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

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## Abstract

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

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 \(1977\)](#), [Marinos and Hoek \(2001\)](#), and [Marinos \(2019\)](#) 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 [Marinos, 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.

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## 656 **References**

- 657 Afifipour, M., Moarefvand, P., 2014. Mechanical behavior of bimrocks having high rock block  
 658 proportion. *Int. J. Rock Mech. Min. Sci.* 65, 40–48.  
 659 <https://doi.org/10.1016/j.ijrmms.2013.11.008>
- 660 Alonso, J.L., Marcos, A., Villa, E., Suarez, A., Merino-Tomé, O.A., Fernandez, L.P., 2015. Mélanges  
 661 and other types of block-in-matrix formations in the Cantabrian Zone (Variscan Orogen,  
 662 northwest Spain): origin and significance. *Int. Geol. Rev.* 57 (5–8), 563–580.
- 663 Amerman, R., Trudgill, B., Nelson, E.P., Pyles, D.R., 2009. 4-D distribution of deepwater mass-  
 664 transport deposits (Late Cretaceous Gosau Subgroup, Muttekopg Area, Northern Calcareous  
 665 Alps, Austria): implications for syndepositional structural reconstruction. *AAPG Datapages*.  
 666 Search and Discovery Article #30108.
- 667 Anagnostou, G., Schuerch, R., Ramoni, M., 2014. TBM tunnelling in complex rock formations, in:  
 668 Chapter 15, In: XV MIR Conference “Interventi e Opere Nelle Formazioni Complesse”, 19-20  
 669 November, Torino. pp. 307–330.
- 670 Avşar, E., 2021. An experimental investigation of shear strength behavior of a welded bimrock by  
 671 meso-scale direct shear tests. *Eng. Geol.* 294. <https://doi.org/10.1016/j.enggeo.2021.106321>
- 672 Barla, G., Perello, P., 2014. Introduzione alla caratterizzazione geologica e geotecnica delle  
 673 formazioni complesse, in: Ed, C. (Ed.), *MIR 2014 - XV Ciclo Di Conferenze Di Meccanica e*  
 674 *Ingegneria Delle Rocce*. Torino, 19-20 novembre 2014, pp. 11–38.
- 675 Balestro, G., Nosenzo, F., Cadoppi, P., Fioraso, G., Groppo, C., Festa, A., 2020. Geology of the  
 676 southern Dora-Maira Massif: insights from a sector with mixed ophiolitic and continental rocks  
 677 (Valmala Tectonic Unit, Western Alps). *J. Maps* 16(2), 736–744.
- 678 Barbero, E., Festa, A., Sacconi, E., Catanzariti, R., D’Onofrio, R., 2020. Redefinition of the Ligurian  
 679 Units at the Alps-Appennines junction (NW Italy) and their role in the evolution of the Ligurian  
 680 accretionary wedge: constraints from mélanges and broken formations. *J. Geol. Soc. London*  
 681 177, 562-574. <https://doi.org/10.1144/jgs2019-022>
- 682 Barnes, P.M., Korsch, R.J., 1991. Mélange and related structures in Torlesse accretionary wedge,  
 683 Wairarapa, New Zealand. *N. Z. J. Geol. Geophys.* 34, 517–532.
- 684 Berkland, J.O., Raymond, L.A., Kramer, J.C., Moores, E.M., O’Day, M., 1972. What is Franciscan?  
 685 *AAPG Bull.* 56, 2295–2302
- 686 Bettelli, G., Conti, S., Panini, F., Vannucchi, P., Fioroni, C., Fregni, P., Bonacci, M., Gibellini, R.,  
 687 Mondani, C., 2004. The mapping of chaotic rocks in Abruzzo (Central Italy): comparison with  
 688 selected examples from Northern Appennines. In: Pasquarè, G., Venturini, C., Grippelli, G. (Eds),  
 689 *Mapping geology in Italy*. Firenze, APAT – SELCA, 199–206

- 690 Bettelli, G., Panini, F. 1985. Il mélange sedimentario della Val Tiepido (Appennino modenese)—  
691 composizione litologica, distribuzione areale e posizione stratigrafica. *Atti Soc. Nat. Mat.*  
692 *Modena* 115, 91–106.
- 693 Bettelli, G., Panini, F., 1987. I mélanges dell'Appennino settentrionale dal T. Tresinaro al T. Sillaro.  
694 *Mem. Soc. Geol. It.* 39, 187–214.
