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Mechanisms and processes of stratal disruption and mixing in the development of mélanges and broken formations: redefining and classifying mélanges

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4 **Mechanisms and processes of stratal disruption and mixing in the**
5 **development of mélanges and broken formations:**
6 **redefining and classifying mélanges**
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ABSTRACT

The terms *mélange* and *broken formation* have been used in different ways in the literature. The lack of agreement on their definition often leads to confusion and misinterpretations. An evaluation of the various uses of these terms allows us to consider several types of chaotic rock bodies originated by tectonic, sedimentary and diapiric processes in different tectonic settings. Our review of stratal disruption and mixing processes shows that there exists a continuum of deformation structures and processes in the generation of mélanges and broken formations. This continuum is directly controlled by the increase of the degree of consolidation with burial. In tectonically active environments, at the shallow structural levels, the occurrence of poorly consolidated sediments favors gravitational deformation. At deeper structural levels, the deformation related to tectonic forces becomes gradually more significant with depth. Sedimentary (and diapiric) mélanges and broken formations represent the products of punctuated stratal disruption mechanisms recording the instantaneous physical conditions in the geological environment at the time of their formation. The different kinematics, the composition and lithification degree of sediments, the geometry and morphology of the basins, and the mode of failure propagation control the transition between different types of mass-transported chaotic bodies, the style of stratal disruption, and the amount of rock mixing. Tectonically broken formations and mélanges record a continuum of deformation that occurs through time and different degrees of lithification during a progressive increase of the degree of consolidation and of the diagenetic and metamorphic mineral transformation. Systematic documentation of the mechanisms and processes of the formation of different broken formations and mélanges and their interplay in time and space are highly important to increase the understanding of the evolutionary history of accretionary wedges and orogenic belts.

Key words: Tectonic and sedimentary mélanges, diapiric mélanges, broken formations, mélange forming processes, stratal disruption and mixing of rocks, mass-transport deposits and processes.

1. Introduction

Mélanges and broken formations represent a significant component of most convergent margins and orogens around the world (Fig. 1), and the details of their block-in-matrix character reflect a close relationship between the processes and the tectonic setting of their formation (Suzuki, 1986; Festa et al., 2010a). However, the lack of agreement on the definition of *mélange* (e.g., Silver and Beutner, 1980; Rast and Horton, 1989; also compare Şengör, 2003 with Pini, 1999; Cowan and Pini, 2001; Festa et al., 2010a; Wakabayashi, 2011) has led to some confusion and misinterpretations in the literature. At shallow structural levels in tectonically active environments, sediments are subject to small-scale deformation immediately after deposition at rates and in ways dependent on the interplay between gravitational deformation and tectonic burial (e.g., Byrne, 1994; Maltman, 1994). The downward increase in both the consolidation and lithification of buried sediments and tectonic forces controls the progressive increase in deformation and, in cases, stratal disruption (Maltman, 1994 and references therein; Onishi and Kimura, 1995; Yamamoto et al., 2012a). The result of these conditions is a continuum of development of structures in the originally coherent stratigraphic successions via stratal disruption and mixing processes, which play a major role in the genesis of broken formations and *mélanges* (e.g., Hsü, 1968; Raymond, 1984; Cowan, 1985).

Time-progressive evolution of deformation structures in chaotic rock units, such as broken formations to *mélanges*, has been rarely described in the literature (see e.g., Smith et al., 1979; Raymond, 1984; Cowan, 1985; Needham, 1995; Harris et al., 1998; Lucente and Pini, 2003; Ogata et al., 2012a; Pini et al., 2012; Yamamoto et al., 2012a). This is in part due to the fact that collisional and post-collisional shortening, magmatism, extensional deformation, and strike-slip tectonics may have obscured or strongly remodified the structural evidence for the pre-existing continuum. Nevertheless, a careful examination of the rock record and the internal fabric of the chaotic rock bodies, together with their contact relationships with the country rocks, reveals important clues about the larger-scale processes that occurred in different tectonic settings and at shallow structural levels during *mélange* formation. The most important *mélange* forming process at deeper structural levels is thought to have

1 taken place in subduction channels (e.g., Cloos, 1982; Cloos and Shreve, 1988a, 1988b; Ogawa,
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3 1998; Gerya et al., 2002; Guillot et al., 2004; Ernst, 2006; Federico et al., 2007; Blanco-Quitero et al.,
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5 2010; Malatesta et al., 2012), in which high degrees of mixing of rocks (including ultramafic rocks)
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7 with differing P-T-t histories and metamorphic grades may occur.
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12 This paper is aimed at streamlining the existing discussions on the mechanisms and
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14 processes of stratal disruption and mixing in the development of mélanges and broken formations,
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16 and at redefining and reclassifying the mélanges and related rock units. In the first part of the paper,
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18 we briefly review and discuss the definitions of the terms mélange and broken formation and re-define
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20 these terms in light of recent observations and interpretations made by the international scientific
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22 community. We also discuss the origins of the chaotic rock masses (tectonic, sedimentary, diapiric,
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24 and polygenetic) and review their global occurrences, expanding on the tectonic-genetic classification
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26 of chaotic rocks we proposed earlier (see Festa et al., 2010a). In the second part of the paper, we
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28 present several models for the formation of various types of mélanges and broken formations at
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30 shallow structural levels in accretionary wedges and orogenic belts (where metamorphism is very low
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32 grade or absent). Here, we review and synthesize the existing data, and demonstrate that a
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34 continuum of stratal disruption and mixing processes operates across different structural levels or
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36 depths of burial in various tectonic settings. The nomenclature we propose here and the continuum of
37
38 stratal disruption and mixing described at shallow structural levels provide a useful and coherent
39
40 framework for future studies in mélange terrains. Redefinition and more systematic, process-oriented
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42 classification of mélanges should also be highly insightful for the recognition of these chaotic rock
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44 bodies in the Precambrian greenstone belts (Dilek and Ahmed, 2003; Dilek and Polat, 2008).
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52 **2. Mélange and broken formation terminology**

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57 “*Mélange*” is a descriptive, non-genetic term that must be used only in describing a mappable
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59 (at 1:25,000 or smaller scale) body of internally disrupted and mixed rocks in (or rarely without) a
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1 pervasively deformed matrix (Berkland et al., 1972; Wood, 1974; Silver and Beutner, 1980; Raymond,
2 1984; Cowan, 1985). Yet, the debate and discussions on the *mélange* concept continue after nearly
3
4 four decades of extensive studies of *mélanges* and related rock units around the world (Silver and
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6 Beutner, 1980; Raymond, 1984; Rast and Horton, 1989; Wakabayashi and Dilek, 2011). We refer the
7
8 reader to Hsü (1968), Cowan (1974, 1985), Raymond (1984), Suzuki (1986), Rast and Horton (1989),
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10 Pini (1999), Şengör (2003), Camerlenghi and Pini (2009), Festa et al. (2010a), Vannucchi and Bettelli
11
12 (2010), Wakabayashi and Dilek (2011) and Ogata et al. (2012b) for various discussions on the
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14 conflicting uses of the term *mélange*.
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19 The term *mélange*, in its classical descriptive and non-genetic definition (Berkland et al., 1972;
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21 Wood, 1974; Silver and Beutner, 1980; Raymond, 1984; Cowan, 1985), does not restrict the nature of
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23 lithological units involved (sedimentary, metamorphic or igneous); contact relationships between
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25 these diverse lithological units can be tectonic, stratigraphic or intrusive, depending on the process of
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27 *mélange* formation (Tab. 1). This definition implies that the term *mélange* can be used only, at least in
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29 part, as a synonym of *complex* (see Salvador, 1994). However, the controversial definition of
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31 *complex*, as a lithodeme subunit (NACSN, 2005), suggests a mostly tectonic origin of its contacts
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33 (see also Pasquarè et al., 1992; Vannucchi and Bettelli, 2010). The term *complex*, however, is also a
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35 formal lithostratigraphic term, defining any rock body that is characterized by complicated deformation
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37 patterns and bounded by primary (i.e. stratigraphic) contacts (see also Pasquarè et al., 1992;
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39 Salvador, 1994). Only “sedimentary *mélanges*” (olistostromes) are compatible with the classic
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41 principles of stratigraphic superposition, whereas many *mélange* occurrences in nature do not follow
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43 these principles (Silver and Beutner, 1980) because they are not bounded by stratigraphic contacts.
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49 The classical definitions of the term *mélange* (Hsü, 1968; Berkland et al., 1972; Silver and
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51 Beutner, 1980) portray these rock bodies to “commonly” include a “*pervasively deformed matrix*”
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53 (Silver and Beutner, 1980) or a “*fragmented matrix of finer-grained material*” (Raymond, 1984). Some
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55 researchers have avoided in these definitions any specification of the origin of that matrix as tectonic,
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57 sedimentary or diapiric. This matter is particularly important in studying sedimentary *mélanges* in that
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59 it restricts the use of the term *mélange* only to mass-transport deposits, which display a chaotic
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1 internal arrangement and mixing of exotic and native blocks in a deformed matrix (debris flows,
 2 hyperconcentrated flows, blocky flows, Mutti et al., 2006; Ogata et al., 2012a). It also excludes other
 3 sedimentary deposits such as turbidites. Glacial till (e.g., Hoffmann and Piotrowski, 2001) or the
 4 Martian chaos (e.g., Kargel et al., 2007) may be included in this definition of *mélange* because they,
 5 too, form by mixing of different blocks as a result of slope failure, mass-transport processes, gas
 6 outburst by clathrate dissociation, mud volcanism, and bolide impacts on the surface of the planet.
 7

8 Mixing of rocks is clearly stated in the definition of *mélange* by Hsü (1968) and Silver and
 9 Beutner (1980), and is addressed by Raymond (1984) as one of the two fundamental *mélange*-
 10 forming processes, but the significance and the amount of mixing is not clearly defined in these earlier
 11 definitions. In addition, the meaning of the terms “exotic” and “native” blocks is ambiguous (Tab. 1)
 12 mainly because the concept of an exotic origin changes dramatically in different tectonic settings,
 13 structural levels, and according to the different origins of *mélanges*. A restrictive usage of the term
 14 “exotic” is consistent with a virtual association between exotic blocks and subduction settings (e.g.,
 15 Bailey et al., 1964; Cowan, 1978, 1985; Aalto, 1981; Cloos, 1982; Barber et al., 1986; Brown and
 16 Westbrook, 1988; Cloos and Shreve, 1988a, 1988b; Onishi and Kimura, 1995; Meschede et al., 1999;
 17 Wakabayashi, 2004, 2011; Ikesawa et al., 2005; Federico et al., 2007; Malatesta et al., 2012) partly
 18 because subduction channel is the most popular setting where exotic blocks (e.g., HP eclogite blocks)
 19 become encased in epizonal metamorphic binders (e.g., Cloos, 1982; Cloos and Shreve, 1988a,
 20 1988b; Ogawa, 1998).
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22 At shallow structural levels in subduction zone settings or in other tectonic environments (e.g.,
 23 continental to intracontinental deformation settings, strike-slip tectonics, extensional settings), the
 24 meaning of “exotic” must be extended to a wider range of blocks. Hsü (1968) defined an exotic
 25 component as a “*tectonic inclusion detached from some stratigraphic rock units foreign to the main*
 26 *body of mélange*”, whereas native components are “*disrupted brittle layers interbedded with the*
 27 *ductilely deformed matrix*”: Berkland et al. (1972) clearly distinguished between “exotic” and “tectonic”
 28 blocks, whereas Hsü (1968) considered them to be synonymous. These authors defined “exotic”
 29 blocks as “*variably sized masses of rock occurring in a lithological association foreign to that in which*
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1 *the mass formed*". "Tectonic" blocks are then considered more restricted in origin because they
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3 consist of only blocks "*transported through the operation of tectonic processes*". Then, not all
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5 "tectonic" blocks are "exotic", and not all "exotic" blocks are tectonic in origin (Berkland et al., 1972).
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8 Sedimentary and diapiric processes and a combination and superposition of them with
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10 tectonic processes have been widely accepted to play a major role in the incorporation and mixing of
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12 exotic blocks during *mélange* formation (e.g., Hsü, 1968; Berkland et al., 1972; Cowan, 1974; Cowan
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14 and Page, 1975; Aalto, 1989; Harris et al., 1998; Erickson, 2011; Osozawa et al., 2011; Wakabayashi,
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16 2011). Exotic component can be "foreign" at different levels with respect to the "native" component of
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18 the main body, varying from simply extra-formational (e.g., Panini et al., 2002; Codegone et al.,
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20 2012b), to an extra-basinal origin (e.g., Lash, 1987; Ogata et al., 2012c), up to having been derived
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22 from different structural units (Abbate et al., 1970, 1981; Alonso et al., 2006; Lucente and Pini, 2008
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24 and references therein), paleogeographic domains, tectonic settings or structural levels (P-T
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26 conditions, diagenetic/metamorphic degree) (e.g., Cloos, 1982; Cowan, 1985; Cloos and Shreve,
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28 1988a, 1988b; Dilek, 1989; Harris et al., 1998; Ogawa, 1998; Dilek et al., 1990, 1999, 2007;
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30 Wakabayashi, 2011, 2012; Ukar, 2012).
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35 The processes of exotic block incorporation into *mélanges* can provide important information
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37 about the *mélange* genesis. Fragmentation and dismemberment may exceed the strength of a given
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39 lithostratigraphic unit (or formation), and the rocks that formed in different geological environments at
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41 different times may involve extensive mixing (Raymond, 1984). If fragmentation and dismemberment
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43 does not exceed the strength of a given lithostratigraphic unit (or formation), we must then use the
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45 term "broken formation" (*sensu* Hsü, 1968) to describe a stratally disrupted unit, which contains no
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47 exotic blocks but only "native" components. These broken formations preserve their lithological and
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49 chronological identity ("tectonosomes" *sensu* Pini 1999). Here, stratal disruptions and fragmentation
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51 occur without mixing (Hsü, 1968; Cowan, 1985) (Tab. 1) and broken formations show a gradual
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53 transition from a bedded succession to a strongly disrupted block-in-matrix fabric (Lash, 1987; Barnes
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55 and Korsch, 1991; Sunesson, 1993; De Libero, 1998; Festa et al., 2010a; Codegone et al., 2012a)
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57 representing the intraformational equivalent of *mélanges* (Tab. 1). In this sense, this definition
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1 embodies “broken” and “dismembered units”, as described by Raymond (1984), that were proposed
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3 to differ from each other in the degree of stratal disruption and from mélanges by the lack of exotic
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5 blocks. Cowan (1985) chose not to use the exotic block requirement in defining mélanges, and the
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7 four types of mélanges he defined included the broken formation of Hsü (1968) and Raymond (1984).
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10 In this article and as our common practice (Codegone et al., 2012a, 2012b; Ogata et al.,
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12 2012b), we consider mélanges and broken formations two end-members, which differ from each other
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14 in terms of the nature of blocks (exotic vs. native) and the mechanisms of their formation (mixing plus
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16 stratal disruption vs. only stratal disruption; e.g., Hsü, 1968; Harris et al., 1998). They can also both
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18 form by tectonic, sedimentary or diapiric processes (Tab. 1) or through a combination and
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20 superposition of these processes. Independently from their deformational path and origin, we favor to
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22 define a disrupted rock body without exotic blocks and rock mixing as a broken formation and not as
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24 mélanges. Following Raymond (1975), we define mélange as a body of mixed rocks, containing blocks
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26 (exotics and native) that are derived from different stratigraphic units or sequences, different tectonic
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28 units, various paleogeographic domains, and/or dissimilar metamorphic zones.
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32 The scale of observation is highly important in characterization of mélanges. Although
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34 extension of the mélange term to bodies that are non-mappable at 1:25,000 or smaller scales renders
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36 the term mélange useless (e.g., Raymond, 1984), it is not unusual to find this term used in describing
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38 small-scale or meso-scale mélanges (e.g., Bosworth and Vollmer, 1981; Bradley and Kusky, 1992;
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40 Wakita, 1988, 2000; Fukui and Kano, 2007). To avoid any confusion, we agree to the use of the terms
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42 “small-scale mélanges and broken formations” (see Codegone et al., 2012b) or “meso-scale mélange”
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44 (see Bradley and Kusky, 1992) in order to indicate not-mappable (at 1:25,000 scale) mélanges and
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46 broken formations, whereas “chaotic or disrupted (rock) units” (*sensu*, e.g., Yamamoto et al., 2009;
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48 Festa, 2011) must be considered a general term to indicate bodies apart from the nature of the
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50 embedded blocks. These terms do not define micro-scale mélanges and broken formations, nor do
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52 they suggest applying these terms to chaotic bodies at the scale of sedimentary layers/beds.
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55 However, they are to be used in describing chaotic rock units mappable on a scale that is larger than
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1 1:25,000 according to the requirement of geological map databases and GIS technologies used for
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3 the production of modern geological maps.
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10 **3. Types, processes of formation and triggering mechanisms of broken formation and** 11 **mélanges** 12 13

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17 The re-defined terms *mélange* and *broken formation* and their clarified meaning could be
18 extended to a large number of bodies of mixed rocks formed at different structural levels and in
19 various tectonic settings (Fig. 1, and Tab. 2; see Suzuki, 1986; Festa et al., 2010a, 2010b and
20 reference therein). It is important, however, to distinguish *mélange*-forming processes from triggering
21 mechanisms in each of these tectonic settings (Tab. 2; Moore and Wheeler, 1978; Cloos, 1982;
22 Saleeby, 1984; Barber et al., 1986; Raymond et al., 1989; Orange, 1990; Festa et al., 2010a; Festa,
23 2011).
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32 **3.1. *Mélanges and tectonic settings of their formation*** 33 34

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37 When we compare some of the exhumed, ancient chaotic rock bodies and their modern
38 analogues that developed as a result of different tectonic processes in different geodynamic
39 environments, we realize that several examples of “tectonic *mélanges*” described in the literature do
40 not include exotic blocks (see, e.g., Cowan, 1974, 1985; Vollmer and Bosworth, 1984; Lash, 1987;
41 Brandon, 1989; Wakabayashi, 1992, 2011; Harris et al., 1998; Onishi et al., 2001; Vannucchi and
42 Bettelli, 2002) (Tab. 2). Instead, they consist of variably disrupted units or well-developed block-in-
43 matrix units corresponding to broken formations (*sensu* Hsü, 1968), which are transitional to slightly
44 boudinaged beds and coherent layered units. These broken formations were formed by stratal
45 disruption of the original coherent successions in various tectonic environments, mainly related to
46 subduction zone processes (Type 4b in Tab. 2, and Figs. 2B and 2D), arc-continent and continent-
47 continent collisions (Type 5 in Tab. 2, and Fig. 2E), intra-continental deformation (Types 6a3, 6b2 and
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6c2 in Tab. 2, and Fig. 2E) and strike-slip tectonics (Type 3 in Tab. 2, and Fig. 2F). Some of the most salient examples of broken formations include the Ligurian mélanges in the eastern Northern Apennines (Fig. 3C) (e.g., Pini, 1999; Vannucchi and Bettelli, 2010), part of the *Argille Varicolori* and “Flysch Rosso” (Figs. 3A and 3B) in the Central-Southern Apennines (Festa et al., 2010a, 2010b; Vezzani et al., 2010), the Costal Range mélange of Hikurangi margin, and the Esk Head (Fig. 3D) and similar chaotic rocks in the Torlesse Complex in New Zealand (e.g., Pettinga, 1982; Barnes and Korsch, 1991), part of the Franciscan Complex in California (e.g., Wakabayashi, 1992, 2011; Meneghini et al., 2009), the youngest section of the Shimanto Belt in Japan (Ditullio and Byrne, 1990), the Bobonaro Mélange of the active Banda arc-continent collision (Harris et al., 1998; Harris, 2011), and the Taconic mélanges in the Central-Northern Appalachians (e.g., Vollmer and Bosworth, 1984; Lash, 1987; Codegone et al., 2012a).

