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STATE-OF-ART AND REMARKS ON SOME OPEN QUESTIONS ABOUT DSGSDs: HINTS FROM A REVIEW OF THE SCIENTIFIC LITERATURE ON RELATED TOPICS

Marco Emanuele DISCENZA[(*)] & Carlo ESPOSITO[(**)]

[(*)] Geoservizi S.r.l., Via Luigi e Nicola Marinelli, 86025 Ripalimosani, Italy
[(**)]Sapienza Università di Roma, Dipartimento di Scienze della Terra e Centro di Ricerca, Previsione, Prevenzione e Controllo dei Rischi Geologici (CERI), Piazza Aldo Moro, 00185 Roma, Italy
Corresponding author: discenza@geoservizisrl.net

EXTENDED ABSTRACT

Il termine Deformazioni Gravitative Profonde di Versante (DGPV), in inglese Deep-Seated Gravitational Slope Deformations (DSGSDs), è stato ed è tuttora usato per descrivere un insieme di lenti e complessi processi deformativi guidati dalla gravità, che coinvolgono interi versanti o larghe porzioni di essi su lunghi periodi di tempo. Questi fenomeni si verificano nelle più diverse condizioni morfostrutturali e sono caratterizzati da numerose evidenze morfologiche (sdoppiamenti di cresta, depressioni sommitali, trincee, scarpate, controscarpate, fratture da trazione, rigonfiamenti), generalmente distribuite lungo tutto il sistema crinale-versante-fondovalle. Le deformazioni gravitative a grande scala interessano l'ammasso roccioso per spessori di diverse decine o centinaia di metri e, generalmente, sono caratterizzate da tassi di deformazione estremamente ridotti se comparati con le loro dimensioni, nell'ordine dei millimetri/anno. Oltre a condizionare l'assetto morfologico del rilievo, questi fenomeni determinano lo sviluppo di numerose frane secondarie. Non di rado, le DSGSDs presentano una evoluzione catastrofica e portano allo sviluppo grandi frane altamente pericolose a causa degli elevati volumi in gioco e delle alte velocità di spostamento.

Le deformazioni gravitative a grande scala sono particolarmente importanti sia per il loro ruolo morfogenetico che per il rischio associato alle deformazioni indotte e alla possibile evoluzione in grandi frane catastrofiche. Per questi motivi, negli ultimi decenni sono stati condotti numerosi studi specialistici su questi fenomeni. La mancanza di una classificazione generale e universalmente riconosciuta, unitamente alla grande variabilità di morfologie e caratteristiche, ha portato allo sviluppo di numerose terminologie e definizioni, che rendono l'approccio a questi fenomeni particolarmente complesso. Nonostante ciò, è possibile identificare alcune caratteristiche fondamentali, sia in termini di cinematismo ed elementi morfologici prodotti che in termini di fattori di controllo e possibile evoluzione.

Le DSGSDs possiedono caratteristiche che le collocano in una posizione intermedia tra le frane *s.s.* e la tettonica gravitativa. Tra le diverse tipologie di fenomeni non esiste un limite netto e ben definito, anche se nel corso degli anni sono stati prodotti diversi studi sugli elementi che consentono di discriminare i vari processi. In particolare, come elemento caratteristico delle DSGSDs alcuni autori hanno considerato l'assenza di una superficie di scivolamento continua, mentre altri la mancanza di limiti esterni ben definiti. La prima condizione ha perso di valore a causa della scoperta di superfici di scivolamento continue in molte deformazioni gravitative, mentre la seconda è strettamente dipendente dalle caratteristiche geologico-strutturali dei versanti coinvolti e dal grado di evoluzione del fenomeno, anche se appare piuttosto comune in natura.

Negli ultimi anni, alcuni studi hanno evidenziato l'importanza delle elevate scale spaziali e temporali che contraddistinguono le DSGSDs. Le scale su cui esse agiscono sono strettamente connesse al comportamento reologico tempo-dipendente degli ammassi rocciosi coinvolti, che rappresenta un elemento distintivo e caratteristico di tali fenomeni. L'analisi della letteratura scientifica esistente ha permesso di definire i range che contraddistinguono questi processi deformativi guidati dalla gravità. Le DSGSDs presentano dimensioni generalmente comprese tra 10^6 e 10^9 m^3, localmente fino a 10^{10} - 10^{11} m^3, e si sviluppano su intervalli di tempo variabili tra 10^3 e 10^4 anni, in alcuni casi fino a 10^5 anni.