- 695 Bettelli, G., Vannucchi, P., 2003. Structural style of the offscraped Ligurian oceanic sequences of  
696 the Northern Apennines: new hypothesis concerning the development of mélange block-in-  
697 matrix fabric. *J. Struct. Geol.* 25, 371–388.
- 698 Bortolotti, V., Chiari, M., Marroni, M., Pandolfi, L., Principi, G., Sacconi, E., 2013. Geodynamic  
699 evolution of ophiolites from Albania and Greece (Dinaric–Hellenic belt): one, two, or more  
700 oceanic basins? *Int. J. Earth Sci.* 102, 783–811.
- 701 Burg, J.P., Bernoulli, D., Smit, J., Dolati, A., Bahroudi, A., 2008. A giant catastrophic mud and debris  
702 flow in the Miocene Makran. *Terra Nova* 20, 181–193.
- 703 Bürgmann, R., 2018. The geophysics, geology and mechanics of slow fault slip. *Earth Planet. Sci.*  
704 *Lett.* 195, 112–134.
- 705 Cancelli, A., 1986. The determination of shear strength parameters for sheared clay shales, in:  
706 *Proceedings of the International Symposium on Engineering in Complex Rock Formations.*  
707 Beijing, China, pp. 297–304.
- 708 Cerchiari, A., Remitti, F., Mittempergher, S., Festa, A., Lugli, F. & Cipriani, A. 2020. Cyclical variations  
709 of fluid sources and stress state in a shallow megathrust zone mélange. *J. Geol. Soc. London* 177,  
710 647-659. <https://doi.org/10.1144/jgs2019-072>.
- 711 Clausmman, B., Bailleaul, J., Chanier, F., Mahieux, G., Caron, V., McArthur, A.D., Chaptal, C.,  
712 Morgans, H.E.G., Vendeville, B.C., 2021a. Shelf-derived mass-transport deposits: origin and  
713 significance in the stratigraphic development of trench-slope basins. *N. Z. J. Geol. Geophys.*,  
714 Published online: 27 May 2021, <https://doi.org/10.1080/00288306.2021.1918729>
- 715 Clausmman, B., Bailleaul, J., Chanier, F., Mahieux, G., Caron, V., McArthur, A.D., Mahieux, G.,  
716 Chaptal, Vendeville, B.C., 2021b. Contrasting mixed siliciclastic-carbonate shelf-derived gravity-  
717 driven systems in compressional intra-slope basins (southern Hikurangi margin, New Zealand).  
718 *Mar. Pet. Geol.* 134, 105252. <https://doi.org/10.1016/j.marpetgeo.2021.105252>
- 719 Cloos, M., 1982. Flow melanges: numerical modeling and geologic constraints on their origin in the  
720 Franciscan subduction complex, California. *Geological Society of America Bulletin* 93, 330–345.
- 721 Codegone, G., Festa, A., Dilek, Y., Pini, G.A., 2012. Small-scale polygenetic mélanges in the Ligurian  
722 accretionary complex, Northern Apennines, Italy, and the role of shale diapirism in superposed  
723 mélange evolution in orogenic belts. *Tectonophysics* 568–569, 170–184.
- 724 Coli, N., Tanzini, M., 2013. Characterization of the “Chaotic Complex” (Northern Apennines, Italy),  
725 in: Taylor & Francis Group (Ed.), *Rock Mechanics for Resources, Energy and Environment.*  
726 London, pp. 111–116.
- 727 Cowan, D.S., 1985. Structural styles in Mesozoic and Cenozoic mélanges in the western Cordillera  
728 of North America. *Geol. Soc. Am. Bull.* 96, 451–462. [https://doi.org/10.1130/0016-](https://doi.org/10.1130/0016-7606(1985)96<451)  
729 [7606\(1985\)96<451](https://doi.org/10.1130/0016-7606(1985)96<451)

- 730 Dela Pierre, F., Festa, A., Irace, A., 2007. Interaction of tectonic, sedimentary and diapiric processes  
731 in the origin of chaotic sediments: an example from the Messinian of the Torino Hill (Tertiary  
732 Piedmont Basin, NW Italy). *Geol. Soc. Am. Bull.* 119, 1107–1119.
- 733 D’Elia, B., Distefano, D., Esu, F., Federico, G., 1986. Slope movements in structurally complex  
734 formations, in: *Proceedings of the International Symposium on Engineering in Complex Rock*  
735 *Formations*, 3-7 November, 1986, Beijing, China. pp. 430–436.