The origin of exotic blocks and the nature of processes responsible for their emplacement and mixing within a mélange are a subject of long-lasting debate and controversy (e.g., Bailey et al., 1964; Hsü, 1968; Coleman and Lanphere, 1971; Berkland et al., 1972; Cowan, 1974, 1985; Raymond, 1984; Suzuki, 1986; Aalto, 1989; Harris et al., 1998; Şengör, 2003; Osozawa et al., 2011; Wakabayashi, 2011). Tectonic mélanges with exotic blocks mixed solely by tectonic processes (Tab. 2) are predominant in shear zones (Figs. 3E and 3F, see also Type 3 in Fig. 2F), and occur at different scales in (1) narrow, anastomosing and coalescent fault zones (Fig. 3F; see, e.g., Coleman and Lanphere, 1971; Suppe, 1972; Cowan, 1974; Pettinga, 1982; Kimura et al., 1996; Hashimoto and Kimura, 1999; Codegone et al., 2012b), (2) crustal-scale thrust fault zones (e.g., Moore and Sample, 1986; Doubleday and Trenter, 1992; Kusky et al., 1997; Meneghini et al., 2009), (3) plate boundaries (e.g., Wakabayashi, 1992; Ogawa, 1998; Onishi et al., 2001; Vannucchi et al., 2008; Meneghini et al., 2009; Kusky and Jianghai, 2010; Kimura et al., 2012) and transform fault or fracture zones (e.g., Moseley and Abbotts, 1979; Suzuki, 1986; Dilek, 1989; Saleeby, 1989; Dilek et al., 1991; Shervais et al., 2011), where they may be as thick as 1000-2000 meters, and (4) subduction channels (e.g., Cloos, 1982; Federico et al., 2007; Blanco-Quitero et al., 2010; see Type 4b in Fig. 2C) where flow-mélanges form (e.g., Cloos, 1982; Shreve and Cloos, 1986; Ukar, 2012). In these settings tectonic

1 processes incorporate exotic blocks into the *mélange* matrix by offscraping, underplating, sinking of
2 roof thrust rocks, and tectonic slicing (see Type 4b in Figs. 2B, 2C and 2D). In view of similar
3 observations, Cowan (1974) suggested that tectonic *mélanges* are structurally equivalent to faults,
4 along which the tectonic dislocation “*has expanded from a plane (i.e., fault) to a zone of several*
5 *members to kilometers in width (i.e., tectonic mélange)*”. However, *mélanges* with exotic blocks
6 originated from sedimentary (e.g., Hsü, 1968; Cowan and Page, 1975; Abbate et al., 1981; Naylor,
7 1982; Cowan, 1985; Liu and Einsele, 1996; Burg et al., 2008; Erickson, 2011; Wakabayashi, 2011;
8 Cieszkowski et al., 2012; Codegone et al., 2012b; El Bahariya, 2012; Hitz and Wakabayashi, 2012;
9 Pini et al., 2012) and diapiric processes (e.g., Maxwell, 1974; Cloos, 1983; Becker and Cloos, 1985;
10 Maekawa et al., 1993; Fryer et al., 1999; Camerlenghi and Pini, 2009) are common in other tectonic
11 settings (Tab. 2). Both of these *mélange* types may subsequently be overprinted and structurally
12 reworked by tectonic processes such as shearing and tectonic mixing when placed in an accretionary
13 wedge or in a subduction channel (e.g., Cowan and Page, 1975; Cloos, 1982; Cowan, 1985; Cloos
14 and Shreve, 1988a, 1988b; Medialtea et al., 2004; Dilek and Thy, 2006; Burg et al., 2008; Osozawa et
15 al., 2009, 2011; Cowan and Brandon, 2011; Wakabayashi, 2011; Fig. 2C; see Type 4b in Tab. 2; see
16 also Figs. 4A and 4B), or by thrusting and folding in a collisional belt (e.g., Brandon, 1989; Pini, 1999;
17 Dilek, 2006; Camerlenghi and Pini, 2009; Osozawa et al., 2009, 2011; Festa et al., 2010a, 2010b;
18 Codegone et al., 2012b; Ogata et al., 2012b; Fig. 3A; see Types 6a2 and 6b2 in Tab. 2 and Fig. 2E).
19 These *mélanges* (with exotic blocks) mainly represent “polygenetic” *mélanges*, in which the
20 occurrence of exotic blocks in their matrix is commonly due to different types of mass-transport
21 (slides, debris flows and avalanches, etc.) or diapiric processes (Fig. 4C) rather than due solely to
22 tectonic processes.

23 Although subsequent tectonic processes commonly affect and overprint the existing
24 sedimentary and diapiric *mélanges* (Cowan and Page, 1975; Osozawa et al., 2011), it is not
25 uncommon for tectonic *mélanges* and broken formations to be, in turn, reworked and overprinted by
26 later sedimentary or diapiric processes (e.g., Aalto, 1981). The occurrences of mud diapirs, which
27 reworked some previously formed tectonic *mélanges* and broken formations, have been described
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1 from the wedge-top succession of the Tertiary Piedmont Basin (Dela Pierre et al., 2007, Festa, 2011)
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3 and from the frontal part of the ancient External Ligurian accretionary complex of the Northern
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5 Apennines (Codegone et al., 2012b) in NW Italy. Large-scale sedimentary processes reworking
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7 tectonic mélanges and broken formations are responsible for the development of basin-wide
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9 olistostromes in the wedge-top and foredeep Tertiary basin of the Apennines (Abbate et al., 1970,
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11 1981; Pini, 1999; Lucente and Pini, 2003, 2008; Cavazza and Barone, 2010; Vezzani et al., 2010;
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13 Remitti et al., 2011). Diapiric processes overprinting sedimentary mélanges occur, for example, in the
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15 Hoh accretionary complex in the Olympic Peninsula (e.g., Cowan and Brandon, 2011), in the
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17 Hamburg Klippe of central Pennsylvania (Lash, 1987; Codegone et al., 2012a), in the Timor region of
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19 the Banda arc (Harris et al., 1998) and in several offshore cases (Camerlenghi and Pini, 2009 and
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21 references therein). Diapiric mélanges and shale diapirs reworked by sedimentary processes occur in
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23 the accretionary complex of Timor in Indonesia (e.g., Barber et al., 1986; Barber and Brown, 1988;
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25 Harris et al., 1998).

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30 Sedimentary mélanges (Figs. 4D, 4E and 4F) may occur in many tectonic environments, but
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32 they prevail particularly in extensional (Type 1 in Tab. 2, and Fig. 2A; e.g., Bernoulli, 2001; Alonso et
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34 al., 2008) and passive margin settings (Types 2a and 2b in Tab. 2, and Fig. 2A; e.g., Naylor, 1982; Liu
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36 and Einsele, 1996; Dilek et al., 2005; Camerlenghi and Pini, 2009; Robertson et al., 2009; Ghikas et
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38 al., 2010; Bonev et al., 2012), where the direct contribution of extensional tectonic processes (e.g.,
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40 crushing and mixing in normal fault zones) is negligible. Sedimentary processes commonly take place
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42 at the front and atop of a nappe stack in collisional and intra-continental deformation zones (Types 5,
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44 6a1 and 6a2 in Tab. 2, and Fig. 2E; e.g., Dilek et al., 1999; Remitti et al., 2011; Hernaiz Huerta et al.,
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46 2012; Ogata et al., 2012a, 2012b) of ancient, submarine collisional orogens as in the “Alpine-
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48 Himalayan” chains (e.g., Abbate et al., 1970; Smith et al., 1979; Liu and Einsele, 1996; Marroni and
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50 Pandolfi, 2001; Burg et al., 2008), and modern ones as in the Gela Nappe in the Sicily Channel
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52 (Tricardi and Argnani, 1990; Minisini et al., 2009) and Adriatic Sea (Tricardi et al., 2004; Argnani et al.,
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54 2011). Their occurrence in exhumed accretionary wedge and in subduction settings (Type 4a in Tab.
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56 2, and Figs. 2A, 2C, and 2D) is relatively minor, although it has been recently re-evaluated in some
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1 on-land examples of ancient accretionary complexes (e.g., Collot et al., 2001; Burg et al., 2008;
2 Yamamoto et al., 2012b). These mélanges occur at the wedge front of subduction settings (Yamada
3 et al., 2010) and are mainly related to subduction of seamounts and to the reactivation of normal
4 faults (Fig. 2A) in a downgoing plate (see e.g., Marroni and Pandolfi, 2001; Martinez Catalan et al.,
5 1997). Some may also form when accretion is replaced by tectonic erosion at a convergent margin
6 (e.g., von Huene and Lallemand, 1990; Ranero and von Huene, 2000; von Huene et al., 2004; Remitti
7 et al., 2011). Sedimentary processes might also have been responsible for the formation of different
8 types of sub-aerial mélanges (Type 7a in Tab. 2), such as debris flow and avalanches, alluvial fan
9 deposits, talus breccias (scree deposits) and megabreccias, block falls, and glacial till (see Hoffmann
10 and Piotrowski, 2001).
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26 **3.2. Tectonics as a prominent triggering mechanism**

27 The occurrence of different types of sedimentary mélanges in most geodynamic environments
28 (Tab. 2) could be simply related to the fact that sedimentary processes are more efficient in terms of
29 conservation of kinetic energy in comparison to tectonic and diapiric ones. These processes may also
30 play a prominent role in maintaining the dynamic equilibrium in active tectonic settings (e.g., frontal
31 erosion in accretionary complexes, slope failure on steep margins of carbonate platforms or passive
32 margins). However, tectonic processes, rather than sedimentary or diapiric ones, constitute the most
33 effective triggering mechanisms (both directly and indirectly) (see Tab. 2). Hence, they play a primary
34 role in controlling the processes and mechanisms of stratal disruption and mixing, and in the
35 formation of tectonic, sedimentary or diapiric mélanges (Fig. 5).
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48 The direct role played by tectonics is achieved mainly by seismic faulting associated with
49 strike-slip or contractional deformation (Fig. 5). Faulting is an effective mechanism of disruption of a
50 coherent stratigraphic succession (e.g., Cowan, 1974, 1985; Vollmer and Bosworth, 1984; Karig et al.,
51 1986; Needham, 1995; Rassios and Dilek, 2009; Ghikas et al., 2010; Festa et al., 2010a). The
52 superposition of displacements along innumerable subparallel, meso-scale shear faults and fractures
53 develop zones of distributed shear from several meters to kilometers in width (Coleman and
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1 Lanphere, 1971; Suppe, 1972; Pettinga, 1982; Moore and Sample, 1986; Kimura et al., 1996; Kusky
2 et al., 1997; Ogawa, 1998; Meneghini et al., 2009; Bradbury et al., 2011). This process represents an
3 effective mechanism of formation of tectonic mélanges and broken formations with different end-
4 members, from brittle broken formations to flow mélanges according to the tectonic setting and
5 structural level of their formation.
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12 In poorly- or non-consolidated sedimentary successions, faults represent the preferential
13 pathways for the upward rise of overpressured fluids (Fig. 5) that facilitate *in situ* stratal disruption,
14 diapiric deformation and related processes. These fluids are able, in turn, to increase the driving
15 forces along the slope, inducing gravitational processes and the formation of sedimentary mélanges.
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21 Tectonic processes can also play an indirect role in triggering stratal disruption and mixing in
22 most geodynamic settings (Fig. 5). Tectonic activities can trigger mass-transport processes by both
23 (1) reducing the shear strength of sediments (e.g. higher sedimentation rates, gas hydrates
24 dissociation, etc.) and, thus decreasing the resisting forces along the slope, and (2) magnifying the
25 effect of other driving mechanisms, processes and events along the slope (e.g., failure by slope
26 oversteepening, mud diapirism and mud volcanism, sea level fluctuation, etc.).
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35 Sedimentary instability may be caused by the upward rise of over-pressured fluids from a
36 subduction zone. The upward rise of these fluids is commonly related to tectonic loading (Fig. 5)
37 along the decollement surface developed at the toe of an accretionary wedge (e.g., Brown and
38 Westbrook, 1988; Brown, 1990) or to fluids pumped-up along strike-slip faults (e.g., Dela Pierre et al.,
39 2007). The abrupt emplacement of mass-transport chaotic bodies can strongly increase the
40 magnitude of sedimentary loading, causing overpressure and consequent sediment liquefaction (Figs.
41 4G and 4H), which in turn induces diapiric processes forming diapiric mélanges (Fig. 5). The
42 emergence of diapiric bodies (e.g., sedimentary diatremes, mud volcanoes or diapirs) may create
43 instability in unconsolidated material and then gravitational movement along the slope, forming mass-
44 transport chaotic bodies (e.g., Barber et al., 1986; Camerlenghi and Pini, 2009). This complicated
45 interplay of different processes induced mainly by tectonics is strongly controlled, in each tectonic
46 setting, by the physical conditions (e.g. water content, overpressure, P-T conditions, etc.), the nature
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1 and state of consolidation of sediments, and the burial depth or structural level at which broken
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3 formations and mélanges form (see below).
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8 **4. Mechanisms of stratal disruption, mixing and related chaotic products**

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12 At shallow structural depths in different tectonic environments, the final structural texture and
13 the fabric of chaotic rock units are commonly achieved through progressive deformation of originally
14 coherent stratigraphic successions (stratal disruption), and through series of interacting or overlapping
15 mechanisms (Fig. 6). This progressive deformation is directly controlled by the increase of the degree
16 of consolidation with burial, or with the increasing depth of the structural level in which these
17 processes commonly operate (see Tab. 2, and Fig. 7). Consolidation controls the change of
18 mechanical strength of sediments from deposition to progressive burial (e.g., Lash, 1989; Jones et al.,
19 1991); it is time-dependent and closely related to changes in pore-volume, expulsion of pore-fluid, and
20 interaction and packing of grain particles (e.g., Maltman, 1994; Maltman and Bolton, 2003). Then, the
21 occurrence of poorly consolidated sediments in the shallow part of accretionary prisms or sedimentary
22 piles favors gravitational deformation, whereas with the downward increase of consolidation at depth,
23 the deformation related to tectonic forces becomes gradually more significant (Fig. 6, see also
24 Maltman, 1994). However, tectonics and related stress conditions may greatly affect this linear
25 relationship between consolidation and structural or burial level (see below), changing the local
26 physical properties of sediments (e.g., permeability, strength; see Maltman, 1994; Michiguchi and
27 Ogawa, 2011).
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50 **4.1. Sedimentary stratal disruption and mixing**

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52 At shallow structural levels, sedimentary mass transport processes are the most efficient
53 causes for stratal disruption (Figs. 6A and 6B), occurring both inside of a sliding body of rocks (e.g.
54 via partial disaggregation of still stratified blocks) and outside (e.g. within the uppermost portion of the
55 overridden substrate) during its downslope motion. This kind of deformation commonly involves
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1 poorly-lithified or loose material, and results in the formation of a broad spectrum of structures (Figs.
2 6A and 6B) ranging from folded and boudinaged successions (e.g. slump deposits) to block-in-matrix
3 bodies (e.g. debris flow deposits; Figs. 6A and 6B). These products are characterized by the
4 occurrence of a strongly mixed, liquidized matrix (i.e. hyper-concentrated suspension *sensu* Mutti,
5 1992) enveloping disrupted layers and blocks. Those layers or blocks may show different degrees of
6 lithification, and represent the final artifacts of progressive down-slope, soft sediment deformation
7 (e.g., Maltman, 1994; Ogata, 2010). The latter deformation is enabled by the relative movement (i.e.,
8 fast vs. slow) of unlithified masses with progressive flow transformation, stratal disruption, or both, of
9 the partially-to largely lithified sediments (Pini et al., 2012).

10 The different velocities of movement, the composition and lithification degree of sediments
11 (related to the stratigraphic level of the rupture surface), the geometry and morphology of the
12 depositional setting, and the mode of failure propagation (progressive vs. regressive collapse)
13 commonly control the nature of the transition between different types of mass-transport chaotic bodies
14 (Fig. 8A). Pini et al. (2012; see also Lucente and Pini, 2003) distinguished three main types of mass-
15 transport chaotic bodies, representing the end-members of a continuum of chaotic products and
16 displaying different characteristics. First, viscous-flow, which is dominated by shearing in fine-grained
17 sediments, is responsible for the movement and emplacement mode of classic olistostromes (Figs.
18 8A and 8B; see also Figs. 4D, 4E and 4F), which are characterized by centimeter-to meters sized
19 hard blocks that are randomly distributed in a mud-rich, brecciated matrix (Fig. 8C) (e.g., Swarbrick
20 and Naylor, 1980; Abbate et al., 1970, 1981). Commonly, at the base of these bodies, a shear zone
21 may form accommodating the flow of sediments (e.g. Pini, 1999; Ogata et al., 2012a) and deforming
22 poorly consolidated blocks (Figs. 8A and 8D). These bodies may assume different shapes depending
23 on the deformation style (flattening vs. simple-shear) and strain magnitude (see Type 1 MTC of Pini et
24 al., 2012). Second, overpressure of fluids sustaining mud-silt-sandy sediments, controls the down-
25 slope movement of hyper-concentrated suspension (*sensu* Mutti, 1992) characterized by a block-
26 dominated part overlying a matrix-dominated one (Fig. 8A; see Ogata, 2010; Ogata et al., 2012a,
27 2012b). Third, narrow and over-pressured shear zones (millimeters-to decimeters thick, see Dykstra,
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1 2005) allow the emplacement of chaotic, sandy sediments displaying folds, boudinage, extensional
2 and contractional duplexes, and showing a gradual downward increase of stratal disruption (Figs. 8A,
3 8E and 8F; see Pini et al., 2012). Localized zones of liquefaction of sandy sediments can also be
4 locally related to the emplacement of these chaotic bodies (see Lucente and Pini, 2003 for detail).
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10 In all these types of mass-transport chaotic bodies, the mixing of rocks and the incorporation
11 of exotic blocks are controlled by two fundamental factors. The first one is the depth reached by the
12 slope failure and its propagation toward the basin margins. Mixing of the rocks derived from the basin
13 margins with those sediments in the basin is a common process in the formation of mass-transport
14 bodies (Page and Suppe, 1981; Callot et al., 2008; Ogata et al., 2012c). During deposition, these
15 "exotic" rocks were extraformational, extrabasinal, older and much more consolidated than the basin
16 sediments. The second factor involves the exhumation and uplift and the subsequent reworking of
17 older rocks. The emplacement of submarine nappes can supply extrabasinal blocks of different size,
18 centimeters to hundreds of meters, to mass-transport deposits in the foredeep basins. Originated from
19 different structural units, these blocks are composed of rocks that were completely consolidated,
20 tectonically deformed and metamorphosed at the time of deposition. Classic examples include the
21 precursory olistostromes in the Apennines of Italy (see, e.g., Abbate et al., 1970, 1981; Elter and
22 Trevisan, 1973; Lucente and Pini, 2008 and references therein), the Porma mélange in the
23 Cantabrian chain (Alonso et al., 2006), the "wildflysch" of the Alps (Trümpy, 2007) and the "klippen
24 zones" in the Carpathians (Camerlenghi and Pini, 2009 and references therein; Cieszkowski et al.,
25 2012; Ślęczka et al., 2012). The same scenario could occur in oblique subduction (Hernaiz Huerta et
26 al., 2012) and transpressional tectonic zones (Marroni et al., 2001). In the Franciscan Complex, the
27 HP (and medium pressure) blocks, hosted by a low metamorphic epizonal matrix, can be explained
28 as clasts (see Cowan and Page, 1975) eroded from exhumed blueschists facies rocks and deposited
29 as debris flows and avalanches in the accretionary prism front (Erickson, 2011; Wakabayashi, 2011).
30 Exhumation of subduction channels, such as in Timor and Taiwan, represents the source of exotic
31 blocks of different metamorphic grades and mantle origins (e.g., Guillot et al., 2009; Ota and Kaneko,
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1 2010) that may be mixed together by mass-transport processes forming sedimentary mélanges or
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3 supplying UHP-HP "knockers".
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6 7 8 **4.2. Diapiric stratal disruption and mixing** 9

