limestone within a limestone matrix (Muttekopf,
 1057 Calcareous Alps, Austria; see [Amerman et al., 2009](#); [Ortner, 2001](#)). The mountain side is about
 1058 300m high. (**G**) Close-up view of a bimsoil (diamicton, i.e., glacial till) showing the random
 1059 distribution (i.e., isotropic texture) of angular blocks and clasts, which are suspended in a fine-
 1060 grained (clay) matrix (Aosta Valley, Italy). (**H**) Bimsoil detail, consisting of unsorted to poorly sorted
 1061 terrigenous sediments embedding rounded hard clasts (diamicton). Note that the block-in-matrix
 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
1065 clayey matrix, which overprints and rework the primary block-in-matrix fabric of the diamicton
1066 (Ivrea Morainic Amphitheatre, Northwestern Alps of Italy). Hammer for scale. (J) Panoramic view
1067 of the diapiric *mélange*, showing the internal zoning of deformation and the block-in-matrix
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
1073 contacts (red lines). Hammer for scale. (L) Close-up view of the marginal zone of a diapiric *mélange*
1074 showing phacoidal (rarely tabular) limestone and sandstone blocks aligned parallel to the
1075 subvertical fluidal fabric (dashed white lines) of the shaly matrix (Northern Apennines, Italy; see
1076 [Festa et al. 2013](#) for details).

1077

1078 **Figure 6** – Proposed classification of geotechnically complex formations with block-in-matrix fabric,
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
1081 different types of broken formation and *mélange* independently of the forming process (tectonic,
1082 sedimentary, and diapiric). Four parameters, which have a primary role in controlling the
1083 geotechnical behavior of bimunits, are at the base of this new classification: (i) the composition
1084 and nature of blocks and the matrix that affects the water sensitivity over a short period (Hard
1085 bimrocks, Soft bimrocks and Bimsoils); (ii) the degree of anisotropy (anisotropic - A, isotropic - I,
1086 and mixed - M) of the block-in-matrix fabric; (iii) the degree of stratal disruption and mixing (from
1087 1 – lower - to 6 - higher); and (iv) the volumetric block proportion - VBP (high – H, or low - L). See
1088 text for explanation.