Sulla base di quanto esposto, si ritiene che la loro differenziazione rispetto alle frane convenzionali e alla tettonica gravitativa non possa essere fatta in riferimento a un singolo elemento, ma piuttosto tenendo conto di tutta una serie di fattori caratteristici. In sintesi, i principali elementi che contraddistinguono le DSGSDs sono: (*i*) dimensioni comparabili con quelle dell'intero versante (o gran parte di esso); (*ii*) limiti esterni o margini diffusi, discontinui o non ben definiti, con fianchi talora coincidenti con elementi idrografici o tettonici; (*iii*) distribuzione peculiare di alcuni elementi morfologici (sdoppiamenti di cresta, depressioni sommitali, trincee, scarpate, controscarpate, fratture da trazione, rigonfiamenti), generalmente distribuiti lungo l'intero sistema crinale-versante-fondovalle; (*iv)* tassi di deformazione estremamente ridotti (nell'ordine dei millimetri/anno); (*v*) ampie scale spaziali e temporali (volumi compresi tra 10^6 e 10^{11} m^3 e intervalli di tempo compresi tra 10^3 e 10^5 anni); (*vi*) complessi processi deformativi (deformazioni fragili, duttili e visco-plastiche sia in ammasso che lungo bande e piani di taglio); (*vii*) ammassi rocciosi intensamente fratturati e deformati (non completamente disturbati, con struttura originaria ancora riconoscibile, a meno che nelle zone di taglio); (*viii*) presenza di frane secondarie e grandi collassi di versante (in tutto o in parte del versante).

ABSTRACT

Deep-Seated Gravitational Slope Deformations (DSGSDs) are complex, slope-scale, gravity-driven phenomena, which are placed between landslide movements *s.s.* and gravitational tectonics. These processes, which develop over very long time periods, are considerably relevant both for the remarkable influence on the evolution of hillslope morphology and for risk associated with the induced deformations and the possible evolution into catastrophic landslides. A large number of studies on DSGSDs was produced in the scientific literature; the lack of a widely recognized classification, together with the great variability of shapes and characteristics, have led to the development of numerous terminologies and definitions, which make the approach to these phenomena particularly complex. Despite this, it is possible to identify some fundamental characteristics, both in terms of kinematic mechanisms and induced morphological elements and of controlling factors and possible evolution. In more recent years, some studies highlighted the relevance of the elevated spatial and temporal scales that feature DSGSDs, with specific reference to the time-dependent rheology regulating the deformation of rock masses as a prominent distinctive feature of such processes. This study describes the current state of the art, starting from both the numerous works present in the literature and specialized review articles aimed at individual aspects of these phenomena. The work is developed in order to describe both the history of scientific progress in this field and all the main aspects that characterize the phenomena in question, both in terms of intrinsic characteristics and in relation to the control factors and possible evolution. Through the analyzes of literature data, indications are given on the space-time scale and on the characteristics that allow to distinguish DSGSDs from other gravitational phenomena.

Keywords: *DSGSDs, sackung (sagging), classification, nomenclature, kinematics, morphological features, rock mass rheology, creep*

INTRODUCTION

The term Deep-Seated Gravitational Slope Deformations (DSGSDs *Auct.*) refers to a set of slow and complex deformational processes driven by gravity, which involve entire slopes (or large portions of them) over long time intervals (Dramis & Sorriso-Valvo, 1994; Agliardi *et alii,* 2012). These phenomena take place in a wide variety of morpho-structural conditions (Fig. 1) and are characterized by typical morphological features (e.g., double ridges, ridge top depressions, trenches, scarps, counterscarps, tension cracks, toe bulging) generally distributed along the entire ridge-slope-valley floor system (Radbruch-Hall, 1978; Bovis, 1982; Savage & Varnes, 1987; Agliardi *et alii*, 2001, 2012; Jaboyedoff *et alii*, 2013; Esposito *et alii,* 2014; Discenza *et alii,* 2021).

Some Authors refer to these processes with different names, such as Slope Tectonics (ST – Jaboyedoff *et alii*, 2011), Mass Rock Creep (MRC – Radbruch-Hall, 1978; Chigira, 1992) or Rock Slope Deformation (RSD – Hungr *et alii,* 2014; Jarman & Harrison, 2019). These terms have the advantage of not referring to the binding concept of depth, rather emphasizing the importance of stress fields and related deformations (as in the case of ST), implying high spatial scales, or the mechanical behavior (as in the case of MRC), implying significant temporal scales. In this study, for uniformity, reference will be made to the term DSGSD as it is more widespread in the international scientific literature, while stressing that the different terms are interchangeable.

DSGSDs involve large rock masses, with thickness of many tens or hundreds of meters (Pánek & Klimeš, 2016) and have dimensions comparable with those of the entire slope or ridges (Agliardi *et alii,* 2001; Jaboyedoff *et alii,* 2013). Generally, these phenomena are characterized by very small deformation rates if compared with their dimensions (Dramis & Sorriso-Valvo, 1994), in the order of mm per years (Varnes *et alii,* 1990; Agliardi *et alii,* 2001; Ambrosi & Crosta, 2006; Agliardi *et alii,* 2012; Jaboyedoff *et alii,* 2013; Pánek & Klimeš, 2016; Della Seta *et alii,* 2017).