10 Liquefaction of sediments is a primary factor in controlling the downslope mobilization of
11 unconsolidated or incompletely lithified sediments (Maltman and Bolton, 2003), but it is also highly
12 important for *in situ* stratal disruption processes characterized by relatively limited transport of
13 material. At shallow crustal-levels, injectites and seismites (Figs. 4G, 4H and 6B) may develop in
14 response to slope tectonics and seismic shocks (at least at the micro-and meso-scales). Yamamoto
15 et al. (2009) described some notable examples of these structures from the Miura-Boso accretionary
16 complex that formed during the early stages of accretion (Fig. 4G; Central Japan) and Codegone et
17 al. (2012a) from the Hamburg Klippe in the central Appalachians (Central-eastern Pennsylvania).
18 These authors described some good examples of injectites and seismites intruding the overlying and
19 underlying sandy layers, and showing a randomly oriented "block-in-homogeneous sandy matrix".
20 These examples lack sedimentary features such as lamination, grain-size grading or small-block
21 preferred orientation (Fig. 4G). Another important diagnostic feature of injectites and seismites is the
22 lack of a basal erosive surface and internal slip planes. The injectites and seismites in other chaotic
23 bodies are characterized by a liquefied matrix and constitute hyper-concentrated density flows
24 (Lucente and Pini, 2003; Ogata, 2010).
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43 With an increase of the consolidation degree and the rheological contrast between the layers
44 of the stratigraphic succession, an abrupt increase of tectonic or lithostatic loading, gas hydrates
45 dissociation, density inversion, and diagenetic transformation (Kopf, 2002) may cause the
46 overpressurization of fluids at relatively deeper structural levels. Over-pressured fluids may then result
47 in the development of sedimentary diatremes (e.g., Borgia et al., 2006), mud-volcanoes (e.g., Kopf,
48 2002; Camerlenghi and Pini, 2009) and diapiric bodies (Fig. 4C; e.g., Barber et al., 1986; Orange,
49 1990; Festa, 2011) of unconsolidated sediments. These structures may show a great diversity
50 stemming from the origin of the fluid phases (e.g., Kopf, 2002; Camerlenghi and Pini, 2009). Diapiric
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1 processes are widespread as subordinate processes in most tectonic environments (see Tab. 2, Fig.
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3 2) and occur where the necessary physical and mechanical conditions (such as fluid overpressure)
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5 exist (e.g., Brown and Westbrook, 1988; Kopf, 2002; Dela Pierre et al., 2007; Camerlenghi and Pini,
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7 2009; Festa, 2011). The mixing of exotic blocks is mainly achieved by a combination of
8
9 hydrofracturing processes and the progressive incorporation of the wall-rock material (collapse and
10
11 assimilation of the roof and margins of the structure) and flow. Notable examples of mud volcanoes
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13 with exotic blocks of blueschist rocks contained in serpentine-dominated muds have been described
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15 from the forearc region of the active Mariana subduction zone (Maekawa et al., 1993; Fryer et al.,
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17 1999). These exotic blocks, originated from the metamorphosed subducted plate, were entrained in
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19 rising serpentine mud diapirs (up to 30 km wide and 2 km high), and were then extruded from the mud
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21 volcanoes onto the sea floor.
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26 Blocks may be also derived from the previously formed underlying mélanges (Camerlenghi
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28 and Pini, 2009). Cyclic diapiric reactivation of the previously formed sedimentary or tectonic mélanges
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30 (Fig. 4C) may also occur when the physical conditions are sufficient, leading to the formation of a
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32 complex polygenetic mélange (Barber et al., 1986; Henry et al., 1990; Brown and Orange, 1993;
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34 Cronin et al., 1997; Camerlenghi and Pini, 2009; Festa et al., 2010a; Festa, 2011; Codegone et al.,
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36 2012b).
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41 **4.3. Tectonic stratal disruption and mixing**

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43 Immediately after deposition, sediments may start undergoing deformation due to the interplay
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45 between gravitational forces and tectonic stresses during progressive burial (see Maltman, 1994).
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47 There exists an overlapping zone at shallow structural levels, where the block-in-matrix fabric of
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49 broken formations shows a strong convergence of fabric with sedimentary mélanges.
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53 In general, layer-parallel extension occurring in all directions records a coaxial strain history
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55 compatible with sedimentary processes on gently dipping slopes (Fig. 9A and 9A1; e.g., Lash, 1987,
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57 1989; Cowan, 1985), whereas layer-parallel shearing records a non-coaxial strain history commonly
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59 related to extensional slicing across a basal shear zone and underthrusting (e.g., Cowan, 1985;
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1 Byrne, 1984; Fisher and Byrne, 1987; Hashimoto and Kimura, 1999). The development of layer-
2 parallel extension and shearing may change as a function of the relationships between the
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4 parallel extension and shearing may change as a function of the relationships between the
5 consolidation degree, dewatering processes, and the magnitude of strain occurring in the tectonic
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7 setting, whereas tectonic loading may produce layer-parallel extension with coaxial strain on sub-
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9 horizontal bedded succession.

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12 Tectonic loading related to pre-thrusting deformation during the advancement of an
13 accretionary wedge or a continental nappe stack is an effective mechanism in triggering dewatering
14 and fluid expulsion (Breen et al., 1986; Harris et al., 1998) (Fig. 6C). These fluid-driven processes
15
16 result in layer-parallel disruption and in the development of boudinage or dismemberment of the most
17
18 lithified layers due to hydrofracturing and fluid overpressure (e.g., blocky veins, see Meneghini et al.,
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20 2009; web-like fragmentation, see Kimura et al., 2012; brecciation, etc.). Depending on the degree of
21
22 consolidation and rheological contrasts within a stratigraphic succession (see Bettelli and Vannucchi,
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24 2003), layer-parallel disruption can evolve into an incipient foliation, formation of a scaly fabric in the
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26 less competent layers (e.g., claystone, limestone, mudstone), and development of a progressive
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28 boudinage structure in competent layers (Figs. 9A; e.g., sandstone; see Lash, 1989; Kimura and
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30 Mukai, 1991; Onishi and Kimura, 1995). Pinch-and-swell structures and irregular boudinage features
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32 defining ellipsoidal-shaped blocks are commonly related to coaxial strain that induced heterogeneous
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34 flattening in all directions (Figs. 9A and 9A1; Harris et al., 1998; Pini, 1999). Regular boudinage
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36 features form as a result of non-coaxial strain and may produce lozenge-to sigmoidal shaped blocks
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38 (Figs. 9B and 9B1).

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41 With the gradual increase of consolidation, conjugate extensional fractures may develop into
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43 symmetrical brittle boudinage structures, which may turn into asymmetric shear planes with increased
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45 shearing (Figs. 9F, 9F1, 9G, 9G1 and 9G2; see also Kimura et al., 2012). Boudinage structures may
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47 also form due to the propagation of Y, P, R, R" shear surfaces (Figs. 9G, 9G1 and 9G2; see also
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49 Needham, 1995; Pini, 1999). In lithified sediments, extensional veining (Figs. 9C and 9C1), cataclastic
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51 deformation and brecciation at necks and tails of boudins (Figs. 9D and 9D1), and asymmetric veins
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53 (Fig. 9E) may develop as a result of a sequential process of cataclasis, fracturing, and Riedel
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1 shearing leading to boudinage formation (see Kimura et al., 2012). The style and degree of block
2 fragmentation may change as a function of block aspect ratio (see Needham, 1995), whereas at
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4 seismogenic depths the increase of diagenesis and metamorphic grade may also change the shape
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6 of boudinaged blocks from elongate and oblate to a spherical shape (Kimura et al., 2012).
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10 With the increase of shear and consolidation, mixing process in fault/shear zones cause
11 mechanical crushing of the hanging and footwall rocks, which then becomes progressively
12 incorporated into an evolving tectonic *mélange* (Figs. 4E and 6D; Cowan, 1974, 1985; Pettinga, 1982;
13 Barnes and Korsch, 1991; Onishi and Kimura, 1995; Ogawa, 1998). Flattening of subcreted thrust
14 sheets, as they are detached from the footwall, also represents an effective mechanism of disruption
15 of fractured layers into broken strata and *mélange*, as for example along the Sonnebad Disruption
16 Zone in the Timor region of Indonesia (Harris et al., 1998). Tectonic *mélanges* formed in these ways
17 commonly display (Tab. 2; Fig. 2) a pervasive, scaly fabric, which is most pronounced in fine-grained
18 lithologies (Figs. 3C and 3D). At relatively deeper structural levels in an accretionary prism, faulting
19 (e.g., Cowan, 1985; Wakabayashi, 1992; Pettinga, 1992; Needham, 1995; Ogawa, 1998) and folding
20 (e.g., Moore, 1973; Onishi and Kimura, 1995; Kusky and Bradley, 1999; Vannucchi and Bettelli, 2002;
21 Bettelli and Vannucchi, 2003) are the main mechanisms of stratal disruption (Figs. 6E1, and 6E2).
22 Deformation here is concentrated within fault and shear zones (Figs. 3F), and tectonic thickening
23 occurs due to duplexing, antiformal stacking (Figs. 6D, and 6F) and out-of-sequence thrusting (e.g.,
24 Pettinga, 1982; Needham, 1995). This phenomenon explains why tectonic *mélanges* with exotic
25 blocks occur exclusively in different scale shear zones, as discussed earlier. Localized fault zones
26 (Fig. 3F) are strictly responsible for large-scale tectonic mixing processes (e.g., Cowan, 1974; Festa
27 et al., 2010a).
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50 Although in this study we focus only on *mélanges* formed at shallow structural levels, at
51 deeper levels diagenetic and metamorphic processes significantly influence the deformational style by
52 enhancing the competence contrast between different layers through the formation of new mineral
53 phases and by dehydration of the clay minerals (e.g. increasing pore pressure). Diagenetic and
54 metamorphic processes collectively favor the occurrence of mixing processes, forming tectonic
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1 mélanges (Fig. 2C). Brittle or semi-brittle deformation becomes gradually replaced by ductile
2 deformation with the progressive increase of the temperature and pressure (e.g., Blanco-Quintero et
3 al., 2011). Within a subduction channel (Shreve and Cloos, 1986), for example, tectonic processes
4 facilitate the formation of flow mélanges, and control the upward trajectories of exotic rocks
5 (blueschist or serpentinized peridotite) (Cloos and Shreve, 1988b; Federico et al., 2007; Blanco-
6 Quintero et al., 2011) and large-scale serpentinite diapirism (e.g., Maekawa et al., 1993; Fryer et al.,
7 1999). Here, the buoyancy of subducting sediments affects the flow, and the deformed sediments
8 become incorporated into the upper plate of the subduction channel (Fig. 2C). The block-in-matrix
9 fabric and the pattern of underplating depend on the shear stress distribution along the hanging-wall
10 of the subduction channel, the sediment supply along this channel, the geometry, properties and
11 permeability of the overriding units, and particularly the nature of the back-stop (Shreve and Cloos,
12 1986; Cloos and Shreve, 1988a, 1988b).

30 **4.4. Small-scale and localized horizons of stratal disruption and mixing**

31 All the examples described so far show that a “continuum” of stratal disruption and mixing may
32 exist (Figs. 6, 8 and 9), recording the history of progressive burial and shear strengthening at shallow
33 structural levels (see also Needham, 1995). However, the development of tectonic surfaces, the
34 occurrence of impermeable barriers or strong rheological contrasts within stratigraphic successions,
35 or both, can define thin horizons of deformation zones (up to tens of meters thick) that can affect the
36 progressive increase of stratal disruption related to the burial conditions (Fig. 3F; e.g., Bosworth and
37 Vollmer, 1981; Bosworth, 1989; Lash, 1989; Byrne, 1994). Within these horizons, fluid pressure can
38 increase up to overpressure point, a level of which drives the sediments toward a critical state
39 condition (Maltman and Bolton, 2003), promoting stratal disruption and mixing processes that produce
40 broken formations and mélanges. The physical superposition of these horizons, as well as that of
41 different mechanisms and processes, further complicate the above described “continuum” of stratal
42 disruption and mixing, and can favor the formation of polygenetic mélanges. Although the last
43 pervasive process commonly obliterates the products of the previously formed ones (e.g., Raymond,
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1 1984; Raymond et al., 1989; Ogawa, 1998; Dela Pierre et al., 2007; Festa et al., 2010a; Festa, 2011;
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3 Codegone et al., 2012b), polygenetic mélanges may display a continuum of stratal disruption and
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5 mixing shown by the superposition of different products formed by tectonic, sedimentary and diapiric
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7 processes. The understanding of the interplay and superposition of these different processes is of
8
9 primary importance in understanding the mechanisms of broken formation, mélange, and polygenetic
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11 mélange development as well as the evolution of the tectonic setting in which they formed.
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16 **5. Conclusions**

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21 A redefinition of the terms *broken formation* and *mélange* and a clearer distinction between
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23 them allow us to extend these definitions to a more diverse occurrence of chaotic rock bodies
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25 developed in different tectonic settings. Tectonic events represent the most prominent triggering
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27 mechanism inducing, directly or indirectly, different processes of stratal disruption and mixing that
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29 produce a broad spectrum of chaotic rock bodies. The block-in-matrix arrangement in these chaotic
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31 rock bodies is mainly controlled by a linear relationship between the degree of consolidation (including
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33 tectonically-induced compaction) and progressive burial (Fig. 10). As a result, a continuum of
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35 processes and deformation structures gives rise to gradual disruption and mixing processes that are
36
37 significant for the development of broken formations and mélanges.
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41 At shallow structural levels in tectonically active environments the occurrence of poorly
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43 consolidated sediments favors gravitational deformation. Sedimentary (mass-transport) and diapiric
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45 chaotic products record punctuated and instantaneous stratal disruption features, which provide
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47 important clues about the physical conditions of their formation (e.g., consolidation, fluid pressure,
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49 changes of pore-volume, expulsion of pore-fluid and strength of sediments), and about the evolution
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51 of their tectonic setting of formation (Fig. 10). In the geological record, the occurrence of these
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53 sedimentary and diapiric chaotic bodies and their tectonic or stratigraphic relationships with other
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55 chaotic bodies and coherent stratigraphic successions allow us to better constrain the changes in the
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57 dynamic equilibrium in a geological setting. A good example of the control exerted by these processes
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1 on the dynamic equilibrium would be the switch from an accretionary tectonics to an erosion tectonics
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3 at the wedge front of accretionary complexes (e.g., von Huene and Lallemand, 1990; von Huene et
4
5 al., 2004; Remitti et al., 2011).
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8 With the downward increase of consolidation at depth, the deformation related to tectonic
9
10 forces becomes gradually more significant. Tectonically broken formations and mélanges record a
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12 continuum of deformation that occurs through time and different degrees of lithification during a
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14 progressive increase of the degree of consolidation and of the diagenetic and metamorphic mineral
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16 transformation (Fig. 10). At shallow structural levels the sediments are affected by a brittle to more
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18 ductile deformation that follows their progressive dewatering and strengthening as a result of burial. At
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20 deeper structural levels, diagenetic and metamorphic mineral transformation accompanies
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22 deformation patterns that are controlled strongly by the increase of P-T conditions. Several tectonic,
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24 chaotic products may record a deeper progressive evolution in a continuum of deformation that is
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26 related to several mechanisms of stratal disruption and mixing (i.e., *in situ* stratal disruption, faulting,
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28 shearing, thrusting and faulting).
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33 The superposition of different mechanisms and processes of disruption and mixing of rocks in
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35 some tectonic settings may lead to the reworking of existing mélange products and to the formation of
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37 polygenetic mélange types. The previously formed chaotic products may then change their block-in-
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39 matrix arrangement according to the last deformation style, strain rate, stress direction, alternating
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41 coaxial and non-coaxial strain paths, and variations in consolidation degrees. Polygenetic mélanges
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43 may thus provide useful information on their multiphase evolution (e.g., Festa, 2011; Osozawa et al.,
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45 2011), the spatial and temporal relationships between the physical conditions (e.g., burial loading,
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47 porosity and fluid pressure), and the mechanisms and processes that acted in the depositional
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49 environment or within the sedimentary succession where they formed.
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53 None of the geological processes forming mélanges operates in isolation. They commonly
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55 interact in a continuum of stratal disruption and mixing processes (Figs. 5 and 6). These processes
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57 and their mode are also strongly controlled by the balance between the hydrological activities and the
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1 rate at which the fluids are produced by burial-related consolidation, mineral dehydration
 2 mechanisms, diagenesis, and metamorphism in any given tectonic setting (e.g., Byrne, 1994).
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 43
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 46

47 **References**

- 48
 49
 50
 51 Aalto, K.R., 1981. Multistage mélangé formation in the Franciscan Complex, northernmost California.
 52 *Geology* 9, 602-607.
 53
 54 Aalto, K.R., 1989. Franciscan Complex olistostrome at Crescent City, northern California.
 55 *Sedimentology* 36, 471-495.
 56
 57
 58 Abbate, E., Bortolotti, V., Passerini, P., 1970. Olistostromes and olistoliths. *Sedimentary Geology*, 4,
 59 521-557.
 60
 61
 62
 63
 64
 65