- 736 D’Elia, B., Picarelli, L., Leroueil, S., Vaunant, J., 1998. Geotechnical characterisation of slope  
737 movements in structurally complex clay soil and stiff jointed clays. *Riv. Ital. di Geotec.* 3, 5–32.
- 738 Elter, P., Raggi, G., 1965. Contributo alla conoscenza dell’Apennino ligure: 1. Osservazioni  
739 preliminari sulla posizione delle ofioliti nella zona di Zignago (La Spezia); 2. Considerazioni sul  
740 problema degli olistostromi. *Boll. della Soc. Geol. Ital.* 84, 303–322.
- 741 Elter, P., Marroni, M., Molli, G., Pandolfi, L., 1991. Le caratteristiche stratigrafiche del Complesso di  
742 M. Penna/Casanova (Alta Val di Trebbia, Appennino Settentrionale). *Atti Tic. Sc. Terra* 34, 97–  
743 106.
- 744 Esu, F., 1977. Behaviour of Slopes in Structurally Complex Formations, in: *General Report, Session*  
745 *IV. Proc. Int. Symp. The Geotechnics of Structurally Complex Formations*, Capri, Italy. pp. 292–  
746 304.
- 747 Fagereng, Å., Sibson, R.H., 2010. Mélange rheology and seismic style. *Geology* 38, 751–754.
- 748 Festa, A., 2011. Tectonic, sedimentary, and diapiric formation of the Messinian melange: Tertiary  
749 Piedmont Basin (northwestern Italy). In: Wakabayashi, J., Dilek, Y. (Eds.), *Melanges: Processes*  
750 *of formation and societal significance*. *Geol. Soc. Am. Spe. Pap.* 480, 215–232,  
751 [http://dx.doi.org/10.1130/2011.2480\(10\)](http://dx.doi.org/10.1130/2011.2480(10)).
- 752 Festa, A., Dilek, Y., Codegone, G., Cavagna, S., Pini, G.A., 2013. Structural anatomy of the Ligurian  
753 accretionary wedge (Monferrato, NW Italy), and evolution of superposed mélanges. *Geol. Soc.*  
754 *Am. Bull.* 125 (9–10), 1580–1598. <http://dx.doi.org/10.1130/B30847.1>.
- 755 Festa, A., Dilek, Y., Pini, G.A., Codegone, G., Ogata, K., 2012. Mechanisms and processes of stratal  
756 disruption and mixing in the development of mélanges and broken formations : Redefining and  
757 classifying mélanges. *Tectonophysics* 568–569, 7–24.  
758 <https://doi.org/10.1016/j.tecto.2012.05.021>
- 759 Festa, A., Dilek, Y., Mittempergher, S., Ogata, K., Pini, G.A., Remitti, F., 2018. Does subduction of  
760 mass transport deposits (MTDs) control seismic behavior of shallow-level megathrusts at  
761 convergent margins? *Gondwana Res.* 60, 186-193.
- 762 Festa, A.; Ogata, K.; and Pini, G. A., 2020. Polygenetic mélanges: a glimpse on tectonic, sedimentary  
763 and diapiric recycling in convergent margins. *J. Geol. Soc. London* 177, 551–561.
- 764 Festa, A., Ogata, K., Pini, G.A., Dilek, Y., Alonso, J.L., 2016. Origin and significance of olistostromes  
765 in the evolution of orogenic belts: a global synthesis. *Gondwana Res.* 39, 180–203.
- 766 Festa, A., Ogata, K., Pini, G.A., Dilek, Y., Codegone, G., 2015. Late Oligocene–early Miocene  
767 olistostromes (sedimentary mélanges) as tectono-stratigraphic constraints to the geodynamic  
768 evolution of the exhumed Ligurian accretionary complex (Northern Apennines, NW Italy). *Int.*  
769 *Geol. Rev.* 57 (5–8), 540–562.

- 770 Festa, A., Pini, G.A., Dilek, Y., Codegone, G., 2010. Mélanges and mélange-forming processes: a  
771 historical overview and new concepts. *Int. Geol. Rev.* 52, 1040–1105.  
772 <https://doi.org/10.1080/00206810903557704>
- 773 Festa, A., Pini, G.A., Ogata, K., Dilek, Y., 2019. Diagnostic features and field-criteria in recognition  
774 of tectonic, sedimentary and diapiric mélanges in orogenic belts and exhumed subduction-  
775 accretion complexes. *Gondwana Res.* 74, 11–34.