Large-scale deformational processes often show characteristics similar to purely tectonic ones (Agliardi *et alii,* 2012) and, in general, there is no clear and well-defined limit between the two processes (Jaboyedoff *et alii,* 2011, 2013). As in the case of tectonics, slope deformations can also induce both brittle and ductile deformations in the involved rock masses, such as folds, faults, and shear zones (Zischinsky, 1969; Nemčok *et alii*, 1972; Mahr & Nemčok, 1977; Fleming & Johnson, 1989; Chigira, 1992; Braathen *et alii*, 2004). Gravity-induced features can be extended and linear if set on pre-existing tectonic lineaments, but generally they are less persistent than tectonic ones, with more arcuate shape and peculiar assemblage along the slope (Radbruch-Hall, 1978; Agliardi *et alii*, 2012).

As a distinctive element among landslides and DSGSDs, both the lack of a continuous sliding surface or basal shear zone (Dramis & Sorriso-Valvo, 1994) and the absence of continuous and well-defined external boundaries (Agliardi *et alii*, 2001; Jarman, 2006; Agliardi *et alii,* 2012; Crosta *et alii*, 2013; Jarman & Harrison, 2019) have been considered. Some authors suggested the use of the size of phenomena (Sorriso-Valvo, 1984, 1995; Jaboyedoff *et alii,* 2011; Hungr *et alii,* 2014). The complexity in the identification of peculiar characteristics (recognizable and quantifiable) makes it difficult to choose a single element as distinctive (and specific) of DSGSDs with respect to conventional landslides and gravitational tectonics. Much more reasonable is to distinguish these different phenomena by using more than one element, as described below. Among these