- 1 Abbate, E., Bortolotti, V., Sagri, M., 1981. Excursion No. 5: Olistostromes in the Oligocene Macigno
2 formation (Florence area), introduction: An approach to olistostrome interpretation, in: Ricci
3 Lucchi, F. (Ed.), International Association of Sedimentologist: Second European Regional
4 Meeting, Bologna, 1981, Excursion Guidebook. Tecnoprint, Bologna, 165–185.
- 5
6
7 Alonso, J.L., Marcos, A., Suárez, A., 2006. Structure and organization of the Porma mélange:
8 Progressive denudation of a submarine nappe toe by gravitational collapse. *Am. J. Sci.* 306,
9 32–65.
- 10
11 Alonso, J.L., Gallastegui, J., García-Sansegundo, J., Farias, P., Rodríguez Fernández, L.R., Ramos,
12 V.A., 2008. Extensional tectonics and gravitational collapse in an Ordovician passive margin:
13 the Western Argentine Precordillera. *Gondw. Res.* 13, 204-215.
- 14
15 Argnani, A., Tinti, S., Zaniboni, F., Pagnoni, G., Armigliato, A., Panetta, D., Tonini, R., 2011. The
16 eastern slope of the southern Adriatic basin: a case study of submarine landslide
17 characterization and tsunamigenic potential assessment. *Marine Geoph. Res.* 32, 299-311.
- 18
19
20 Bailey, E.H., Irwin, W.P., Jones, D.L., 1964. Franciscan and related rocks, and their significance in the
21 geology of western California: California Division of Mines and Geology Bulletin 83, 1-177.
- 22
23 Barber, T., Brown, K., 1988. Mud diapirism: the origin of melanges in accretionary complexes?.
24 *Geology Today* 4, 89-94.
- 25
26 Barber, A.J., Tjokrosapoetro, S., Charlton, T.R., 1986. Mud volcanoes, shale diapirs, wrench faults
27 and mélanges in accretionary complexes, Eastern Indonesia. *Am. Ass. Petr. Geol. Bull.* 70,
28 1729-1741.
- 29
30
31 Barnes, P.M., Korsch, R.J., 1991. Mélange and related structures in Torlesse accretionary wedge,
32 Wairarapa, New Zealand. *New Zealand J. Geol. Geophys.* 34, 517–532.
- 33
34
35 Becker, D.G., Cloos, M., 1985. Melange diapirs into the Cambria slab: a Franciscan trench slope
36 basin near Cambria, California. *J. Geol.* 93 (2), 101-110.
- 37
38 Berkland, J.O., Raymond, L.A., Kramer, J.C., Moores, E.M., O'Day, M., 1972. What is Franciscan?.
39 *Am. Ass. Petr. Geol. Bull.* 56, 2295-2302.
- 40
41 Bernoulli, D., 2001. Mesozoic-Tertiary carbonate platforms, slope and basins of the external
42 Apennines and Sicily, in: Vai, G.B., Martini, I.P. (Eds.), *Anatomy of an Orogen: the*
43 *Apennines and Adjacent Mediterranean Basins.* Kluwer Academic Publishers, Great Britain,
44 307-325.
- 45
46 Bettelli, G., Vannucchi, P., 2003. Structural style of the offscraped Ligurian oceanic sequences of the
47 Northern Apennines: new hypothesis concerning the development of mélange block-in-matrix
48 fabric. *J. Struct. Geol.* 25, 371-388.
- 49
50
51 Blanco-Quintero, I.F., García-Casco, A., Rojas-Agramonte, Y., Rodríguez-Vega, A., Lázaro, C.,
52 Iturralde-Vinent, M.A., 2010. Metamorphic evolution of subducted hot oceanic crust (La
53 Corea Mélange, Cuba). *Am. J. Sci.* 310 (9), 889-915.
- 54
55 Blanco-Quintero, I.F., Rojas-Agramonte, Y., García-Casco, A., Kröner, A., Mertz, D.F., Lázaro, C.,
56 Blanco-Moreno, J., Renne, P.R., 2011. Timing of subduction and exhumation in a subduction
57 channel: evidence from slab melts from La Corea Mélange (eastern Cuba). *Lithos* 127, 86-
58 100.
- 59
60
61
62
63
64
65

- 1 Bonev, N., Dilek, Y., Hanchar, J.M., Bogdanov, K., Klain, L., 2012. Nd–Sr–Pb isotopic composition
 2 and mantle sources of Triassic rift units in the Serbo-Macedonian and the western Rhodope
 3 massifs (Bulgaria–Greece). *Geological Magazine* 149, 146–152, DOI:
 4 <http://dx.doi.org/10.1017/S0016756811000938>.
 5
 6
 7 Borgia, A., Grieco, G., Brondi, F., Badalì, M., Merle, O., Pasquarè, G., Martelli, L., di Nardo, T., 2006.
 8 Shale diapirism in the Quaternary tectonic evolution of the Northern Apennine, Bologna, Italy.
 9 *J. Geophys. Res.* 111, B08406, 25 pp.
 10
 11 Bosworth, W., 1989. Mélange fabrics in the unmetamorphosed external terranes of the northern
 12 Appalachians, in: Horton, J.W., Jr., Rast, N. (Eds.), *Mélanges and olistostromes of the*
 13 *Appalachians*. *Geol. Soc. Am. Spec. Pap.* 228, 65–91.
 14
 15 Bosworth, W., Vollmer, F.W., 1981. Structures of the medial Ordovician Flysch of Eeastern New York:
 16 deformation of synorogenic deposits in an overthrust environment. *J. Geol.* 89, 551–568.
 17
 18 Bradley, D.C., Kusky, T.M., 1992. Deformation history of the McHugh Complex, Seldovia Quadrangle,
 19 South-Central Alaska, in: Bradley, D.C., Ford, A. (Eds.), *Geologic studies in Alaska by the*
 20 *U.S. Geological Survey, 1990. USGS Bull., 1999, 17–32.*
 21
 22
 23 Bradbury, K.L., Evans, J.P., Chester, J.S., Chester, F.M., Kirschner, D.L., 2011. Lithology and internal
 24 structure of the San Andreas fault at depth based on characterization of Phase 3 whole-rock
 25 core in the San Andreas Fault Observatory at Depth (SAFOD) borehole. *Earth and Plan. Sc.*
 26 *Lett.* 310, 131–144.
 27
 28
 29 Brandon, M.T., 1989. Deformational styles in a sequence of olistostromal mélanges, Pacific Rim
 30 Complex, western Vancouver Island, Canada. *Geol. Soc Am. Bull.* 101, 1520–1542.
 31
 32
 33 Breen, N.A., Silver, E.A., Hussong, D.M., 1986. Structural styles of an accretionary wedge south of
 34 the island of Sumba, Indonesia, revealed by Seamarc II side scan sonar. *Geol. Soc. Am.*
 35 *Bull.* 64, 868–915.
 36
 37
 38 Brown, K.M., 1990. The nature and hydrogeologic significance of mud diapirs and diatremes for
 39 accretionary systems. *J. Geophys. Res.* 95, 8969–8982.
 40
 41
 42 Brown, K.M., 1994. Fluids in deforming sediments, in: Maltman, A.J. (Ed.), *Geological deformation of*
 43 *sediments*. Chapman & Hall, 205–238.
 44
 45
 46 Brown, K.M., Orange, D.L., 1993. Structural aspects of diapiric mélange emplacement: the Duck
 47 Creek diapir. *J. Struct. Geol.* 15, 831–847.
 48
 49
 50 Brown, K.M., Westbrook, G.K., 1988. Mud diapirism and subcretion in the Barbados ridge
 51 accretionary complex: the role of fluids in the accretionary processes. *Tectonics* 7, 613–640.
 52
 53
 54 Burg, J.P., Bernoulli, D., Smit, J., Dolati, A., Bahroudi, A., 2008. A giant catastrophic mud and debris
 55 flow in the Miocene Makran. *Terra Nova* 20, 181–193.
 56
 57
 58 Byrne, T., 1984. Early deformation in mélange terranes of the Ghost Rocks Formation, Kodiak
 59 islands, Alaska, in: Raymond, L.A. (Ed.), *Mélanges: Their nature, origin, and significance.*
 60 *Geol. Soc. Am. Spec. Pap.* 198, 21–52.
 61
 62
 63 Byrne, T., 1994. Sediment deformation, dewatering and diagenesis: illustrations from selected
 64 mélange zones, in: Maltman, A. (Ed.), *Geological deformation of sediments*. Chapman &
 65 Hall, 239–260.

- 1 Callot, P., Sempere, T., Odonne, F., Robert, E., 2008. Giant submarine collapse of a carbonate
2 platform at the Turonian-Coniacian transition: The Ayabacas Formation, southern Peru. *Bas.*
3 *Res.* 20, 333-357, doi: 10.1111/j.1365-2117.2008.00358.x
4
- 5 Camerlenghi, A., Pini, G.A., 2009. Mud volcanoes, olistostromes and Argille scagliose in the
6 Mediterranean region. *Sedimentology* 56, 319-365.
7
- 8 Cavazza, W., Barone, M., 2010. Large-scale sedimentary recycling of tectonic mélanges in a forearc
9 setting: the Ionian basin (Oligocene-Quaternary; southern Italy). *Geol. Soc. Am. Bull.* 122,
10 1932-1949.
11
- 12 Cieszkowski, M., Golonka, J., Ślęczka, A., Waśkowska, A., 2012. Role of the olistostromes and
13 olistoliths in tectonostratigraphic evolution of the Silesian Basin in the Outer West
14 Carpatians. *Tectonophysics*, this volume, doi: 10.1016/j.tecto.2012.01.030
15
- 16 Cloos, M., 1982. Flow melanges: numerical modeling and geologic constraints on their origin in the
17 Franciscan subduction complex, California. *Geol. Soc. Am. Bull.* 93, 330-345.
18
- 19 Cloos, M., 1983. Comparative study of mélanges matrix and metashales from the Franciscan
20 subduction complex with the basal Great Valley Sequence, California. *J. Geol.* 91, 291-306.
21
- 22 Cloos, M., Shreve, R.L., 1988a. Subduction-Channel model of prism accretion, melange formation,
23 sediment subduction, and subduction erosion at convergent plate margins: 1. Background
24 and description. *Pure and Appl. Geoph.* 128 (3-4), 455-500.
25
- 26 Cloos, M., Shreve, R.L., 1988b. Subduction-Channel model of prism accretion, melange formation,
27 sediment subduction, and subduction erosion at convergent plate margins: 2. Implications
28 and discussion. *Pure and Appl. Geoph.* 128 (3-4), 501-545.
29
- 30 Codegone, G., Festa, A., Dilek, Y., 2012a. Formation of Taconic Mélanges and Broken Formations in
31 the Hamburg Klippe, Central Appalachian Orogenic Belt, Eastern Pennsylvania.
32 *Tectonophysics*, this volume, doi: 10.1016/j.tecto.2012.03.017
33
- 34 Codegone, G., Festa, A., Dilek, Y., Pini, G.A., 2012b. Small-scale polygenetic mélanges in the
35 Ligurian accretionary complex, Northern Apennines, Italy, and the role of shale diapirism in
36 superposed mélanges evolution in orogenic belts. *Tectonophysics*, this volume, doi:
37 10.1016/j.tecto.2012.02.003
38
- 39 Coleman, R.G., Lanphere, M.A., 1971. Distribution and age of high-grade blueschists, associated
40 eclogites and amphibolites from Oregon and California. *Geol. Soc. Am. Bull.* 82, 2397-2412.
41
- 42 Collison, J., 1994. Sedimentary deformational structures, in: Maltman, A.J. (Ed.), *Geological*
43 *deformation of sediments*. Chapman & Hall, 95-125.
44
- 45 Collot, J-Y., Lewis, K., Lamarche, G., Lallemand, S., 2001. The giant Ruatoria debris avalanche on
46 the northern Hikurangi margin, New Zealand: result of oblique seamount subduction. *J.*
47 *Geophys. Res.* 106 (9), 19271-19297.
48
- 49 Cowan, D.S., 1974. Deformation and metamorphism of the Franciscan Subduction Zone Complex
50 northwest of Pacheco Pass, California. *Geol. Soc. Am. Bull.* 85, 1623-1634.
51
- 52 Cowan, D.S., 1978. Origin of blueschist-bearing chaotic rocks in the Franciscan Complex, San
53 Simeon, California. *Geol. Soc. Am. Bull.* 89, 1415-1423.
54
55
56
57
58
59
60
61
62
63
64
65

- 1 Cowan, D.S., 1985. Structural styles in Mesozoic and Cenozoic mélanges in the western Cordillera of
2 North America. *Geol. Soc. Am. Bull.* 96, 451-462.
3
- 4 Cowan, D.S., Brandon, M.T., 2011. Olistostromes are the source of melange in diapirs in the
5 Cascadia-Olympics accretionary wedge, NW USA. Abstract 721E-07 presented at 2011 Fall
6 Meeting, AGU, San Francisco, California, 5-9 Dec.
7
- 8
9 Cowan, D.S., Page, B.M., 1975. Recycled Franciscan material in Franciscan mélange West of Paso
10 Robles, California. *Geol. Soc. Am. Bull.* 86, 1089-1095.
11
- 12 Cowan, D.S., Pini, G.A., 2001. Disrupted and chaotic rock units in the Apennines, in G.B. Vai, I.P.
13 Martini, (Eds.), *Anatomy of a Mountain Belt: The Apennines and Adjacent Mediterranean*
14 *Basins*. Kluwer Academic Publishers, Dordrecht, 165-176.
15
- 16
17 Cronin, B.T., Ivanov, M.K., Limonov, A.F., Egorov, A., Akhmanov, G.G., Akhmetjanov, A.M., Kozlova,
18 E.V., Shipboard Scientific Party TTR- 3, 1997. New discoveries of mud volcanoes on the
19 Eastern Mediterranean Ridge. *J. Geol. Soc. London* 154:173-182.
20
- 21 Dela Pierre, F., Festa, A., Irace, A., 2007. Interaction of tectonic, sedimentary and diapiric processes
22 in the origin of chaotic sediments: an example from the Messinian of the Torino Hill (Tertiary
23 Piedmont Basin, NW Italy). *Geol. Soc. Am. Bull.* 119, 1107-1119.
24
- 25 De Libero, C.M., 1998. Sedimentary vs. tectonic deformation in the „Argille Scagliose” of Mt. Modino
26 (Northern Apennines). *Giorn. Geol.* 56, 143-166.
27
- 28 Dilek, Y., 1989, Structure and tectonics of an Early Mesozoic oceanic basement in the northern Sierra
29 Nevada Metamorphic Belt, California: Evidence for transform faulting and ensimatic arc
30 evolution. *Tectonics* 8, 999-1014.
31
- 32
33 Dilek, Y., 2006. Collision tectonics of the Eastern Mediterranean region: causes and consequences.
34 *Geol. Soc. Am. Spec. Pap.* 409, 1-13. doi:10.1130/2006.2409(1).
35
- 36 Dilek, Y., Ahmed, Z., 2003, 2003. Proterozoic ophiolites of the Arabian Shield and their significance in
37 Precambrian tectonics, in: Dilek, Y., Robinson, P.T. (Eds.), *Ophiolites in Earth History*. *Geol.*
38 *Soc. London Spec. Publ.* 218, 685-700.
39
- 40
41 Dilek, Y., Polat, A., 2008. Suprasubduction zone ophiolites and Archean tectonics. *Geology* 36, 431-
42 432.
43
- 44 Dilek, Y., Thy, P., 2006. Age and petrogenesis of plagiogranite intrusions in the Ankara mélange,
45 central Turkey. *Island Arc* 15, 44-57, DOI: 10.1111/j.1440-1738.2006.00522.x.
46
- 47 Dilek, Y., Furnes, H., and Shallo, M., 2007, Suprasubduction zone ophiolite formation along the
48 periphery of Mesozoic Gondwana. *Gondwana Research*, v. 11, p. 453-475.
49
- 50
51 Dilek, Y., Shallo, M., Furnes, H., 2005. Rift-drift, seafloor spreading, and subduction zone tectonics of
52 Albanian ophiolites. *Int. Geol. Rev.* 47, 147-176.
53
- 54 Dilek, Y., Thy, P., Moores, E.M., 1991. Episodic dike intrusions in the northwestern Sierra Nevada,
55 California: Implications for multi-stage evolution of a Jurassic arc terrane. *Geology* 19, 180-
56 184.
57
- 58 Dilek, Y., Thy, P., Hacker, B., Grundvig, S., 1999, Structure and petrology of Tauride ophiolites and
59 mafic dike intrusions (Turkey): Implications for the Neotethyan ocean. *Geol. Soc. Am. Bull.*
60 111, 1192-1216, doi: 10.1130/0016-7006(1999)111<1192:SAPOTO>2.3.CO;2
61
62
63
64
65

- 1 Dilek, Y., Thy, P., Moores, E.M., Grundvig, S., 1990. Late Paleozoic-early Mesozoic oceanic basement
2 of a Jurassic arc terrane in the northwestern Sierra Nevada, California, in: Harwood, D.S.,
3 Miller, M.M. (Eds.), Paleozoic and early Mesozoic paleogeographic relations; Sierra Nevada,
4 Klamath Mountains, and related terranes: Boulder, Colorado. Geol. Soc. Am. Spec. Pap.
5 255, 351-369.
6
- 7
8 Ditullio, L., Byrne, T., 1990. Deformation paths in the shallow levels of an accretionary prism: The
9 Eocene Shimanto belt of southwest Japan. Geol. Soc. Am. Bull. 102, 1420–1438.
10
- 11 Doubleday, P.A., Trenter, T.H., 1992. Modes of formation and accretion of oceanic material in the
12 Mesozoic fore-arc of the Central and Southern Alexander Island, Antarctica: A summary, in:
13 Yoshida, Y., Kaminuma, K., Shiraishi, K. (Eds.), Recent progress in Antarctic Earth Science.
14 Tokyo. Terra Scientific Publishing Company (TERRAPUB), 377–382.
15
- 16
17 Dykstra, M., 2005. Dynamics of sediment mass-transport from the shelf to the deep seas.
18 Unpublished Ph.D. Dissertation, University of California, Santa Barbara, 159 pp.
19
- 20 El Bahariya, G.A., 2012. Classification and origin of the Neoproterozoic ophiolitic mélanges in the
21 Central Eastern Desert of Egypt. Tectonophysics, this volume, doi:
22 10.1016/j.tecto.2012.03.020
23
- 24 Elter, P., Trevisan, L., 1973. Olistostromes in the tectonic evolution of the Northern Apennines, in: De
25 Jong, K.A., Scholten, R. (Eds.), Gravity and tectonics. New York, John Willey and Sons,
26 175–188.
27
- 28
29 Erickson, R., 2011. Petrology of a Franciscan olistostrome with a massive sandstone matrix: the King
30 Ridge Road mélange at Cazadero, California, in: Wakabayashi, J., Dilek, Y. (Eds.),
31 Melanges: Processes of formation and societal significance. Geol. Soc. Am. Spec. Pap. 480,
32 171-188.
33
- 34
35 Ernst, W.G., 2006. Preservation/exhumation of ultrahigh-pressure subduction complexes. Lithos 92,
36 321-335.
37
- 38 Federico, L., Crispini, L., Scambelluri, M., Capponi, G., 2007. Ophiolite mélange zone records
39 exhumation in a fossil subduction channel. Geology 35, 499–502.
40
- 41 Festa, A., 2011. Tectonic, sedimentary, and diapiric formation of the Messinian melange: Tertiary
42 Piedmont Basin (northwestern Italy), in: Wakabayashi, J., Dilek, Y. (Eds.), Melanges:
43 Processes of formation and societal significance. Geol. Soc. Am. Spec. Pap. 480, 215-232,
44 doi: 10.1130/2011.2480(10)
45
- 46 Festa, A., Pini, G.A., Dilek, Y., Codegone, G., 2010a. Mélanges and mélange-forming processes: a
47 historical overview and new concepts, in: Dilek, Y. (Ed.), Alpine Concept in Geology. Int.
48 Geol. Rev. 52 (10-12), 1040-1105, doi: 10.1080/00206810903557704
49
- 50
51 Festa, A., Pini, G.A., Dilek, Y., Codegone, G., Vezzani, L., Ghisetti, F., Lucente, C.C., Ogata, K.,
52 2010b. Peri-Adriatic mélanges and their evolution in the Tethyan realm, in: Dilek, Y. (Ed.),
53 Eastern Mediterranean geodynamics (Part II). Int. Geol. Rev. 52 (4-6), 369-406, doi:
54 10.1080/00206810902949886
55
- 56
57 Fisher, D., Byrne, T., 1987. Structural evolution of underthrust sediments, Kodiak Islands, Alaska.
58 Tectonics 6. 775-793.
59
- 60 Fryer, P., Wheat, C.G., Mottl, M.J., 1999. Mariana blueschist mud volcanism: implications for
61 conditions within the subduction zone. Geology 27, 103-106.
62
63
64
65