- 776 Festa, A., Barbero, E., Remitti, F., Ogata, K., Pini G.A., 2022. Mélanges and chaotic rock units:  
777 Implications for exhumed subduction complexes and orogenic belts. *Geosystems and*  
778 *Geoenvironment* 1(2), 100030. <https://doi.org/10.1016/j.geogeo.2022.100030>.
- 779 Fisher, D., Byrne, T., 1987. Structural evolution of underthrust sediments, Kodiak Islands, Alaska.  
780 *Tectonics* 6, 775–793.
- 781 Gokceoglu, C., Zorlu, K., 2004. A fuzzy model to predict the uniaxial compressive strength and the  
782 modulus of elasticity of a problematic rock. *Eng. Appl. Artif. Intell.* 17, 61–72.  
783 <https://doi.org/10.1016/j.engappai.2003.11.006>
- 784 Gong, J., Liu, J., 2015. Analysis on the mechanical behaviors of soil-rock mixtures using Discrete  
785 Element Method. *Procedia Eng.* 102, 1783–1792. <https://doi.org/10.1016/j.proeng.2015.01.315>
- 786 Goodman, R.E., Ahlgren, C.S., 2000. Evaluating Safety of Concrete Gravity Dam on Weak Rock: Scott  
787 Dam. *J. Geotech. Geoenvironmental Eng.* 126, 429–442. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2000\)126:5\(429\)](https://doi.org/10.1061/(ASCE)1090-0241(2000)126:5(429))
- 789 Greenly, E., 1919. The geology of Anglesey, vols I and II. *Mem. Geol. Survey.* HM Stationary Office,  
790 London, pp. 1–388, 390–980.
- 791 Harrison, J.P., 2014. What do we mean about complexity?, in: Chapter 2, In: XV MIR Conference  
792 “Interventi e Opere Nelle Formazioni Complesse”, Torino. pp. 39–48.
- 793 Hoek, E., 1994. Strength of rock and rock masses. *ISRM News J.* 2, 4–16.
- 794 Hsu, K.J., 1968. Principles of Melanges and Their Bearing on the Franciscan-Knoxville Paradox. *Geol.*  
795 *Soc. Am. Bull.* 79, 1063–1074.
- 796 Huang, X., Wei, Y., Ai, W., Jiang, P., 2021. Stability analysis of soil - rock slope ( SRS ) with an  
797 improved stochastic method and physical models. *Environ. Earth Sci.* 80, 1–21.  
798 <https://doi.org/10.1007/s12665-021-09939-2>
- 799 Kahraman, S., Alber, M., 2008. Triaxial strength of a fault breccia of weak rocks in a strong matrix.  
800 *Bull. Eng. Geol. Environ.* 67, 435–441. <https://doi.org/10.1007/s10064-008-0152-3>
- 801 Kalender, A., Sonmez, H., Medley, E., Tunusluoglu, C., Kasapoglu, K.E., 2014. An approach to  
802 predicting the overall strengths of unwelded bimrocks and bimsoils. *Eng. Geol.* 183, 65–79.  
803 <https://doi.org/10.1016/j.enggeo.2014.10.007>
- 804 Khorasani, E., Amini, M., Hossaini, M., Medley, E., 2019a. Evaluating the effects of the inclinations  
805 of rock blocks on the stability of Bimrock slopes. *Geomech. Eng.* 17, 281–287.  
806 <https://doi.org/10.12989/gae.2019.17.3.281>
- 807 Khorasani, E., Amini, M., Hossaini, M.F., Medley, E.W., 2019b. Statistical analysis of bimslope  
808 stability using physical and numerical models. *Eng. Geol.* 254, 13–24.  
809 <https://doi.org/10.1016/j.enggeo.2019.03.023>

- 810 Kidd, W.S.F., Plesch, A., Vollmer, F.W., 1995. Lithofacies and structure of the Taconic Flysch,  
811 Melange, & Allochthon in New York Capital District. In: Garver, J.I., Smith, J.A. (Eds.), Field Trip  
812 Guide for the 67th Annual Meeting of the New York State Geological Association. Union College,  
813 Schenectady, NY, 57–80.
- 814 Kimura, G., Yamaguchi, A., Hojo, M., Kitamura, Y., Kameda, J., Ujiie, K., Hamada, Y., Hamahasi, M.,  
815 Hina, S., 2012. Tectonic mélange as fault rock of subduction plate boundary. *Tectonophysics*  
816 568-569, 25–38
- 817 Lai, L.S-H., Doresy, R.J., Horng, C-S., Chi, W-R-, Shea, K-S., Yen, J-Y., 2021. Polygenetic mélange in  
818 the retrowedge foredeep of an active arc-continent collision, Coastal Range of eastern Taiwan.  