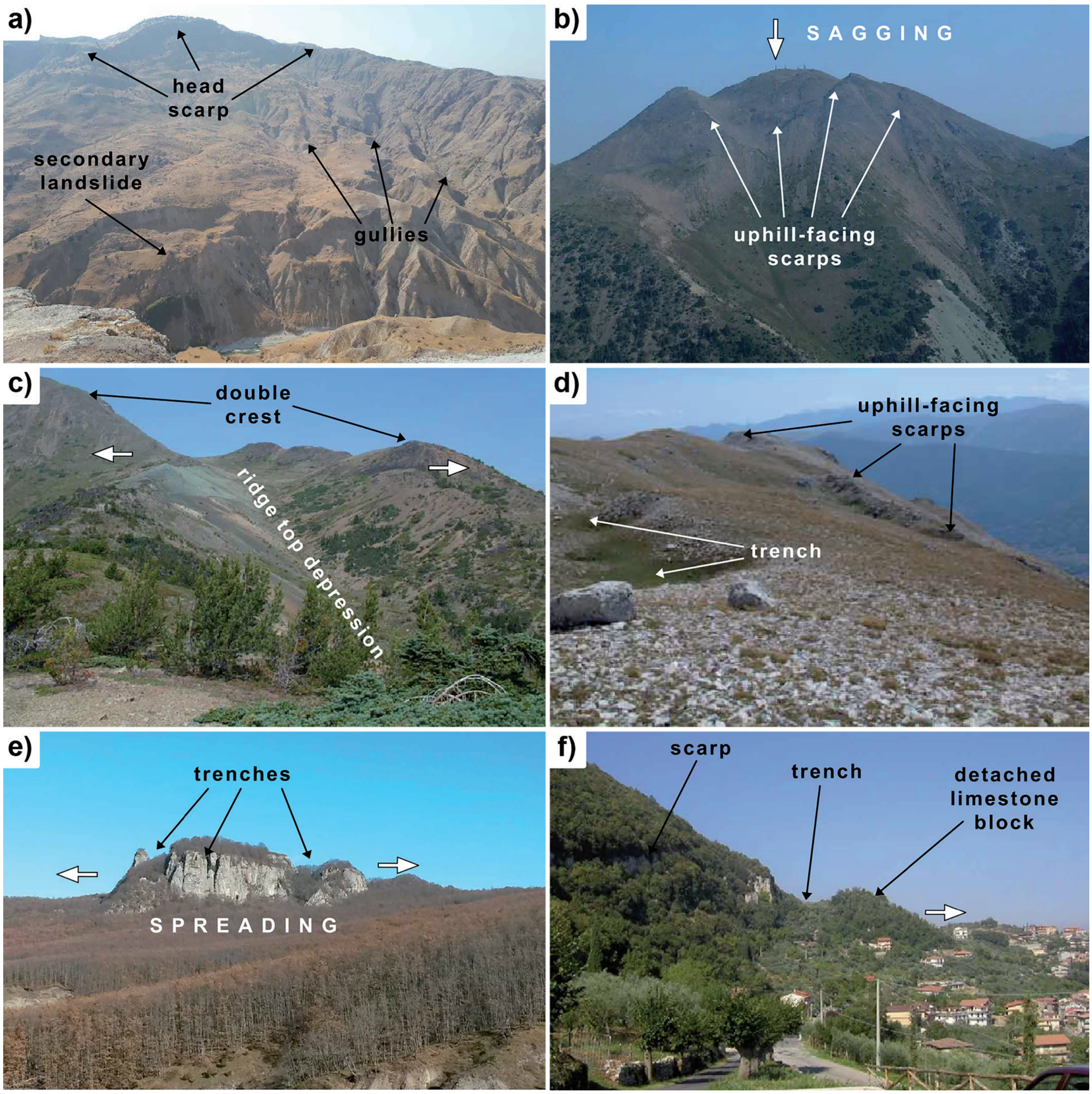

Fig. 1 - Typical examples of DSGSDs and related morphological features: a) frontal view of the gravitational slope deformation at Siah, Zagros Mountains, Iran (photo courtesy of Dr. Michele Delchiaro); b) double-sided sackung, marked by uphill-facing scarps, at Mission Ridge, Pacific Coast Mountains, Canada; c) double crest related to DSGSD at Mission Ridge, Pacific Coast Mountains, Canada; d) trenches and uphill-facing scarps at Maiella Mountain, Central Apennines, Italy; e) spreading phenomenon and related trenches at Sasso Simone, Northern Apennines, Italy; f) lateral spread of thrust front at Sgurgola, Central Apennines, Italy

factors, the high spatial and temporal scales on which DSGSDs act assume particular importance, as a consequence of time-dependent rheology of the involved rock often featuring these processes (Martino *et alii,* 2017).

DSGSDs represent a very important geomorphological element, both from the scientific point of view and for the possible implications in terms of social and economic impact (Záruba & Mencl, 1969; Dramis & Sorriso-Valvo, 1994; Pánek & Klimeš, 2016; Martino *et alii*, 2020). In fact, in addition to the large-scale influence on the morphological elements of the landscape, they determine the development of many secondary landslides at the more local scale. They also produce significant interferences with the anthropic structures and infrastructures present in the territory (Discenza *et alii,* 2011; Frattini *et alii*, 2013). Critically, these phenomena present a catastrophic evolution and can evolve into large landslides, such as fast and highly-dangerous rock avalanches (Hungr & Evans, 2004; Evans *et alii*, 2006; Chigira *et alii,* 2010).

Considering the terminological and sometimes substantial differences existing in the scientific literature for the definition of these processes, this paper aims at constructing an updated state of the art (review), which provides a starting point for discussion and the construction of a comprehensive and uniform classification scheme. This study also summarizes all the main aspects concerning large-scale gravitational deformations and the related reference bibliography. It tries to describe all the various aspect that contribute to the definition of these processes, such as nomenclature, diffusion, types, kinematic mechanisms, and morphological characteristics, thus pointing out at the same time the different definitions and the common aspects.

After providing the updated state of the art on this specific topic, this paper discusses the key principles in order to suggest possible criteria for terminological unification in view of a comprehensive DSGSDs classification. Finally, key criteria for the differentiation between slope-scale gravitational phenomena and conventional landslides or gravitational tectonics are suggested. Figure 2 shows the number of papers considered in this work per decade of publication. Although the reported works are not exhaustive of all the existing scientific literature regarding DSGSDs, the graph nevertheless demonstrates the increase of interest on this topic over time. However, the large number of existing papers and the vast amount of published data are not exhaustive of all the characteristics of DSGSDs, the scale factors that characterize them, and of the various elements that make it possible to identify these phenomena.

NOMENCLATURE AND EXISTING CLASSIFICATIONS

Over the years, many terms and definitions were used by several authors to describe the phenomena acting on large space-time scales, which can be considered as complex, or sometimes multiple, processes deriving from the mutual interaction of many mechanisms of movement (Cancelli & Casagli, 1995). Most of them show a local character and are used in relation to the researcher's geographical interest area. In many cases, specific terms were coined for this type of phenomena, while in other cases the typical nomenclatures of conventional landslides were adopted.

Terms and nomenclature

The term Deep-Seated Gravitational Slope Deformation was introduced by Malgot (1977), while the acronym DSGSD was introduced much later, especially on the basis of the studies of Dramis & Sorriso-Valvo (1994) and Agliardi *et alii* (2001). Although this term (and its acronym) has now become commonplace, numerous other definitions are still used to describe these phenomena.