- 1 Fukui, A., Kano, K-i., 2007. Deformation process and kinematics of mélangé in the Early Cretaceous
2 accretionary complex of the Mino-Tamba Belt, eastern southwest Japan. *Tectonics* 26,
3 TC2006, doi: 10.1029/2006TC001945
4
- 5
6 Gerya, T.V., Stockhert, B., Perchuk, A.L., 2002. Exhumation of high-pressure metamorphic rocks in a
7 subduction channel: a numerical simulation. *Tectonics* 21 (6), 1–19.
8
- 9 Ghikas, A.C., Dilek, Y., Rassios, A.E., 2010. Structure and tectonics of sub-ophiolitic mélanges in the
10 Western Hellenides (Greece) and implications for Ophiolite emplacement tectonics, in: Dilek,
11 Y. (Ed.), *Eastern Mediterranean geodynamics (Part II)*. *Int. Geol. Rev.* 52, 423–453.
12
- 13 Guillot, S., Schwartz, S., Hattori, K., Auzende, A., Lardeaux, J., 2004. The Monviso ophiolitic Massif
14 (Western Alps), a section through a serpentinite subduction channel. Evolution of the
15 western Alps: insights from metamorphism, structural geology, tectonics and geochronology.
16 *The Virtual Explorer* 16, Pap. 3.
17
- 18
19 Guillot, S., Hattori, K., Agard, P., Schwartz, S., Vidal, O., 2009. Exhumation processes in oceanic and
20 continental subduction contexts: a review. *Frontiers in Earth Sci.*, Part V, 175-205.
21
- 22 Harris, R.A., 2011. The nature of the Banda arc-continent collision in the Timor region, in: Brown, D.,
23 Ryan, P. (Eds.), *Arc-continent collision: the making of an orogen*. *Frontiers in Earth Sci.*,
24 Springer, Heidelberg, 163-210.
25
- 26 Harris, R.A., Sawyer, R.K., Audley-Charles, M.G., 1998. Collisional mélangé development: geologic
27 association of active mélangé-forming processes with exhumed mélangé facies in the
28 western Banda orogen, Indonesia. *Tectonics* 17 (3), 458-479.
29
- 30 Hashimoto, Y., Kimura, G., 1999. Underplating process from mélangé formation to duplexing:
31 Example from the Cretaceous Shimanto Belt, Kii Peninsula, southwest Japan. *Tectonics* 18,
32 92-107, doi: 10.1029/1998TC900014
33
- 34
35 Henry, P., Le Pichon, X., Lallemand, S., Foucher, J., Westbrook, G.K., Hobart, M., 1990. Mud volcano
36 seaward of the Barbados accretionary complex: a deep-towed side scan sonary survey. *J.*
37 *Geophys. Res.* 95, 8917-8929.
38
- 39
40 Hernaiz Huerta, P.P., Pérez-Valera, F., Abad, M., Monthel, J., Diaz de Neira, A., 2012. Mélanges and
41 olistostromes in the Puerto Plata area (northern Dominican Republic) as a record of
42 subduction and collisional processes between the Caribbean and North-American plates.
43 *Tectonophysics*, this volume, doi: 10.1016/j.tecto.2011.10.020
44
- 45 Hitz, B., Wakabayashi, J., 2012. Unmetamorphosed sedimentary mélangé with high-pressure
46 metamorphic blocks in a nascent forearc basin setting. *Tectonophysics*, this volume, doi:
47 10.1016/j.tecto.2011.12.006
48
- 49
50 Hoffmann, K., Piotrowski, J.A., 2001. Till mélangé at Amsdorf, central Germany: sediment erosion,
51 transport and deposition in a complex, soft-bedded subglacial system. *Sedim. Geol.* 140,
52 215-234.
53
- 54 Hsü, K.J., 1968. Principles of mélanges and their bearing on the Franciscan-Knoxville Paradox. *Geol.*
55 *Soc. Am. Bull.* 79, 1063-1074.
56
- 57 Huang, C.Y., Chien, C.W., Yao, B., Chang, C.P., 2008. The Lichi Mélangé: A collisional mélangé
58 formation along early arcward backthrusts during forearc basin closure, Taiwan arc-continent
59 collision, in: Draut, A.E., Clift, P.Do., Scholl, D.W. (Eds.), *Formation and Applications of the*
60 *Sedimentary Record in Arc Collision Zones*. *Geol. Soc. Am. Spec. Pap.* 436, 127-154.
61
62
63
64
65

- 1 Ikesawa, E., Kimura, G., Sato, K., Ikehara-Ohmori, K., Kitamura, Y., Yamaguchi, A., Ejiie, K.,
2 Hashimoto, Y., 2005. Tectonic incorporation of the upper part of oceanic crust to overriding
3 plate of a convergent margin: An example from the Cretaceous–early Tertiary Mugli mélangé,
4 the Shimanto Belt, Japan. *Tectonophysics* 401, 217–230.
- 5
6
7 Jones, M.E., Leddra, M.J., Goldsmith, A.S., Yassir, N., 1991. Mechanisms of compaction and flow in
8 porous sedimentary rocks, in: Cosgrove, J., Jones, M.E. (Eds.), *Neotectonics and resources*.
9 Belhaven, London, 16-42.
- 10
11 Kargel, J.S., Furfaro, R., Prieto-Ballesteros, O., Rodriguez, J.A.P., Montgomery, D.R., Gillespie, A.R.,
12 Marion, G.M., Wood, S.E., 2007. Martian hydrogeology sustained by thermally insulating gas
13 and salt hydrates. *Geology* 35 (11), 975-978, doi: 10.1130/G23783A.1
- 14
15
16 Karig, D.E., Sarewitz, D.R., Haeck, G.D., 1986. Role of strike-slip faulting in the evolution of
17 allochthonous terranes in the Philippines. *Geology* 14, 852-855.
- 18
19 Kimura, G., Mukai, A., 1991. Underplated units in an accretionary complex: Melange of the Shimanto
20 belt of eastern Shikoku, southwest Japan. *Tectonics* 10 (1), 31–50.
- 21
22 Kimura, G., Maruyama, S., Isozaki, Y., Terabayashi, M., 1996. Well-preserved underplating structure
23 of the jadeitized Franciscan complex, Pacheco Pass, California. *Geology* 24, 75–78.
- 24
25 Kimura, G., Yamaguchi, A., Hojo, M., Kitamura, Y., Kameda, J., Ujiie, K., Hamada, Y., Hamahasi, M.,
26 Hina, S., 2012. Tectonic mélangé as fault rock of subduction plate boundary.
27 *Tectonophysics*. this volume, doi: 10.1016/j.tecto.2011.08.025
- 28
29
30 Kopf, A., 2002, Significance of mud volcanism. *Rev. Geophys.* 40, 1-51.
- 31
32 Kusky, T.M., Bradley, D.C., 1999. Kinematic analysis of melange fabrics: examples and applications
33 from the McHugh Complex, Kenai Peninsula, Alaska. *J. Struct. Geol.* 21, 1773-1796.
- 34
35 Kusky, T.M., Jianghai, L., 2010. Origin and emplacement of Archean ophiolites of the central orogenic
36 belt, North China craton. *J. Earth Sci.* 21 (5), 744-781.
- 37
38
39 Kusky, T.M., Bradley, D.C., Haeussler, P.J., Karl, S., 1997. Controls on accretion of flysch and
40 mélangé belts at convergent margins: evidence from the Chugach Bay thrust and Iceworm
41 mélangé, Chugach accretionary wedge, Alaska. *Tectonics* 16 (6), 855-878.
- 42
43 Lash, G.G., 1987. Diverse melanges of an ancient subduction complex. *Geology* 15, 652-655.
- 44
45 Lash, G.G., 1989. Documentation and significance of progressive microfabric changes in Middle
46 Ordovician Trench mudstones. *Geol. Soc. Am. Bull.*, 101, 1268 – 1279.
- 47
48
49 Liu, G., Einsele, G., 1996. Various types of olistostromes in a closing ocean basin, Tethyan Himalaya
50 (Cretaceous, Tibet). *Sed. Geol.* 104, 203–226.
- 51
52 Lucente, C.C., Pini, G.A., 2003. Anatomy and emplacement mechanism of a large submarine slide
53 within the Miocene foredeep in the Northern Apennines, Italy: A field perspective. *Am. J. Sci.*
54 303, 565–602.
- 55
56 Lucente, C.C., Pini, G.A., 2008. Basin-wide mass-wasting complexes as markers of the Oligo-
57 Miocene foredeep-accretionary wedge evolution in the Northern Apennines, Italy. *Bas. Res.*
58 20, 49-71.
- 59
60
61
62
63
64
65

- 1 Maekawa, H., Shozul, M., Ishli, T., Fryer, P., Pearce, J.A., 1993. Blueschist metamorphism in and
2 active subduction zone. *Nature* 364, 520-523.
3
- 4 Malatesta, C., Crispini, L., Federico, L., Capponi, G., Scambelluri, M., 2012. The Exhumation of high
5 pressure ophiolites (Voltri Massif, Western Alps): insights from structural and petrologic data
6 on meta gabbro bodies. *Tectonophysics*, this volume, doi: 10.1016/j.tecto.2011.08.024
7
- 8 Maltman, A.J., 1994. Introduction and overview, in: Maltman, A.J. (Ed.), *Geological deformation of*
9 *sediments*. Chapman & Hall, 1-36.
10
- 11 Maltman, A.J., Bolton, A., 2003. How sediments become mobilized. *Geol. Soc. London Spec. Publ.*
12 *216*, 9-20, doi: 10.1144/GSL.SP.2003.216.01.02
13
- 14 Marroni, M., Pandolfi, L., 2001. Debris flow and slide deposits at the top of the Internal Liguride
15 ophiolitic sequence, Northern Apennines, Italy: a record of frontal tectonic erosion in a fossil
16 accretionary wedge. *Island Arc*. 10, 9-21.
17
- 18 Marroni, M., Molli, G., Ottria, G., Pandolfi, L., 2001. Tectono-sedimentary evolution of the External
19 Liguride units (Northern Apennines, Italy): Insight in the pre-collisional history of a fossil
20 ocean-continent transition zone. *Geodin. Acta* 14, 307-320.
21
- 22 Martinez Catalan, J., Arenas, R., Diaz Garcia, F., Abati, J., 1997. Variscan accretionary complex of
23 northwest Iberia: Terrane correlation and succession of tectonothermal events. *Geology*. 25,
24 1103-1103.
25
- 26 Maxwell, J.C., 1974. Anatomy of an orogen. *Geol. Soc. Am. Bull.* 85, 1195-1204.
27
- 28 Medialtea, T., Vegas, R., Somoza, L., Vázquez, J.T., Maldonado, A., Díaz-del-Río, V., Mestro, A.,
29 Córdoba, D., Fernández-Puga, M.C., 2004. Structure and evolution of the "Olistostrome"
30 complex of the Gibraltar Arc in the Gulf of Cádiz (eastern Central Atlantic): evidence from
31 two long seismic cross-sections. *Mar. Geol.* 209, 173-198.
32
- 33 Meneghini, F., Marroni, M., Moore, J.C., Pandolfi, L., Rowe, C.D., 2009. The processes of
34 underthrusting and underplating in the geologic record: structural diversity between the
35 Franciscan Complex (California), the Kodiak Complex (Alaska) and the Internal Ligurian
36 Units (Italy). *Geol. J.* 44, 126-152.
37
- 38 Meschede, M., Zweigel, P., Frisch, W., Völker, D., 1999. Mélange formation by subduction erosion:
39 The case of the Osa mélange in southern Costa Rica. *Terra Nova* 11, 141-148.
40
- 41 Michiguchi, Y., Ogawa, Y., 2011. Implication of dark bands in Miocene-Pliocene accretionary prism,
42 Boso Peninsula, central Japan, in: Wakabayashi, J., Dilek, Y. (Eds.), *Mélanges: Processes of*
43 *formation and societal significance*. *Geol. Soc. Am. Spec. Pap.* 480. 247-260, doi: 10.1130/
44 10.1130/2011.2480(12)
45
- 46 Minisini, D., Trincardi, F., Asioli, A., Canuz, M., Foglini, F., 2009. Morphologic variability of exposed
47 mass-transport deposits on the eastern slope of Gela Basin (Sicily channel). *Basin Research*
48 *19*, 217-240.
49
- 50 Moore, J. C., 1973. Complex deformation of Cretaceous trench deposits, southwestern Alaska. *Geol.*
51 *Soc. Am. Bull.* 84, 2005-2020.
52
- 53 Moore, J.C., Sample, J., 1986. Mechanisms of subduction accretion: recognition in the stratigraphic
54 record. *Mem. Geol. Soc. Italy* 31, G. Merla commemorative volume, 107-118.
55
56
57
58
59
60
61
62
63
64
65

- 1 Moore, J.C., Wheeler, R.L., 1978. Structural fabric of a *mélange*, Kodiak Islands, Alaska. *Am. J. Sci.*
2 278, 739–765.
3
- 4 Moseley, F., Abbotts, I.L., 1979. The ophiolite *mélange* of Masirah, Oman. *J. Geol. Soc.* 136, 713-
5 724.
6
- 7 Mutti, E., 1992. Turbidite Sandstones, San Donato Milanese, Agip-Istituto di Geologia, Università di
8 Parma, 275.
9
- 10 Mutti, E., Carminatti, M., Moreira, J.L.P., Grassi, A.A., 2006. Chaotic Deposits: examples from the
11 Brazilian offshore and ,from outcrop studies in the Spanish Pyrenees and Northern
12 Apennines, Italy. *Am. Ass. Petr. Geol. Annual Meeting*, April 9-12, Houston, Texas.
13
- 14 (NACSN) North American Commission on Stratigraphic Nomenclature, 2005. Amendments to the
15 American stratigraphic code. *Am. Ass. Petrol. Geol. Bull.* 89 (11), 1459-1464.
16
- 17 Naylor, M.A., 1982. The Casanova Complex of the Northern Apennines: A *mélange* formed on a distal
18 passive continental margin. *J. Struct. Geol.* 4, 1–18.
19
- 20 Needham, D.T., 1995, Mechanisms of *mélange* formation: examples from SW Japan and southern
21 Scotland: *J. Struct. Geol.* 17 (7), 971-985.
22
- 23 Ogata, K., 2010. Mass transport complexes in structurally-controlled basins: the Epiligurian Specchio
24 Unit (Northern Apennines, Italy). Unpublished PhD thesis, University of Parma, 476 pp.
25
- 26 Ogata, K., Mutti, E., Pini, G.A., Tinterri, R., 2011. Mass transport-related stratal disruption within
27 sedimentary *mélanges*: Examples from the northern Apennines (Italy) and south-central
28 Pyrenees (Spain). *Tectonophysics*. Article in press, doi: 10.1016/j.tecto.2011.08.021
29
- 30 Ogata, K., Tinterri, R., Pini, G.A., Mutti, E., 2012a. Mass transport-related stratal disruption within
31 sedimentary *mélanges*: Examples from the northern Apennines (Italy) and south-central
32 Pyrenees (Spain). *Tectonophysics*, this volume, doi: 10.1016/j.tecto.2011.08.021
33
- 34 Ogata, K., Pini, G.A., Carè, D., Zélic, M., Dellisanti, F., 2012b. Progressive development of block-in-
35 matrix fabric in a shale-dominated shear zone: Insights from the Bobbio Tectonic Window
36 (Northern Apennines, Italy). *Tectonics* 31, TC1003, doi: 10.1029/2011TC002924
37
- 38 Ogata, K., Tinterri, R., Pini, G.A., Mutti, E., 2012c. The Specchio Unit (Northern Apennines, Italy): an
39 ancient mass transport complex originated from near-coastal areas in an intra-slope setting,
40 in: Yamada, Y. et al.(Eds.), *Submarine mass movements and their consequences*, *Advances*
41 *in natural and technological hazards research* 31, Springer Science+Business Media B.V.,
42 595-605.
43
- 44 Ogawa, Y., 1998. Tectonostratigraphy of the Glen App area, Southern Uplands, Scotland: anatomy of
45 Ordovician accretionary complex. *J. Geol. Soc. London* 155, 651-662.
46
- 47 Onishi, C.T., Kimura, G., 1995. Change in fabric of *mélange* in the Shimanto Belt, Japan: Change in
48 relative convergence?. *Tectonics* 14, 1273–1289.
49
- 50 Onishi, C.T., Kimura, G., Hashimoto, Y., Ikehara-Ohmori, K., Watanabe, T., 2001. Deformation history
51 of tectonic *mélange* and its relationship to the underplating process and relative plate motion:
52 An example from the deeply buried Shimanto Belt, SW Japan. *Tectonics* 20 (3), 376-393,
53 doi: 10.1029/1999TC001154
54
55
56
57
58
59
60
61
62
63
64
65

- 1 Orange, D.L., 1990. Criteria helpful in recognizing shear-zone and diapiric mélanges: examples from
2 the Hoh accretionary complex, Olympic Peninsula, Washington. *Geol. Soc. Am. Bull.* 102,
3 935-951.
4
- 5 Osozawa, S., Morimoto, J., Flower, F.J., 2009. "Block-in-matrix" fabrics that lack shearing but possess
6 composite cleavage planes: a sedimentary mélange origin for the Yuwan accretionary
7 complex in the Ryukyu island arc, Japan. *Geol. Soc. Am. Bull.* 121 (7–8), 1190–1203.
8
9
- 10 Osozawa, S., Pavlis, T., Flowers, M.F.J., 2011. Sedimentary block-in-matrix fabric affected by tectonic
11 shear, Miocene Nabae complex, Japan, in: Wakabayashi, J., Dilek, Y. (Eds.), *Mélanges:
12 Processes of Formation and Societal Significance*. *Geol. Soc. Am. Spec. Pap.* 480, 189-206,
13 doi: 10.1130/2011.2480(08)
14
- 15 Ota, T., Kaneko, Y., 2010. Blueschists, eclogites, and subduction zone tectonics: insights from a
16 review of late Miocene blueschists and eclogites, and related young high-pressure
17 metamorphic rocks. *Gondw. Res.* 18, 167-188.
18
- 19 Page, B.M., Suppe, J., 1981. The Pliocene Lichi melange of Taiwan: its plate-tectonic and
20 olistostromal origin. *Am. J. Sci.* 281, 193-227.
21
22
- 23 Panini, F., Fioroni, C., Fregni, P., Bonacci, M., 2002. Le rocce caotiche dell'Oltrepo Pavese: note
24 illustrative della Carta Geologica dell'Appennino vogherese tra Borgo Priolo e Ruino. *Atti
25 Ticinensi di Scienze della Terra* 43, 83–109.
26
- 27 Pasquarè, G., Abbate, E., Castiglioni, G.B., Merenda, L., Mutti, E., Ortolani, F., Parotto, M., Pignone,
28 R., Polino, R., Premoli Silva, I., Sassi, F.P., 1992. Guida al rilevamento e
29 all'informatizzazione della Carta Geologica d'Italia alla scala 1:50,000. *Quaderni del Servizio
30 Geologico Nazionale, serie III, 1*, 203.
31
32
- 33 Pettinga, J.R., 1982. Upper Cenozoic structural history, coastal southern Hawke's Bay, New Zealand.
34 *New Zealand J. Geol. Geophys.* 25, 149–191.
35
- 36 Pini, G.A., 1999. Tectonosomes and olistostromes in the Argille Scagliose of the Northern Apennines,
37 Italy. *Geol. Soc. Am. Spec. Pap.* 335, 73 pp.
38
39
- 40 Pini, G.A., Ogata, K., Camerlenghi, A., Festa, A., Lucente C.C., Codegone, G., 2012. Sedimentary
41 mélanges and fossil mass-transport complexes: a key for better understanding submarine
42 mass movements?, in: Yamada, Y. et al. (Eds.), *Submarine mass movements and their
43 consequences*, *Advances in natural and technological hazards research* 31, Springer
44 Science+Business Media B.V., 585-594.
45
- 46 Ranero, C.R., von Huene, R., 2000. Subduction erosion along the Middle America convergent margin.
47 *Nature* 404, 748-752.
48
49
- 50 Rassios, A.E., Dilek, Y., 2009. Rotational deformation in the Jurassic Mesohellenic ophiolites, Greece,
51 and its tectonic significance. *Lithos* 108, 207-223.
52
- 53 Rast, N., Horton, J.W., Jr., 1989. Melanges and olistostromes in the Appalachians of the United
54 States and mainland Canada; An assessment, in: Horton, J.W., Jr., Rast, N. (Eds.),
55 *Mélanges and olistostromes of the Appalachians*. *Geol. Soc. Am. Spec. Pap.* 228, 1–16.
56
- 57 Raymond, L.A., 1975. Tectonite and mélange - a distinction. *Geology* 3, 7-9.
58
- 59 Raymond, L.A., 1984. Classification of melanges, in: Raymond, L.A. (Ed.), *Mélanges: Their nature,
60 origin and significance*. Boulder, Colorado. *Geol. Soc. Am. Spec. Pap.* 198, 7-20.
61
62
63
64
65