819 *Sed. Geol.* 418, 105901. <https://doi.org/10.1016/j.sedgeo.2021.105901>
- 820 Li, X., Liao, Q.L., He, J.M., 2004. In situ tests and a stochastic structural model of rock and soil  
821 aggregate in the Three Gorges reservoir area, China. *Int. J. Rock Mech. Min. Sci.* 41, 6.  
822 <https://doi.org/10.1016/j.ijrmmms.2003.12.030>
- 823 Lindquist, E.S., 1994a. The Strength and Deformation Properties of Melange. Ph.D. Thesis.  
824 University of California, Berkeley.
- 825 Lindquist, E.S., 1994b. The mechanical properties of a physical model melange., in: 7th  
826 International IAEG Congress. Austin, Texas; 1-3 June, pp. 819–826.
- 827 Lucente, C.C., Pini, G.A., 2008. Basin-wide mass-wasting complexes as markers of the Oligo-  
828 Miocene foredeep-accretionary wedge evolution in the Northern Apennines, Italy. *Basin Res.*  
829 20, 49 – 71.
- 830 Lunardi, P., Cassani, F., Pennino, F., 2014. Lo scavo a piena sezione di gallerie in formazioni  
831 complesse, in: Chapter 14, In: XV MIR Conference: Interventi e Opere Nelle Formazioni  
832 Complesse, Torino. pp. 277–305.
- 833 Mahdevari, S., Maarefvand, P., 2017. Applying ultrasonic waves to evaluate the volumetric block  
834 proportion of bimrocks. *Arab J Geosci* 10, 204. <https://doi.org/10.1007/s12517-017-2999-8>
- 835 Marinos, P., Hoek, E., 2001. Estimating the geotechnical properties of rock masses such as flysch.  
836 *Bull. Eng. Geol. Environ.* 60, 85–92.
- 837 Marinos, V., 2019. A revised, geotechnical classification GSI system for tectonically disturbed  
838 heterogeneous rock masses, such as flysch. *Bull. Eng. Geol. Environ.* 78, 899–912.  
839 <https://doi.org/10.1007/s10064-017-1151-z>
- 840 Marroni, M., Meneghini, F., Pandolfi, L., 2010, Anatomy of the Ligure-Piemontese subduction  
841 system: evidence from Late Cretaceous–Middle Eocene convergent margin deposits in the  
842 Northern Apennines, Italy. *Int. Geol. Rev.* 52, 1160–1192. doi:10.1080/00206810903545493
- 843 Medley, E.W., 2007. Bimrocks - Part 1: Introduction. *Newsl. Hell. Soc. Soil Mech. Geotech. Eng.*  
844 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.
- 847 Medley, E.W., 1997. Uncertainty in estimates of block volumetric proportions in melange bimrocks.  
848 *Int. Symp. Eng. Geol. Environ.* 267–272.

- 849 Medley, E.W., 1994. The engineering characterization of melanges and similar Block-in-matrix rocks  
850 (Bimrocks). Ph.D. thesis. University of California, Berkeley.
- 851 Medley, E.W., Goodman, R.E., 1994. Estimating the Block Volumetric Proportions of Melanges and  
852 Similar Block-in-Matrix Rocks (Bimrocks), in: Proceedings of the 1st North American Rock  
853 Mechanics Symposium. Austin, Texas; 1-3 June, pp. 851–858.
- 854 Medley, E.W., Sanz Rehermann, P.F., 2004. Characterization of Bimrocks (Rock/Soil Mixtures) With  
855 Application to Slope Stability Problems, in: Eurock 2004 & 53rd Geomechanics Colloquium.  
856 Salzburg, Austria.
- 857 Medley, E.W., Zekkos, D., 2011. Geopractitioner approaches to working with antisocial mélanges,  
858 in: Wakabayashi, J., Dilek, Y. (Eds.), Mélanges: Processes of Formation and Societal Significance  
859 - Geological Society of America Special Paper 480. pp. 261–277. [https://doi.org/10.1016/S0065-  
860 2156\(09\)70001-8](https://doi.org/10.1016/S0065-2156(09)70001-8)
- 861 Moore, G.F., Aung, Lin Thu, Fukuchi, R., Sample, J.C., Hellebrand, E., Kopf, A. et al., 2019, Tectonic,  
862 diapiric and sedimentary chaotic rocks of the Rakhine coast, western Myanmar. *Gondwana Res.*  
863 74, 130–147.