The term *sackung* (Zischinsky, 1966, 1969), in plural *sackungen*, was introduced to indicate instability phenomenon characterized by deformation mainly concentrated along a discrete sliding surface, which does not extend continuously below the moving mass. This deformational process, widespread in jointed rock masses, were described by other authors using terms such as gravitational creep (Nemčok, 1972; Ter-Stepanian, 1974; Malgot, 1977; Radbruch-Hall, 1978), deep

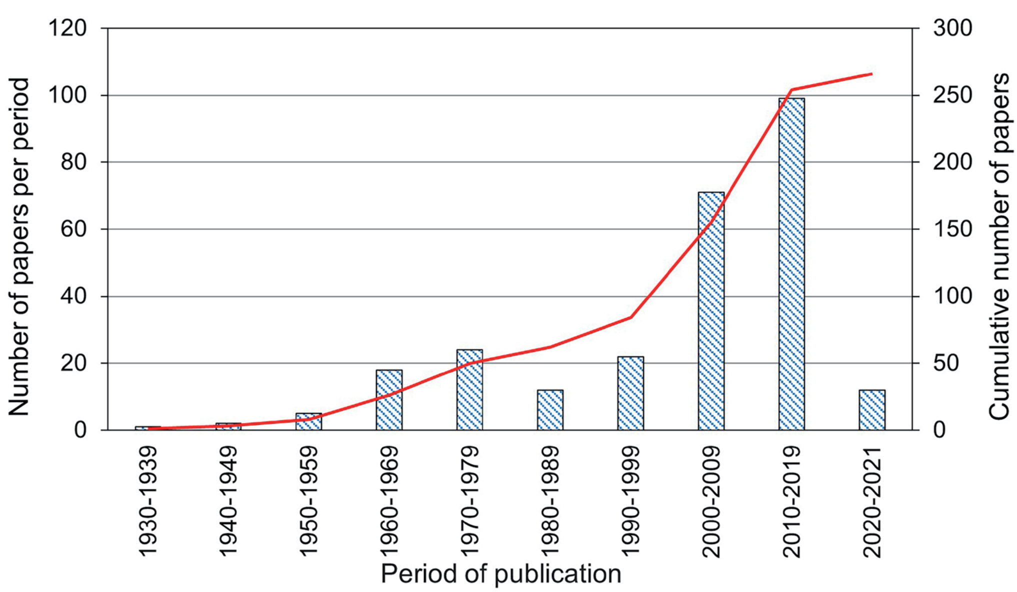

Fig. 2 - Published works on DSGSDs cited in this paper, divided according to the period of publication

seated deformation (Terzaghi, 1962), deep seated creep (Ter-Stepanian, 1966; Nemčok *et alii*, 1972; Mahr & Nemčok, 1977; Hutchinson, 1988), mass rock creep (Radbruch-Hall, 1978; Chigira, 1992), sagging (Kobayashi, 1956; Hutchinson, 1988), and rock flow (Varnes, 1978; Savage & Varnes, 1987; Cruden & Varnes, 1996; Dikau *et alii*, 1996).

For a phenomenon with similar morphological characteristics but mainly produced by large-scale block toppling, other authors introduced terms such as block toppling and flexural toppling (Goodman & Bray, 1976; Bovis, 1982; Nichol *et alii*, 2002; Reitner & Linner, 2009). This same phenomenon is also termed T-sagging (Hutchinson, 1988), because of the characteristics in common with the other phenomena previously described.

The term lateral spreading (Jahn, 1964; Radbruch-Hall *et alii*, 1976; Varnes, 1978; Cancelli & Casagli, 1995; Cruden & Varnes, 1996) is used to indicate a deformational process with predominantly horizontal movement, that commonly affect jointed rigid slabs superimposed on more ductile materials, such as clays and silts. If the deformational phenomenon involves only rock masses, it can be described as rock spreading (Jahn, 1964; Beck, 1968) or rock mass spreading (Martino *et alii*, 2004; Discenza *et alii,* 2011).

The terms of block slide (Voight, 1973; Záruba & Mencl, 1982), block-type movement (Nemčok *et alii*, 1972; Pašek, 1974; Záruba & Mencl, 1976; Pašek & Košťák, 1979; Nemčok, 1982; Hutchinson, 1988), block glide (Voight, 1973), back tilting (Záruba & Mencl, 1982) or *gleitung* (Zischinsky, 1966, 1969) have been used to describe a deformational process characterized by movements along pre-existing, or newly formed discontinuities. This phenomenon, especially in Italian literature, is also referred to rock block slide (Esposito *et alii,* 2007).

Other terms used to describe deformational phenomena as a function of the effects produced on the slope system, such as cambering and valley bulging (Hollingworth *et alii,* 1944; Hutchinson, 1968; Horswill *et alii,* 1976; Záruba & Mencl, 1982; Hutchinson, 1988; Parks, 1991) and deep seated distortion of steep-sided ridges (Varnes *et alii,* 1989). Finally, there are terms that identify phenomena in relation to the structural setting of the relief, such as lateral spread of thrust front (Dramis & Sorriso-Valvo, 1994).