- 1 Raymond, L.A., Yurkovich, S.P., McKinney, M., 1989. Block-in-matrix structures in the North Carolina
2 Blue Ridge belt and their significance for the tectonic history of the southern Appalachian
3 orogen, in: Horton, J.W., Jr., Rast, N. (Eds.), *Mélanges and olistostromes of the*
4 *Appalachians*. Geol. Soc. Am. Spec. Pap. 228, 195-216.
5
6
7 Remitti, F., Vannucchi, P., Bettelli, G., Fantoni, L., Panini, F., Vescovi, P., 2011. Tectonic and
8 sedimentary evolution of the frontal part of an ancient subduction complex at the transition
9 from accretion to erosion: The case of the Ligurian wedge of the northern Apennines, Italy.
10 Geol. Soc. Am. Bull. 123, 51-70.
11
12 Robertson, A.H.F., Parlak, O., Ustaömer, T., 2009. Mélange genesis and ophiolite emplacement
13 related to subduction of the northern margin of the Tauride Anatolide continent, central and
14 western Turkey. Geol. Soc. London Spec. Publ. 311, 9-66.
15
16
17 Saleeby, J., 1984. Tectonic significance of serpentinite mobility and ophiolitic melange, in: Raymond,
18 L.A. (Ed.), *Melanges: Their nature, origin, and significance*. Geol. Soc. Am. Spec. Pap. 198,
19 153–168.
20
21 Saleeby, J.B., Shaw, H.F., Niemeyer, S., Moores, E.M., Edelman, S.H., 1989. U/Pb, Sm/Nd and
22 Rb/Sr geochronological and isotopic study of northern Sierra Nevada ophiolitic assemblages,
23 California. *Contrib. Mineral. Petrol.* 102 (2), 205-220.
24
25 Salvador, A. (Ed.), 1994. *International stratigraphic guide: a guide to stratigraphic classification,*
26 *Terminology and Procedure*, 2nd ed. Norway and Boulder, CO. Int. Un. Geol. Sci. and Geol.
27 Soc. Am. 214.
28
29 Şengör, A.M.C., 2003. The repeated rediscovery of mélanges and its implication for the possibility
30 and the role of objective evidence in the scientific enterprise, in: Dilek, Y., Newcomb, S.
31 (Eds.), *Ophiolite concept and the evolution of geological thought*. Boulder, Colorado, Geol.
32 Soc. Am. Spec. Pap. 373, 385-445.
33
34
35 Shervais, W.J., Choi, S.H., Sharp, W.D., Ross, J., Zoglman-Schuman, M., Mukasa, S.B., 2011.
36 Serpentinite matrix mélange: implications of mixed provenance for mélange formation, in:
37 Wakabayashi, J., Dilek, Y. (Eds.), *Melanges: Processes of formation and societal*
38 *significance*. Geol. Soc. Am. Spec. Pap. 480, 1-30, doi: 10.1130/2011.2480(01)
39
40 Shreve, R.L., Cloos, M., 1986. Dynamics of sediment subduction, mélange formation, and prism
41 accretion. *J. Geophys. Res.* 91, 10229-10245.
42
43
44 Silver, E.A., Beutner, E.C., 1980. Melanges. *Geology* 8, 32-34.
45
46 Ślącza, A., Renda, P., Cieszkowski, M., Golonka, J., Nigro, F., 2012. Sedimentary basin evolution
47 and olistoliths formation: the case of Carpatian and Sicilian regions. *Tectonophysics*, this
48 volume, doi: 10.1016/j.tecto.2012.03.018
49
50
51 Smith, A.G., Woodcock, N.H., Naylor, M.A., 1979. The structural evolution of a Mesozoic continental
52 margin, Othris Mountains, Greece. *J. Geol. Soc. London* 136, 589-601.
53
54 Sunesson, N.H., 1993. The geology of the Torlesse Complex along the Wellington area coast, North
55 Island, New Zealand. *New Zealand J. Geol. Geophys.* 36, 369–384.
56
57 Suppe, J., 1972. Interrelationships of high-pressure metamorphism, deformation and sedimentation in
58 Franciscan tectonics, USA. *Intern. Geol. Congr.*, 24^h, Montreal 1972, *Comptes Rendus*, sec.
59 3, 552-559.
60
61
62
63
64
65

- 1 Suzuki, T., 1986. Melange Problem of Convergent Plate Margins in the Circum-Pacific Regions,
2 Memoirs of the Faculty of Science, Kochi University, Series E. Geology 7, 23-48.
3
- 4 Swarbrick, R.E., Naylor, M.A., 1980. The Kathikas melange, SW Cyprus: late Cretaceous submarine
5 debris flows. *Sedimentology* 27, 63-78.
6
- 7 Trincardi, F., Argnani, A., 1990. Gela submarine slide: A major basin-wide event in the Plio-
8 Quaternary foredeep of Sicily. *Geo Mar. Lett.* 10, 13–21, doi:10.1007/BF02431017.
9
- 10 Trincardi, F., Cattaneo, A., Correggiari, A., Ridente, D., 2004. Evidence of soft sediment deformation,
11 fluid escape, sediment failure and regional weak layers within the late Quaternary mud
12 deposits of the Adriatic Sea. *Marine Geology* 213, 91-119.
13
- 14 Trümpy, R., 2006. Geologie der Iberger Klippen und ihrer Flysch-Unterlage. *Eclogae Geol. Helv.* 99,
15 79–121.
16
- 17 Ukar, E., 2012. Tectonic significance of low-temperature blueschist blocks in the Franciscan mélangé
18 at San Simeon, California. *Tectonophysics*, this volume, doi: 10.1016/j.tecto.2011.12.039
19
- 20 Vannucchi, P., Bettelli, G., 2002. Mechanism of subduction accretion as implied from the broken
21 formations in the Apennines, Italy. *Geology* 30, 835–838.
22
- 23 Vannucchi, P., Bettelli, G., 2010. Myths and recent progress regarding the Argille Scagliose, Northern
24 Apennines, Italy, in: Dilek, Y. (Ed.), *Alpine Concept in Geology. Int. Geol. Rev.* 52 (10-12),
25 1106-1137, doi: 10.1080/00206810903529620
26
- 27 Vannucchi, P., Remitti, F., Bettelli, G., 2008. Geological record of fluid flow and seismogenesis along
28 an erosive subducting plate boundary. *Nature* 451, 699-703.
29
- 30 Vezzani, L., Festa, A., Ghisetti, F., 2010. Geology and Tectonic evolution of the Central-Southern
31 Apennines, Italy: *Geol. Soc. Am. Spec. Pap.* 469, 58, accompanying by a CD-ROM including
32 the “Geological-Structural Map of the Central-Southern Apennines (Italy)” at 1:250.000 scale,
33 Sheets 1 and 2, doi: 10.1130/2010.2469
34
- 35 Vollmer, F.W., Bosworth, W., 1984. Formation of melange in a foreland basin overthrust setting:
36 Example from Taconic Orogen, in: Raymond, L.A. (Ed.), *Melanges: Their nature, origin, and
37 significance. Geol. Soc. Am. Spec. Pap.* 198, 53–70.
38
- 39 von Huene, R., Lallemand, S., 1990. Tectonic erosion along the Japan and Peru convergent margin.
40 *Geol. Soc. Am. Bull.* 102, 704–720.
41
- 42 von Huene, R., Ranero, C.R., Vannucchi, P., 2004. Generic model of subduction erosion. *Geology* 32,
43 913-916.
44
- 45 Wakabayashi, J., 1992. Nappes, tectonics of oblique plate convergence, and metamorphic evolution
46 related to 140 million years of continuous subduction, Franciscan Complex, California. *J.*
47 *Geol.* 100, 19–40.
48
- 49 Wakabayashi, J., 2004. Contrasting setting of serpentinite bodies, San Francisco Bay area, California:
50 Derivation from the subducting plate vs. mantle hanging wall?. *Int. Geol. Rev.* 46, 1103-1118.
51
- 52 Wakabayashi, J., 2011. Mélanges of the Franciscan Complex, California: Diverse structural settings,
53 evidence for sedimentary mixing, and their connection to subduction processes, in:
54 Wakabayashi, J., Dilek, Y. (Eds.), *Melanges: Processes of formation and societal
55 significance. Geol. Soc. Am. Spec. Pap.* 480, 117-141, doi: 10.1130/2011.2480(05)
56
57
58
59
60
61
62
63
64
65

- 1 Wakabayashi, J., 2012. Subducted sedimentary serpentinite mélanges: Record of multiple burial-
2 exhumation cycles and subduction erosion. *Tectonophysics*, this volume, doi:
3 10.1016/j.tecto.2011.11.006
4
- 5 Wakabayashi, J., Dilek, Y., 2011. Introduction: Characteristics and tectonic settings of melanges, and
6 their significance for societal and engineering problems, in: Wakabayashi, J., Dilek, Y. (Eds.),
7 *Melanges: Processes of Formation and Societal Significance*. Geol. Soc. Am. Spec. Pap.
8 480, v-x, doi: 10.1130/2011. 2480(00)
9
- 10 Wakita, K., 1988. Origin of chaotically mixed rock bodies in the Early Jurassic to Early Cretaceous
11 sedimentary complex of the Mino terrane, central Japan. *Bull. Geol. Surv. Japan* 39, 675-
12 757.
13
- 14 Wakita, K., 2000. Mélanges of the Mino terrane. *Mem. Geol. Soc. Jpn.*, 55, 145 – 163.
15
- 16 Wood, D.S., 1974. Ophiolites, mélanges, blue schists, and ignimbrites: early Caledonian subduction
17 in Wales?, in Dott, R.H., Shaver, R.H. (Eds.), *Modern and Ancient Geosynclinal*
18 *Sedimentation*. SEPM Spec. Publ. 19, 334-343.
19
- 20 Yamada, Y., Yamashita, Y., Yamamoto, Y., 2010. Submarine landslides at subduction margins:
21 insight from physical models. *Tectonophysics* 484 (1/4), 156-167.
22
- 23 Yamamoto, Y., Nidaira, M., Ohta, Y., Ogawa, Y., 2009. Formation of chaotic rock units during primary
24 accretion processes: examples from the Miura-Boso accretionary complex, central Japan.
25 *Island Arc* 18, 496-512.
26
- 27 Yamamoto, Y., Tonogai, K., Anma, R., 2012a. Fabric-based criteria to distinguish tectonic from
28 sedimentary mélanges in the Shimanto accretionary complex, Yakushima Island, SW Japan.
29 *Tectonophysics*. this volume, doi: 10.1016/j.tecto.2011.10.018
30
- 31 Yamamoto, Y., Yamada, Y., Yamashita, Y., Chiyonobu, S., Shibata, T., Hojo, M., 2012b. Systematic
32 development of, submarine slope failures at subduction margins: fossil record of accretion-
33 related slope failure in the Miocene Hota Accretionary Complex, Central Japan, in: Yamada,
34 Y. et al. (Eds.), *Submarine mass movements and their consequences*, *Advances in natural*
35 *and technological hazards research* 31, Springer Science+Business Media B.V., 355-364.
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1 **CAPTIONS TO TABLES AND FIGURES**
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 3

4 **Table 1** – Deterministic characters of broken formations and mélanges, representing two end
 5 members involving the nature of blocks (native vs. exotic) and mechanisms (*in situ* stratal disruption
 6 vs. mixing).
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 12 **Table 2** – Subdivision and classification of mélanges and broken formations on the basis of their
 13 geodynamic setting of formation, processes, triggering mechanisms, products and mesoscale
 14 characteristics (modified after Festa et al., 2010a). Acronyms are listed at the bottom of the table.
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22 **Figure 1** – Global distribution of mélanges and mélanges terrains.
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27 **Figure 2** – Conceptual model for the formation and emplacement of mélanges associated with (A)
 28 extensional tectonics (type 1 mélanges), passive margin (type 2a mélanges), ocean-continent
 29 transition settings (type 2b mélanges) and convergent margins (type 4 mélanges). Different models
 30 and cases of subduction settings are shown: (A) open-double verging wedge with a low elevation
 31 backstop; (B) obduction of ophiolites (modified after Rassios and Dilek, 2009); (C) close wedge and
 32 subduction channel (modified after Cloos, 1982); (D) close and smaller wedge with an high elevation
 33 of the backstop; (E) collisional tectonics (type 5 mélanges; modified after Huang et al., 2008; Ghikas
 34 et al., 2010; Festa et al., 2010a), intra-continental deformation (type 6 mélanges), and (F) strike slip
 35 tectonics (type 3 mélanges).
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49 **Figure 3** - Different examples of broken formations and mélanges: (A) layer-parallel extension in the
 50 *Argille varicolori* displaying lozenge-shaped boudins of red clayey marl enveloped in greyish matrix
 51 (broken formation) (Aventino valley, Abruzzi region, Central Apennines of Italy; photograph by E.
 52 Malerba); (B) progressive stratal disruption of well bedded units (Flysch Rosso) forming lozenge-
 53 shaped boudins of mudstone in a clayey marl matrix (broken formation) (Aventino valley, Abruzzi
 54 region, Central Apennines of Italy); (C) progressive stratal disruption of well bedded units (Subligurian
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1 Eocene Canetolo Complex) forming broken formation (Corniglia, La Spezia, western coastal
 2 exposures of the Northern Apennines of Italy); (D) lozenge-shaped boudins of sandstone within a
 3 mudstone matrix displaying a pervasive scaly fabric (broken formation), due to transposition of upright
 4 beds in a fault zone related to an out-of-sequence thrust (Waimarama Beach, South Hawke's Bay,
 5 East Coast of North Island, New Zealand); (E) phacoidal Upper Triassic pelagic limestone blocks in a
 6 heterogeneous and variously deformed matrix composed of shale, mudstone, and sandstone in the
 7 Jurassic-Cretaceous Avdella mélange (Pindos Mountains, Northern Greece); (F) narrow,
 8 anastomosing and coalescent fault zone including exotic blocks of sandstone and mudstone in a
 9 shaly limestone matrix (Taconic mélange) (Hoosic River at Schaghticoke Gorge, eastern NY, Central
 10 Appalachian - USA)
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26 **Figure 4** – Different examples of polygenetic mélanges, diapiric and sedimentary mélanges: (A)
 27 sedimentary mélanges overprinted by tectonic deformation forming a polygenetic mélange in the
 28 footwall of the Taconic Allochthon (Northern Appalachians, USA). Exotic blocks (with respect to the
 29 shaly limestone matrix) of sandstone, mudstone and chert show a lenticular shape resulting from
 30 tectonic shearing (Hoosic River at Schaghticoke Gorge, eastern NY, Central Appalachians – USA);
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 37 (B) Exotic blocks of sandstone and volcanic rocks showing an elongated shape within a shaly matrix
 38 with fluidal feature (tectonic mélange or sheared olistostrome?) (Esk Head mélange, Okuku River,
 39 New Zealand); (C) small-scale diapiric body overprinting a previously formed broken formation
 40 (polygenetic mélange) in the footwall of the Taconic Allochthon. Red lines bound the margin of the
 41 diapiric body. Note the vertical reorientations of blocks enveloped in a fluidal scaly fabric (Poestenkill
 42 Gorge at Troy, eastern NY, Central Appalachians – USA); (D) olistostrome of the uppermost portion
 43 of the Oligocene Macigno Costiero Formation (precursory olistostrome) cropping out in the Cinque
 44 Terre area (La Spezia, westernmost Northern Apennines of Italy); (E) Upper Cretaceous olistostrome
 45 in the external Ligurian units, flattened and slightly deformed by compaction and tectonics (Berceto,
 46 Parma area of the Northern Apennines of Italy); (F) Lower Miocene olistostrome (Val Tiepido –
 47 Canossa olistostrome) of the wedge-top Epiligurian successions. Note the random distribution of hard
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1 block in a marly matrix (Costa del Vento, Montalto P.se area of the Northern Apennines of Italy); (G)
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3 and (H) liquefied sediments into coherent layers by *in situ* injection (Kaitocho, Miura Peninsula,
4
5 Japan).
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10 **Figure 5** – Diagram showing the direct and indirect role of tectonics as a major triggering mechanism
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12 in the formation of mélanges.
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16 **Figure 6** – Composite diagram showing the continuum of processes of stratal disruption. Arrows
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18 indicate the genetic link and the continuum of dismemberment processes from shallow to deeper
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20 structural domains and from sedimentary to tectonic processes. Left and right pictures in Figure A are
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22 modified from Yamamoto et al. (2009) and Cowan (1985), respectively. Pictures in B, C, E1 and E2,
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24 modified from Yamamoto et al. (2009), Meneghini et al. (2009), Cowan and Pini (2001), and Bettelli
25
26 and Vannucchi (2003), respectively.
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32 **Figure 7** – Schematic diagram showing the progressive increase of the consolidation degree (and
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34 decrease of fluid production) with depth. Note that consolidation is time-dependent. Modified after
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36 Collison (1994) and Brown (1994).
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41 **Figure 8** – (A) Progressive transition of stratal disruption and mixing processes in mass-transport
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43 chaotic complexes (modified after Mutti et al., 2006; Ogata et al., 2012a; Pini et al., 2012). Three main
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45 types of chaotic bodies are formed during the progressive increase of lithification and are
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47 characterized by a gradual decrease of matrix amount from debris flows to block flow and slide/slump
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49 bodies (see text for explanation). (B) Example of debris flow (Val Tiepido – Canossa olistostrome at
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51 Mt. Penola, Val Curone, Northern Apennines of Italy). The arrows indicate the erosive basal surface
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53 that is characterized by a decimeters-thick shear zone accommodating the flow of sediments (D).
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55 Away from the basal shear zone, the hard blocks are randomly oriented within the clayey matrix (C).
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57 (E) and (F) examples of slumping and related boudinage in the *Argille varicolori* of External Ligurian
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1 Units (Montalto P.se) and Marnoso arenacea Fm. (Passo dei Mandrioli) in Northern Apennines of
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 3 Italy.
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8 **Figure 9**– Progressive stratal disruption forming different types of broken formations by layer-parallel
 9 extension (see text for explanation). Stratal disruption is controlled by the degree of consolidation and
 10 lithification and the increase of shear (see vertical and horizontal arrows). (A) At shallow structural
 11 levels where sediments are non- to poorly-lithified, pinch-and-swell and boudinage structures are
 12 formed by coaxial strain. Deformation acts in different ways on the basis of the rheology and nature of
 13 the bedded succession, inducing heterogeneous flattening. (A1) Photograph showing an example of
 14 heterogeneous flattening (Marnoso arenacea Fm. at Passo dei Mandrioli, Northern Apennines of
 15 Italy). (B) With the increasing shear, non-coaxial strain forms lozenge- to sigmoidal-shaped blocks as
 16 show in the *Argille varicolori* of photograph (B1) (Monteu da Po, Tertiary Piedmont Basin, NW Italy).
 17 The increasing amount of lithification is coupled by different mechanisms of stratal disruption as, for
 18 example, (C and C1) veining, (D and D1) brecciation in the neck and tails of blocks, (E) veining along
 19 the border of the blocks (modified after Pini, 1999), and (F and F1) extensional fracturing. The
 20 increasing shearing (G, G1, and G2) forms asymmetrical brittle boudinage with the development of Y,
 21 R, R" and P shear surfaces. Photograph localities are: (C1) Taconic flysch at Schaghticoke Gorge,
 22 eastern NY, Central Appalachians – USA, (D1) "Messinian mélange" (see Festa, 2011) in the Tertiary
 23 Piedmont Basin, NW Italy, (F1) Broken formation in the Hamburg Klippe of Eastern Pennsylvania
 24 (south of Albany, Berks County, USA), (G1) Taconic flysch at Schaghticoke Gorge, eastern NY,
 25 Central Appalachians – USA, (G2) *Argille varicolori* in the External Ligurian units at Brusasco, Tertiary
 26 Piedmont Basin, NW Italy.
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53 **Figure 10** – Schematic diagram, showing a conceptual difference between depositionally
 54 (gravitational), diapirically and tectonically induced deformation with respect to the consolidation.
 55 Sedimentary and diapiric chaotic bodies may record only instantaneous and episodic events that
 56 punctuate the consolidation history, whereas tectonic chaotic bodies may record different stages of
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1 deformation that persist through time and different degrees of consolidation and lithification (modified
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3 after Byrne, 1994).
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Table 1[Click here to download Table: Table 1_Festa et al_R2.doc](#)

Products	Nature of blocks	Mechanisms	Lithological unit involved	Contacts with host rocks	Processes
Mélange	Exotic and Native	Mixing	Sedimentary Metamorphic Igneous	Tectonic Stratigraphic	Tectonic Sedimentary
Broken Formation	Intra-formational	Stratal disruption	Sedimentary Metamorphic (?)	Intrusive	Diapiric

Table 1 – Festa et al.