- 864 Murthy, V.N.S., 2003. *Geotechnical Engineering: Principles and Practices of Soil Mechanics and*  
865 *Foundation Engineering*, 1st Editio. ed. CRC Press.  
866 <https://doi.org/https://doi.org/10.1201/9781482275858>
- 867 NACSN North American Commission on Stratigraphic Nomenclature, 2005. Amendments to the  
868 American stratigraphic code. *AAPG Bull.* 89 (11), 1459–1464.
- 869 Napoli, M.L., 2021. 3D slope stability analyses of a complex formation with a block-in-matrix fabric,  
870 in: *Challenges and Innovations in Geomechanics. IACMAG 2021. Lecture Notes in Civil*  
871 *Engineering*, Vol. 126. Springer, Turin, p. 7. [https://doi.org/10.1007/978-3-030-64518-2\\_88](https://doi.org/10.1007/978-3-030-64518-2_88)
- 872 Napoli, M.L., Barbero, M., Scavia, C., 2021a. Geomechanical characterization of an Italian complex  
873 formation with a block-in-matrix fabric, in: *Mechanics and Rock Engineering, from Theory to*  
874 *Practice (EUROCK 2021)*. Torino, Italy; 20-25 September, p. 8.
- 875 Napoli, M.L., Barbero, M., Scavia, C., 2021b. Effects of block shape and inclination on the stability  
876 of melange bimrocks. *Bull. Eng. Geol. Environ.* <https://doi.org/10.1007/s10064-021-02419-8>
- 877 Napoli, M.L., Barbero, M., Scavia, C., 2021c. Tunneling in heterogeneous rock masses with a block-  
878 in-matrix fabric. *Int. J. Rock Mech. Min. Sci.* 138, 11.  
879 <https://doi.org/10.1016/j.ijrmms.2021.104655>
- 880 Napoli, M.L., Barbero, M., Scavia, C., 2019. Slope stability in heterogeneous rock masses with a  
881 block-in-matrix fabric, in: *Rock Mechanics for Natural Resources and Infrastructure*  
882 *Development- Proceedings of the 14th International Congress on Rock Mechanics and Rock*  
883 *Engineering*, ISRM. Foz do Iguassu, Brazil, pp. 3482–3489.
- 884 Napoli, M.L., Barbero, M., Scavia, C., 2018. Analyzing slope stability in bimrocks by means of a  
885 stochastic approach, in: Litvinenko, V. (Ed.), *European Rock Mechanics Symposium, EUROCK*  
886 *2018*. Saint Petersburg; 22-26 May 2018.

- 887 Napoli, M.L., Milan, L., Barbero, M., Scavia, C., 2020. Identifying uncertainty in estimates of  
888 bimrocks volumetric proportions from 2D measurements. *Eng. Geol.* 278.  
889 <https://doi.org/10.1016/j.enggeo.2020.105831>.
- 890 Nikolaidis, G., Saroglou, C., 2016. Engineering geological characterization of block-in-matrix rocks.  
891 *Bull. Geol. Soc. Greece* 50, 874–884.
- 892 Ogata, K., Mountjoy, J.J., Pini, G.A., Festa, A., Tinterri, E., 2014a. Shear zone liquefaction in mass  
893 transport deposit emplacement: a multi-scale integration of seismic reflection and outcrop data.  
894 *Mar. Geol.* 356 (Special Issue), 50–64.
- 895 Ogata, K., Festa, A., Pini, G.A., Alonso, J.L., 2020. Submarine landslide deposits in orogenic belts:  
896 olistostromes and sedimentary mélanges. In: Ogata, K., Festa, A., Pini, G.A. (Eds.), *Submarine  
897 Landslides: subaqueous mass transport deposits from outcrop to seismic profiles*. Geophysical  
898 Monograph 247, First Edition, American Geophysical Union, John Wiley & Sons Inc., USA, 3-26,  
899 <https://doi.org/10.1002/9781119500513.ch1>
- 900 Ogata, K., Festa, A., Pini, G.A., Pogačnik, Ž., 2021. Mélanges in flysch-type formations: Reviewing  
901 geological constraints for a better understanding of complex formations with block-in-matrix  
902 fabric. *Eng. Geol.* 293, 106289, <https://doi.org/10.1016/j.enggeo.2021.106289>
- 903 Ogata, K., Festa, A., Pini, G.A., Pogačnik, Ž., Lucente, C.C., 2019. Substrate deformation and  
904 incorporation in sedimentary mélanges (olistostromes): Examples from the northern Apennines  
905 (Italy) and northwestern Dinarides (Slovenia). *Gondwana Res.* 74, 105–129.