Existing classifications of mass movements

Since the second half of the 1900s, many studies proposed different classifications of landslides and slope movements. Most of them focus on the classification of conventional landslides (at least in terms of size), although some of them reported indications on large-scale gravitational phenomena (Hungr *et alii*, 2014 and reference in therein). Given the large number of classifications of slope phenomena present in literature, only the most important ones for the study of DSGSDs are reported below.

In the well-known versions of the classification of Varnes (1954, 1978), as well as in the review of Cruden & Varnes (1996), large-scale gravitational deformations do not have their own dedicated space. However, they can be included in some categories of landslides *s.s.* by considering analogies in terms of involved material and deformation mechanism (i.e., rock flow and rock spreading). The first term is focused on rather deep phenomena and, therefore, it is often used to describe DSGSDs.

In the classification of Hutchinson (1968, 1988), some large-scale slope processes find a specific denomination. For example, the typology of sagging, introduced in the second version (Hutchinson, 1988), is often used to classify large-scale deformational processes. Within this classification system, other terms that can be used to describe a DSGSD are creep, slide (or landslide), and complex slope deformation (e.g., cambering and valley bulging and block-type movement), some in part already included in the first classification version (e.g., creep, slide, and cambering and valley bulging).

In parallel, Záruba & Mencl (1969) developed a first classification of the gravitational slope processes. In this work, the gravitational movements are divided into four categories mainly related to the geological features of the slope (i.e., slope movement of superficial deposits, slide in pelitic rocks, slope movement involving solid rock, special kind of slope movement which constitute important geological phenomena in particular countries). In this case, large-scale gravitational deformations fall mainly in the category of slope movement involving solid rock and, only partially, in the slide in pelitic rocks.

In the Alpine sectors, Nemčok *et alii* (1972) developed a classification of landslide movements into four main types (i.e., creep, sliding, flow, fall), which in turn can be divided into further groups according to the local geological, morphological, and climatic conditions. In this study is defined a class (i.e., creep) in which large-scale gravitational processes, with limited deformation rates up to a few centimeters per year, can be included. In the case that the material undergoes an evident acceleration, the creep passes into one of the other three categories of landslides *s.s.* (i.e., sliding, flow or fall).

In Italy, Sorriso-Valvo (1984) proposed a classification for the distinction between superficial landslide movements, deep gravitational deformations and gravitational tectonics. At each scale, three types of movement are identified (i.e., lateral spreading, sliding, and flow). The classification was revised a decade later (Sorriso-Valvo, 1995); it kept intact the general framework and the distinctions in three class, even if the aspects related to the scale factors and the influence of the relief morphology were integrated.

A few years later, Hutchinson (1995) proposed a specific classification for deep gravitational movements by suggesting some geometric parameters (and relative limits) for the distinction between deep slips and intermediate thickness landslides. In his work, a brief review of the main types of deep gravitational movements (i.e., deep-seated creep, sagging, toppling, block-type movement, cambering and valley bulging, deformation on plateau edges formed by a rigid tabular, jointed rock stratum overlying argillaceous strata) is also proposed. Furthermore, the deep phenomena were divided into diastrophic (tectonic) and non-diastrophic (gravitational tectonics and gravitational).

In recent years, the Varnes classification was revised by Hungr *et alii* (2014), that introduce the slope deformations as an integration of the previous types of movements, dividing them in turn into mountain slope deformation and rock slope deformation. In the version of Hungr *et alii* (2014), despite the addition of a typology, large-scale gravitational deformations can fall either in slope deformation (e.g., sackung given the elimination of rock flow) or in the different landslide categories (i.e., spreading, sliding, and flexural toppling).

BASICS OF DSGSDs

The distribution over time of published papers on DSGSDs and considered in this work is shown in Fig. 2. The study of large-scale gravitational phenomena began in the 1930s (Heim, 1932) and the following two decades (Stini, 1941; Van Bemmelen, 1950; Stini, 1952; Kobayashi, 1956). In the 1960s there was a moderate increase in the number of publications on these phenomena (Terzaghi, 1962; Von Engelen, 1963; Jahn, 1964; Haefeli, 1965; Nemčok, 1966; Ter-Stepanian, 1966; Zischinsky, 1966; Ferguson, 1967; Beck, 1968; Knill, 1968; Mencl, 1968; Nemčok & Rybář, 1968; Pašek, 1968; Nemčok & Pašek, 1969; Záruba, 1969; Záruba & Mencl, 1969; Zischinsky, 1969).