Table 2

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Types of Mélange related to:	Geodynamic environments	Processes	Triggering mechanisms	Products	Mesoscale characteristics	Minor related products
1. Extensional tectonics	Rifting	MTP (debris avalanches and flows, etc.)	Tectonic	MTD (megabreccias, breccias, olistolith fields, debrites, slide blocks, etc.)	Chaotic angular clasts (cm to >10 m) in fine-grained (pelitic) matrix	Fault zones along normal fault?
2. Passive margin	Passive margins (after rifting)	SSD and mass-wasting related progressive deformation from slumping to debris flow, to complete strata disruption	Tectonic, sedimentary	MTD, poorly sorted olistostromes (olistoliths, slide blocks)	Chaotic monomictic brecciated (matrix-supported) masses	<i>In situ</i> fluidification: mud diapirs?
a. Downslope mass-transport deposits						
b. Mass-transport deposits at the ocean-continent transition (OCT)	Ocean-continent transition	SSD and MTP with related progressive deformation from slumping to debris flows, to gravitational sliding	Tectonic, sedimentary	MTD, olistostromes with continent rock olistoliths (tens of meters to several km slide blocks) in a matrix of oceanic origin	Chaotic polymictic brecciated (matrix-supported) masses (including native, extra-basinal and/or exotic blocks)	
3. Strike-slip tectonics and transform setting	Different types of collision	TSD: fault-to fold-related, fluidification (overprinting previous mass-wasting-related deformation)	Tectonic	BrFm; mélanges (exotic blocks being commonly recycled from other previously formed mélanges)	Structurally ordered BIM fabric (parallel orientation of blocks and matrix features – i.e. pseudo-bedding)	Olistostromes <i>s.l.</i> ; mud diapirs <i>s.l.</i>
4. Convergent margins and oceanic crust subduction	Subduction (at the front of the wedge)	MTP (debris flows and avalanches, slumps, slides, etc.)	Tectonic, sedimentary	MTD, olistostromes (olistoliths, olistolith fields and swarm, slide blocks)	Chaotic BIM fabric (including native, extra-basinal and/or exotic blocks)	Mud diapirs and mud volcanoes, serpentinite
a. Mass-transport deposits at the wedge front						
b. Broken fms and tectonic mélanges	Subduction (at the base of the wedge) and subduction channel	TSD: fault-to fold-related, fluidification (overprinting previous mass-wasting-related deformation); tectonic mixing	Tectonic	BrFm; mélanges (exotic blocks being recycled from other previously formed mélanges or formed by subduct. channel processes)	Structurally ordered BIM fabric (parallel orientation of BIM features – i.e. pseudo-bedding)	
5. Collision	Different types of collision	TSD: fault-to fold-related, fluidification (overprinting previous mass-wasting-related deformation)	Tectonic	BrFm; mélanges? (exotic blocks being commonly recycled from other previously formed mélanges)	Mainly structurally ordered BIM fabric (that in some cases overprinted chaotic BIM fabric)	Olistostromes <i>s.l.</i> ; mud diapirs <i>s.l.</i>
6. Intracontinental deform.						
a. Mass-transport deposits at the wedge front	At the base or at the front of intra-continental thrust sheets or nappes	MTP (debris flows and avalanches, slumps, slides, etc.)	Tectonic, sedimentary	MTD, olistostromes (olistoliths, olistolith fields and swarm, slide blocks)	Chaotic BIM fabric (from matrix-supported cm-to m in size blocks to clast supported >10 m blocks and olistoliths)	Mud diapirs and mud volcanoes
a1. Precursory olistostromes						
a2. Olistostromal carpet						
a3. Tectonic mélanges		TSD: fault-to fold-related, fluidification (overprinting previous mass-wasting-related deformation)	Tectonic, sedimentary	Mélanges (exotic blocks being commonly recycled from other previously formed sedimentary mélanges); BrFm	Chaotic BIM fabric overprinted by tectonic deformation and shearing	
b. Intra-nappe	Within intra-continental thrust sheets or nappes	MTP (debris flows and avalanches, slumps, slides, etc.)	Tectonic, sedimentary	MTD, olistostromes (olistoliths, olistolith fields and swarm, slide blocks)	Chaotic BIM fabric (blocks of intra-basinal origin)	Mud diapirs and mud volcanoes
b1. Sedimentary						
b2. Tectonic and/or tectono-sedimentary		TSD: fault-to fold-related, fluidification (overprinting previous mass-wasting-related deformation)	Tectonic	BrFm; mélanges (exotic blocks being commonly recycled from other previously formed sedimentary mélanges)	Structurally ordered BIM fabric (parallel orientation of blocks and matrix features – i.e. pseudo-bedding)	
c. Epi-nappe	A top of intra-continental thrust sheets or nappes (e.g. piggy back, top thrust basins)	MTP (debris flows and avalanches, slumps, slides, etc.)	Tectonic, sedimentary	MTD, olistostromes (olistoliths, olistolith fields and swarm, slide blocks)	Chaotic BIM fabric (originated from the succession tectonically imbricated in the thrust-sheet)	Mud diapirs and mud volcanoes
c1. Sedimentary						
c2. Tectono-sedim.			TSD (overprinting previous mass-wasting-related deformation)	Tectonic, sedimentary	BrFm, mélanges	Structurally ordered BIM fabric
c3. Diapiric		Extrusion of non-to poorly consolidated sediments	Tectonic, sedimentary	Mud diapirs and mud volcanoes	Zonation of deformation from core to margins	Olistostromes <i>s.l.</i>
7. Sub-aerial deformation	On the Earth and/or other planets surface	MTP and glacial processes (debris flows, avalanches, slides, etc.)	Sedimentary, glacial, tectonic	MTD (debris flows/avalanches, alluvial fan dep., talus breccias/megabreccias, block falls, glacial till, etc.)	Chaotic BIM fabric (block of intra-basinal origin)	
a. Sedimentary						
b. Impact of bodies		Impact of bodies on planet surfaces	Impact processes	Ejected breccias and megabreccias	Chaotic breccias in a fluidal matrix	
BIM – Block-in-matrix BrFm – Broken Formation		MTD – Mass-transport deposits MTP – Mass-transport processes		SSD – Soft sediment deformation TSD – Tectonic stratal disruption		

Table 2 – Festa et al.

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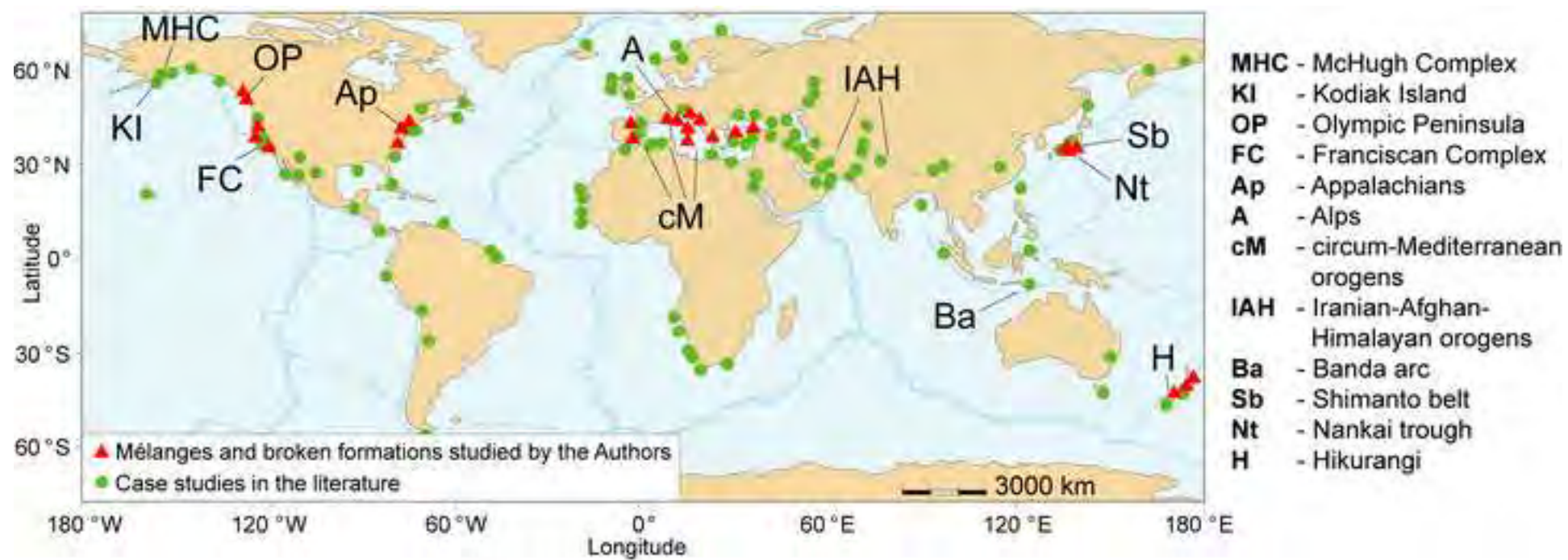


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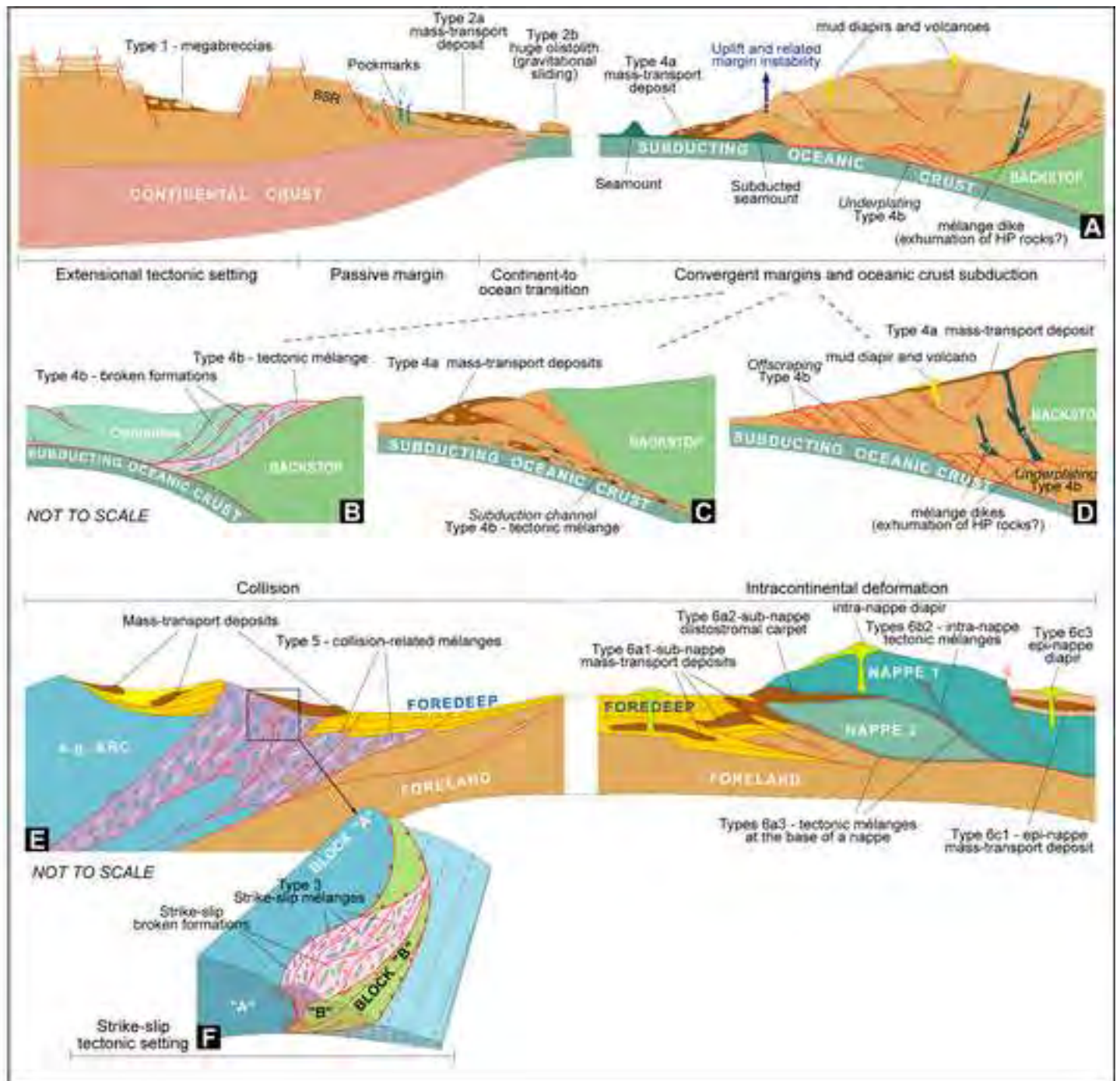


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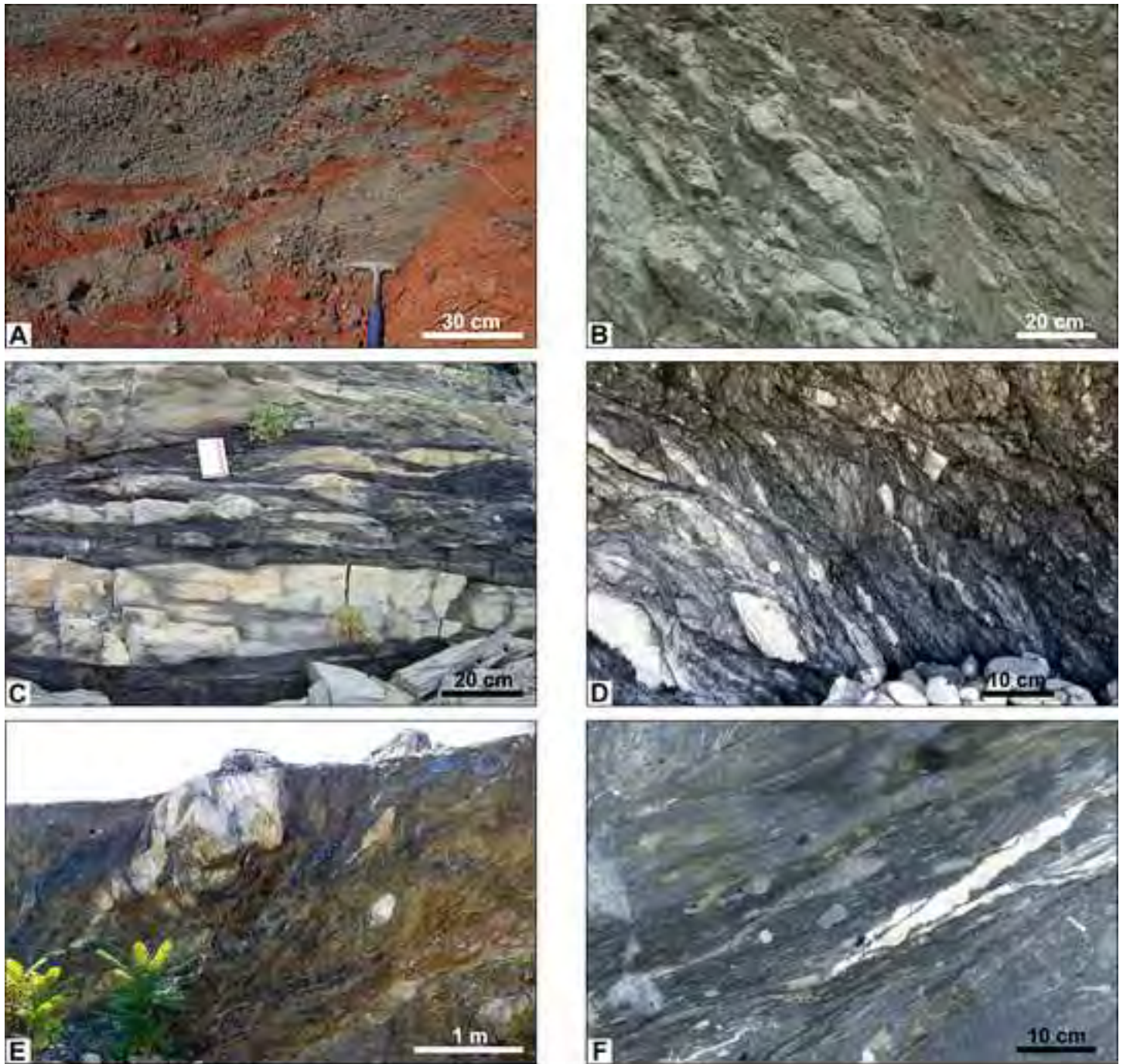