- 906 Ogata, K., Pogačnik, Ž., Pini, G.A., Tunis, G., Festa, A., Camerlenghi, A., Rebesco, M., 2014b. The  
907 carbonate mass transport deposits of the Paleogene Julian-Slovenian Basin (Italy/Slovenia):  
908 internal anatomy and inferred genetic processes. *Mar. Geol.* 356, 88–110.
- 909 Orange, D.L., 1990. Criteria helpful in recognizing shear-zone and diapiric mélanges: examples from  
910 the Hoh accretionary complex, Olympic Peninsula, Washington. *Geol. Soc. Am. Bull.* 102, 935–  
911 951.
- 912 Ortner, H., 2001. Growing folds and sedimentation of the Gosau Group, Muttekopf, Northern  
913 Calcareous Alps, Austria. *Int. J. Earth Sci.* 90, 727–739.
- 914 Panini, F., Fioroni, C., Fregni, P., Bonacci, M., 2002. Le rocce caotiche dell'Oltrepo Pavese: note  
915 illustrative della Carta Geologica dell'Appennino vogherese tra Borgo Priolo e Ruino. *Atti Tic. Sc.*  
916 *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.
- 919 Pini, G.A., Lucente, C.C., Venturi, S., Ogata, K., 2020. Mass-Transport Complexes of the Marnoso-  
920 arenacea foredeep turbidite system (Northern Apennines, Italy): a reappraisal after twenty-  
921 years. In: Ogata, K., Festa, A., Pini, G.A. (Eds.), *Submarine Landslides: subaqueous mass transport  
922 deposits from outcrop to seismic profiles*. Geophysical Monograph 247, First Edition, American  
923 Geophysical Union, John Wiley & Sons Inc., <https://doi.org/10.1002/9781119500513.ch8>
- 924 Pini, G.A., Ogata, K., Camerlenghi, A., Festa, A., Lucente, C.C., Codegone, G., 2012. Sedimentary  
925 mélanges and fossil mass-transport complexes: a key for better understanding submarine mass  
926 movements? In: Yamada, Y., et al. (Eds.), *Submarine Mass Movements and Their Consequences*

- 927 Advances in Natural and Technological Hazards Research 31. Springer Science+Business Media  
928 B.V., pp. 585–594
- 929 Ramos-Cañón, A.M., Castro-Malaver, L.C., Padilla-Bello, N. V., Vega-Posada, C.A., 2020.  
930 Incertidumbre en la determinación del Porcentaje Volumétrico de Bloques de BIMrocks/BIMsoil  
931 a partir de información unidimensional. Rev. Boletín Geol. 42, 69–80.  
932 <https://doi.org/10.18273/revbol.v42n1-2020004>
- 933 Raymond, L.A., 1984. Classification of melanges. In: Raymond, L.A., Boulder, L.A. (Eds.), Melanges:  
934 Their Nature, Origin and Significance, in: Geological Society of America Special Paper 198. pp. 7–  
935 20.
- 936 Raymond, L.A., 2019, Perspectives on the roles of mélanges in subduction accretionary complexes:  
937 A review. Gondwana Res. 74, 72–93.
- 938 Remitti, F., Bettelli, G., Vannucchi, P., 2007. Internal structure and tectonic evolution of an  
939 underthrust tectonic mélange: the Sestola-Vidiciatico tectonic unit of the Northern  
940 Apennines, Italy. Geodin. Acta 20(1-2), 37-51.
- 941 Remitti, F., Vannucchi, P., Bettelli, G., Fantoni, L., Panini, F., Vescovi, P., 2011. Tectonic and  
942 sedimentary evolution of the frontal part of an ancient subduction complex at the transition  
943 from accretion to erosion: the case of the Ligurian wedge of the northern Apennines, Italy.  
944 Geolo. Soc. Am. Bull. 123, 51–70.
- 945 Silver, E.A., Beutner, E.C., 1980. Melanges. Geology 8, 32–34.
- 946 Sonmez, H., Ercanoglu, M., Kalender, A., Dagdelenler, G., Tunusluoglu, C., 2016. Predicting uniaxial  
947 compressive strength and deformation modulus of volcanic bimrock considering engineering  
948 dimension. Int. J. Rock Mech. Min. Sci. 86, 91–103.  