Later, a significant growth of research on DSGSDs occurred in the 1970s, as highlighted by Crosta (1996). In this period, in addition to a large number of studies on the characteristics of phenomena (Tabor, 1971; Nemčok, 1972; Nemčok *et alii*, 1972; Feda, 1973; Radbruch-Hall *et alii,* 1976; Záruba & Mencl, 1976; Mahr, 1977; Mahr & Nemčok, 1977; Radbruch-Hall *et alii*, 1977; Radbruch Hall, 1978; Varnes, 1978; Guerricchio & Melidoro, 1979), the first modellings were also conducted (Košťák, 1977; Emery, 1978). A complete discussion of the history of studies on DSGSDs, especially up to the mid- 1990s, has been provided by Crosta (1996).

Since the end of the last century, the growth of new technologies (e.g., interferometry, GPS, geotechnical monitoring) has led to numerous studies that focus on the monitoring of large-scale gravitational deformations and the analysis of their deformation rates (Ambrosi & Crosta, 2006; Moro *et alii,* 2007; Barla *et alii*, 2010; Agliardi *et alii,* 2012; Frattini *et alii*, 2013; Agnesi *et alii*, 2015; Di Martire *et alii*, 2016; Amato *et alii,* 2018; Cappadonia *et alii*, 2019; Teshebaeva *et alii,* 2019; Crippa *et alii*, 2020). The monitoring data can also be used to define the state of activity and the type of movement (Frattini *et alii*, 2018). In this regard, Pánek & Klimeš (2016) described the studies concerning monitoring and the dating of DSGSDs to analyze the time-dependent behavior.

Although the first numerical modellings of DSGSDs were carried out in the 1970s (Emery, 1978) and in the period between the 1990s and 2000s (Pritchard & Savigny, 1991; Crosta & Berto, 1996; Agliardi *et alii*, 2001; Martino *et alii,* 2004; Kinakin & Stead, 2005; Maffei *et alii,* 2005; Apuani *et alii*, 2007; Esposito *et alii*, 2007; Bachmann *et alii*, 2009; Chemenda *et alii*, 2009), only in recent years the models have significantly contributed to the study and understanding of these phenomena (Ambrosi & Crosta, 2011; Bianchi Fasani *et alii,* 2011; Discenza *et alii,* 2011; Bozzano *et alii*, 2012; Leith, 2012; Hou *et alii,* 2014; Bozzano *et alii,* 2016; Makowska *et alii,* 2016; De Blasio & Martino, 2017; Della Seta *et alii*, 2017; Bois *et alii*, 2018; Agliardi *et alii,* 2019; Alfaro *et alii*, 2019). In parallel, other methods were also used for the study of large-scale gravitational deformations, such as small-scale physical modelling (Košťák, 1977; Bachmann *et alii,* 2004; Chemenda *et alii*, 2005; Bachmann *et alii*, 2006; Bois *et alii,* 2008, 2012; Bozzano *et alii,* 2013; Bretschneider *et alii*, 2013; Del Ventisette *et alii,* 2015; Discenza *et alii,* 2020).

DSGSDs diffusion

Starting from the first studies, a large amount of DSGSD phenomena were identified and analyzed all over the world, as can be observed from the map (Fig. 3) produced by Pánek & Klimeš (2016). In the following sections, only few examples are reported; for any further information reference is made to specialized studies in the various geographical areas.

In recent years, cases of DSGSDs were analyzed in Alaska (McCalpin *et alii*, 2011; Newman, 2013), Alberta (Jaboyedoff *et alii*, 2009), Andalusia (Alfaro *et alii*, 2019), Andes (Vilímek *et alii,* 2007; Audemard *et alii,* 2010; García-Delgado, 2020), Carpathians (Hradecký & Pánek, 2008; Pánek *et alii*, 2011), China (Deng *et alii,* 2000; Chigira *et alii,* 2010), Ethiopian Highland (Mège *et alii,* 2013), Himalaya (Thuro *et alii,* 2004), Iceland (Coquin *et alii*, 2015), Japanese Alps (Chigira, 2009; Chigira *et alii*, 2013a), New Zealand (Korup, 2006a), Norway (Schleier *et alii*, 2016; Vick *et alii,* 2020), Pacific Coast Mountains (Bovis & Evans 1996; Kinakin & Stead, 2005), Pamir-Alaj (Teshebaeva *et alii,* 2019), Pyrenees (Gutiérrez-Santolalla *et alii,* 2005; Lebourg *et alii,* 2014), Rocky Mountains (Varnes *et alii*, 1990; McCalpin & Irvine 1995), and Tien Shan Mountains (Tibaldi *et alii*, 2015).