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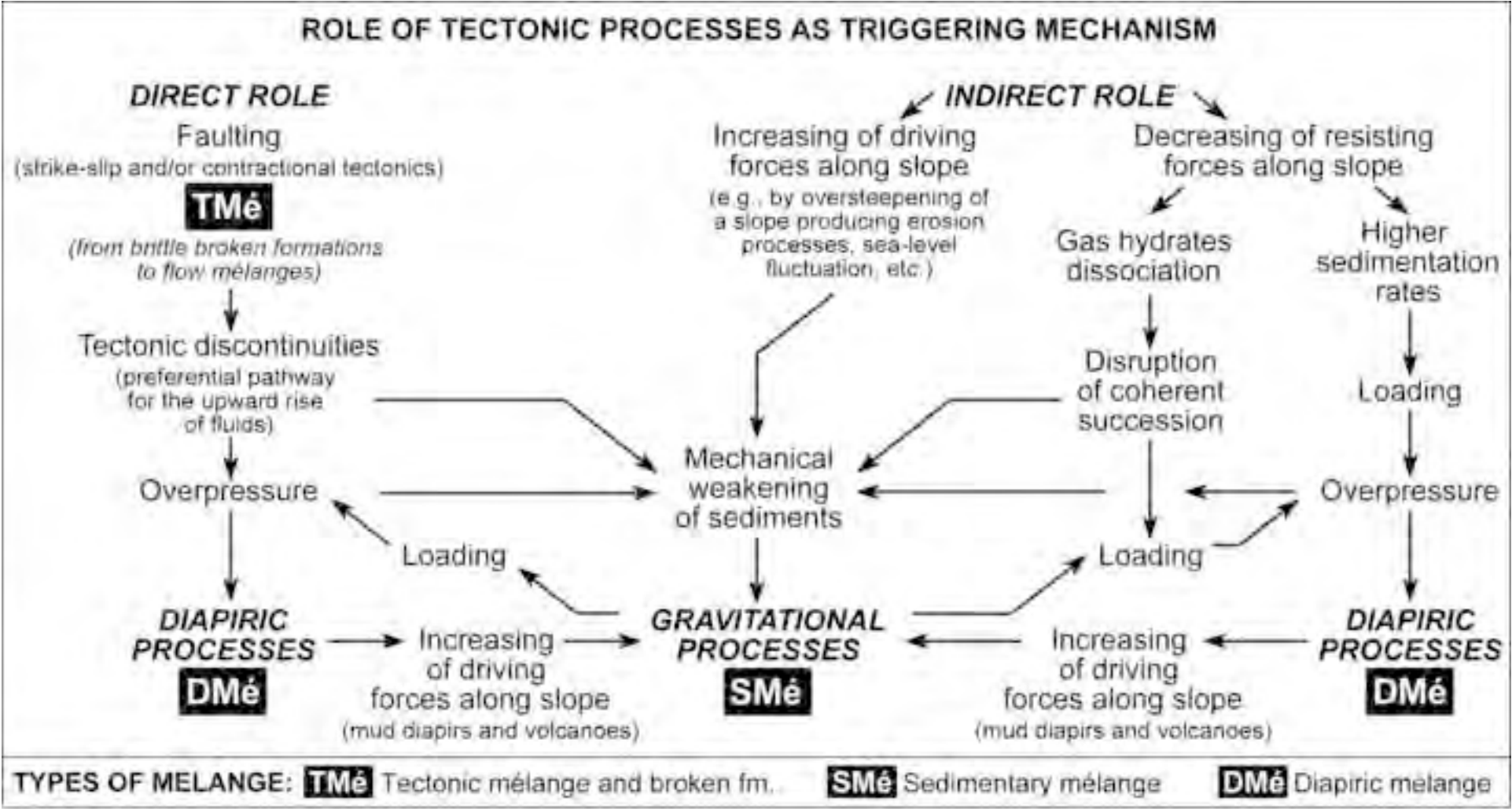


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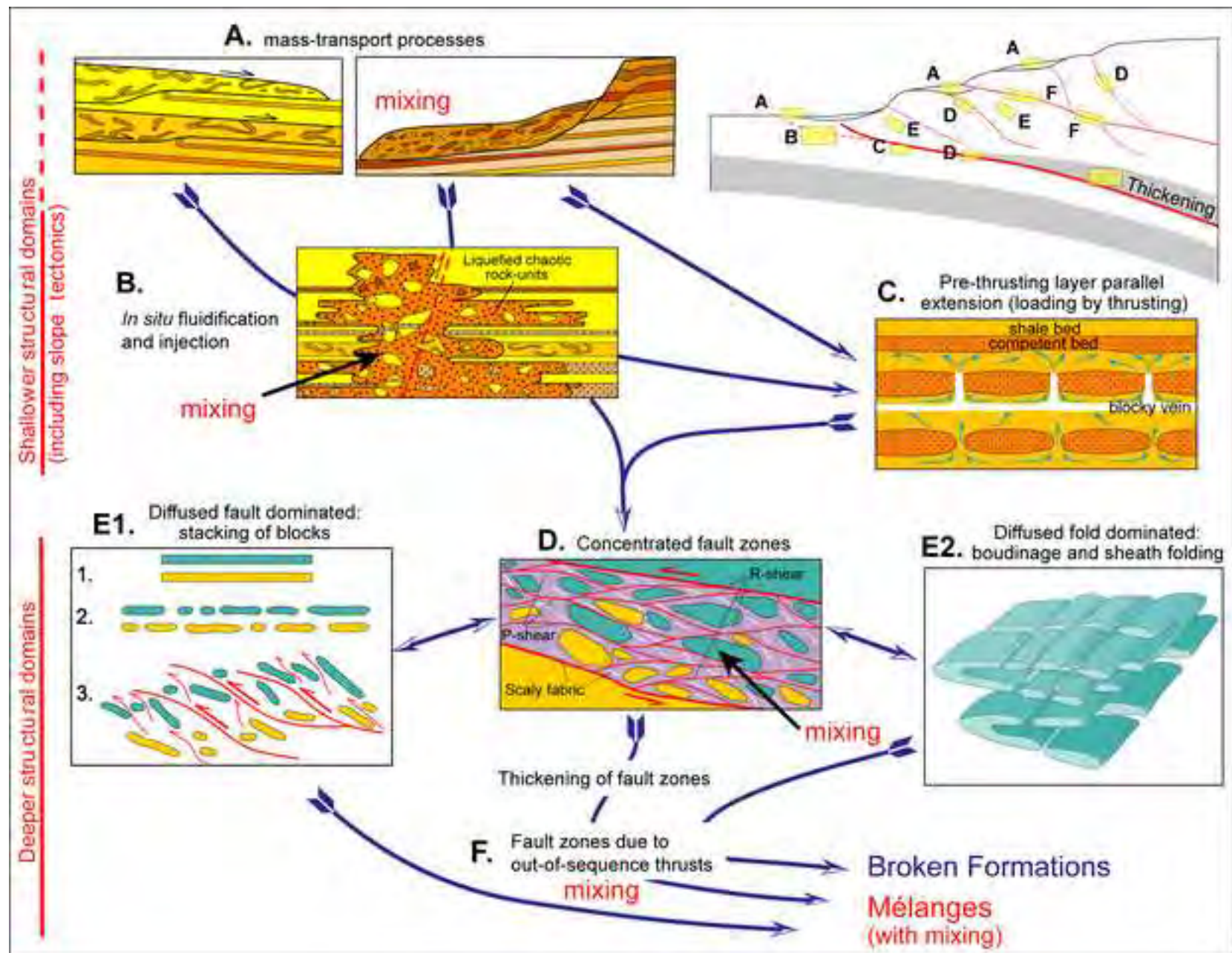


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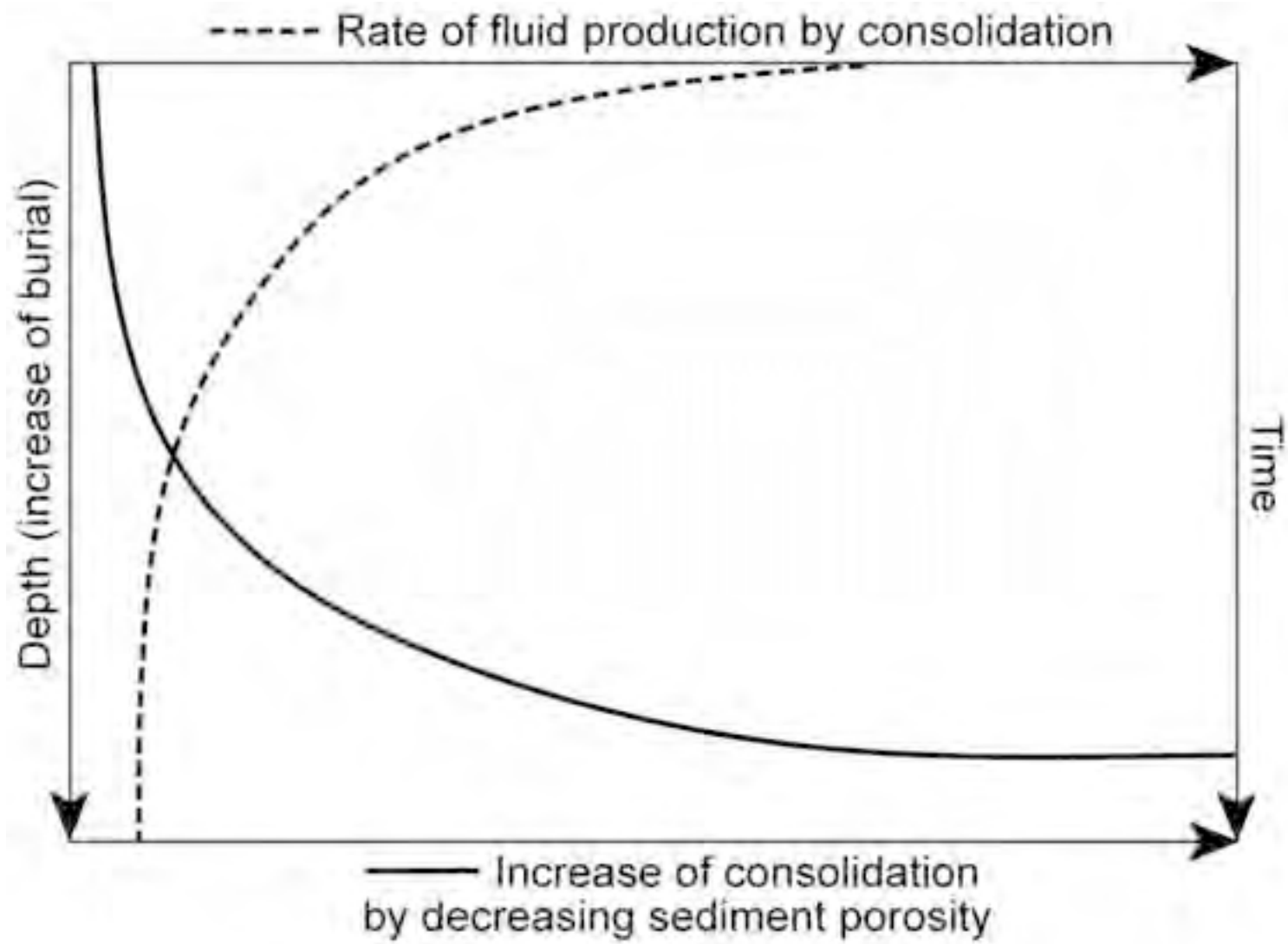


Figure 7 - Festa et al.

Figure 8
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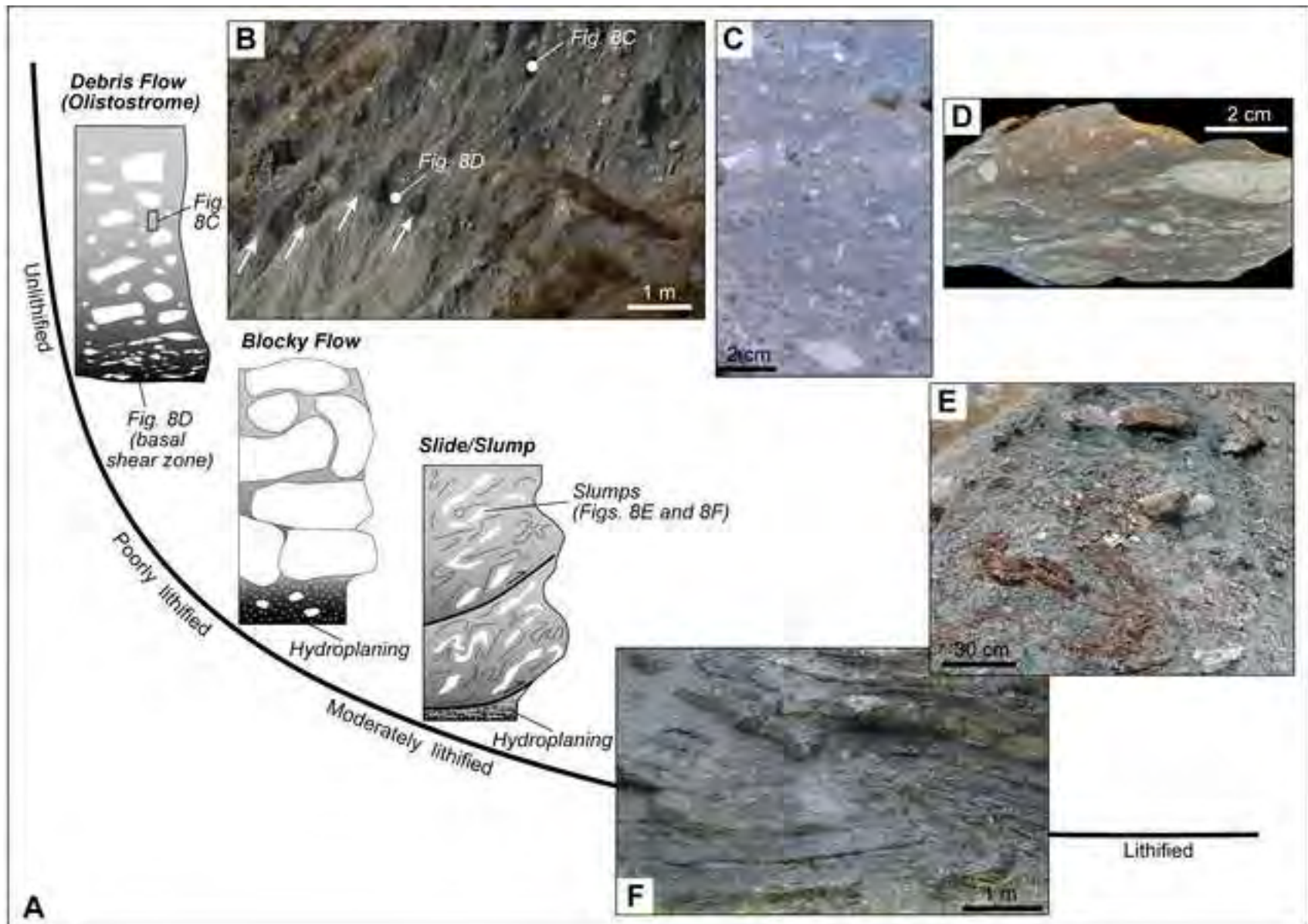


Figure 8 - Festa et al.

Figure 9
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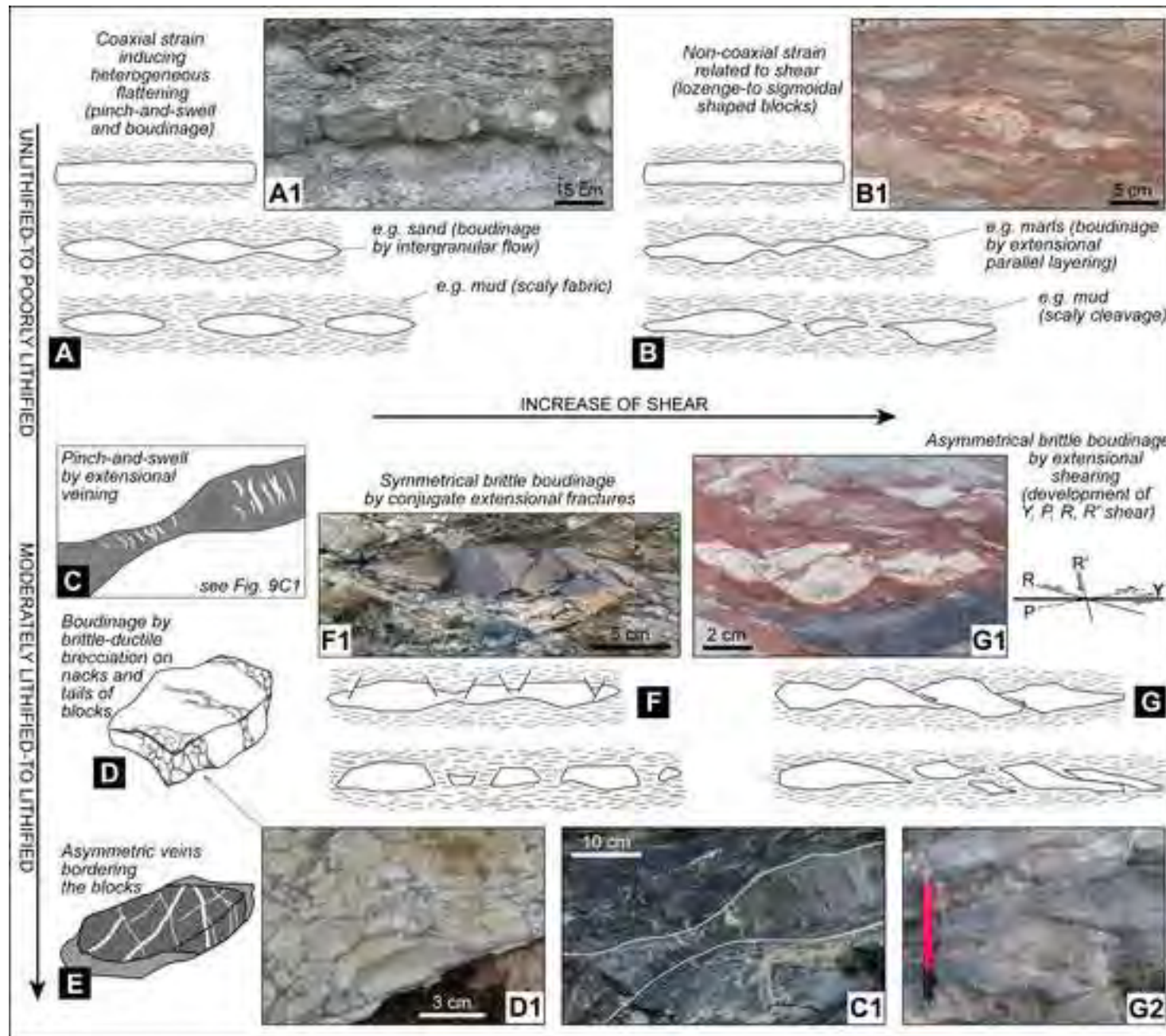


Figure 9 - Festa et al.

Figure 10

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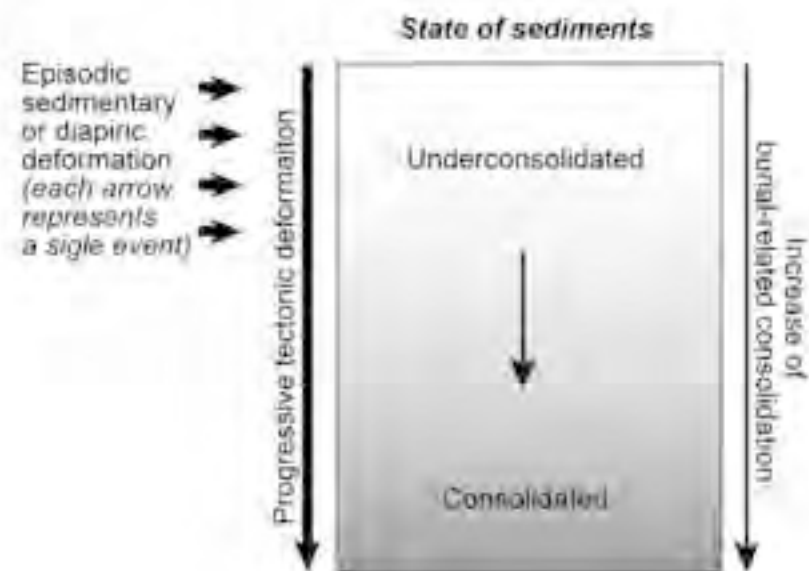


Figure 10 - Festa et al.