949 <https://doi.org/10.1016/j.ijrmmms.2016.03.022>
- 950 Sonmez, H., Kasapoglu, K., Coskun, A., Tunusluglu, C., Medley, E.W., Zimmerman, R.W., 2009. A  
951 conceptual empirical approach for the overall strength of unwelded bimrocks, in: ISRM Regional  
952 Symposium, Rock Engineering in Difficult Ground Condition, Soft Rock and Karst,. Dubrovnik,  
953 Croatia, 29-31 October.
- 954 Sunesson, N.H., 1993. The geology of the Torlesse Complex along the Wellington area coast, North  
955 Island, New Zealand. N. Z. J. Geol. Geophys. 36, 369-384
- 956 Tsesarsky, M., Hazan, M., Gal, E., 2016. Estimating the elastic moduli and isotropy of block in matrix  
957 ( bim ) rocks by computational homogenization. Eng. Geol. 200, 58–65.  
958 <https://doi.org/10.1016/j.enggeo.2015.12.003>
- 959 Vannucchi, P., Bettelli, G., 2010. Myths and recent progress regarding the Argille Scagliose,  
960 Northern Apennines, Italy. In: Dilek, Y. (Ed.), Alpine Concept in Geology. Int. Geol. Rev. 52 (10–  
961 12), 1106–1137.
- 962 Vezzani, L., Festa, A., Ghisetti, F., 2010. Geology and Tectonic evolution of the Central-Southern  
963 Apennines, Italy. Geol. Soc. Am. Spe. Pap. 469, 58 pp., accompanying by a CD-ROM including the  
964 “Geological-Structural Map of the Central-Southern Apennines (Italy)” at 1:250.000 scale,  
965 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.
- 968 Wakabayashi, J., 2021. Field and petrographic reconnaissance of Franciscan complex rocks of  
969 Mount Diablo, California: Imbricated ocean floor stratigraphy with a roof exhumation fault  
970 system. In: Sullivan, R., Sloan, D., Unruh, J.R., Schwartz, D.P. (eds.), *Regional Geology of Mount*  
971 *Diablo, California: Its Tectonic Evolution on the North America Plate Boundary*. *Geol. Soc. Am.*  
972 *Mem.* 217, 155–178, [https://doi.org/10.1130/2021.1217\(09\)](https://doi.org/10.1130/2021.1217(09)).
- 973 Wang, H., 2014. Numerical direct shear tests for outwash deposits with random structure and  
974 composition. <https://doi.org/10.1007/s10035-014-0504-6>
- 975 Wang, S., Li, Y., Gao, X., Xue, Q., Zhang, P., Wu, Z., 2020. Influence of volumetric block proportion  
976 on mechanical properties of virtual soil-rock mixtures. *Eng. Geol.* 278.  
977 <https://doi.org/10.1016/j.enggeo.2020.105850>
- 978 Xu, W., Xu, Q., Hu, R., 2011. Study on the shear strength of soil-rock mixture by large scale direct  
979 shear test. *Int. J. Rock Mech. Min. Sci.* 48, 1235–1247.  
980 <https://doi.org/10.1016/j.ijrmms.2011.09.018>
- 981 Yang, Y., Sun, G., Zheng, H., Qi, Y., 2019. Investigation of the sequential excavation of a soil-rock-  
982 mixture slope using the numerical manifold method. *Eng. Geol.* 256, 93–109.  
983 <https://doi.org/10.1016/j.enggeo.2019.05.005>
- 984 Zhang, Z., Sheng, Q., Fu, X., Zhou, Y., Huang, J., Du, Y., 2020. An approach to predicting the shear  
985 strength of soil-rock mixture based on rock block proportion. *Bull. Eng. Geol. Environ.* 79, 2423–  
986 2437. <https://doi.org/10.1007/s10064-019-01658-0>
- 987 Zhou, H., Zhang, C., Li, Z., Hu, D., Hou, J., 2014. Analysis of mechanical behavior of soft rocks and  
988 stability control in deep tunnels. *J. Rock Mech. Geotech. Eng.* 6, 219–226.  
989 <https://doi.org/10.1016/j.jrmge.2014.03.003>
- 990 Yamamoto, Y., Ogawa, Y., Uchino, T., Muraoka, S., Chiba, T., 2007. Large-scale chaotically mixed  
991 sedimentary body within the Late Pliocene to Pleistocene Chikura Group, Central Japan., *Island*  
992 *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

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.