The European Alps are certainly among the most studied places: many cases have been studied in Italy (Agliardi *et alii,*

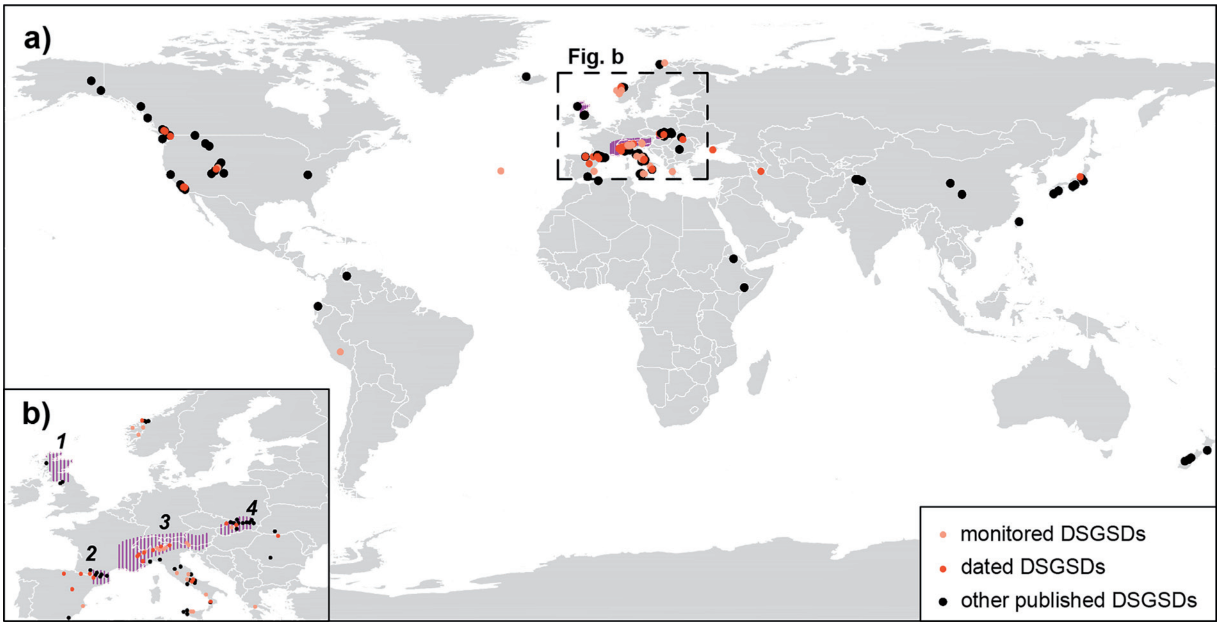

Fig. 3 - Distribution of key DSGSDs in the world, especially cases from studies published since 1990s (redrawn from Pánek & Klimeš, *2016): a) worldwide context; b) detailed view of Europe. The numbered hatched regions contain published databases of DSGSDs from: 1) Scottish Highland (*Jarman, *2006); 2) Eastern Pyrenees (*Jarman *et alii, 2014); 3) European Alps (*Crosta *et alii, 2013); 4) Western Carpathians (*Nemčok, *1982;* Alexandrowicz & Alexandrowicz, *1988)*

2001; Ambrosi & Crosta, 2006; Apuani *et alii*, 2007; Cadoppi *et alii*, 2007; Agliardi *et alii*, 2009; Ambrosi & Crosta, 2011; Ghirotti *et alii*, 2011; Martinotti *et alii*, 2011; Tamburini *et alii,* 2015), France (Hippolyte *et alii,* 2006; Bois *et alii,* 2008; El Bedoui *et alii*, 2009; Hippolyte *et alii*, 2012; Jomard *et alii*, 2014), Austria (Madritsch & Millen, 2007; Imre *et alii*, 2009; Baroň *et alii*, 2016), and Switzerland (Barbarano *et alii*, 2015; Pedrazzini *et alii*, 2016; Agliardi *et alii,* 2019). Many detailed studies have been performed in the Italian Apennines (Di Luzio *et alii,* 2004b; Martino *et alii,* 2004; Maffei *et alii,* 2005; Galadini, 2006; Esposito *et alii*, 2007; Moro *et alii,* 2009; Discenza *et alii,* 2011; Bozzano *et alii,* 2013; Bianchi Fasani *et alii*, 2014; Esposito *et alii,* 2014; Gori *et alii*, 2014; Della Seta *et alii*, 2017; Mariani & Zerboni, 2020; Martino *et alii*, 2020; Esposito *et alii*, 2021), and in the Calabrian Arc (Guerricchio *et alii*, 1996; Tansi *et alii,* 2005; Pellegrino & Prestininzi, 2007; Bonci *et alii,* 2010; Bretschneider *et alii,* 2013), which like all recently raised areas are characterized by numerous gravity-induced gravitational deformations (Martino *et alii*, 2004; Esposito *et alii*, 2014).

Some databases specifically dedicated to or containing also DSGSDs were created for areas of Europe, such as British Mountains (Jarman & Harrison, 2019), Eastern Pyrenees (Jarman *et alii,* 2014), European Alps (Agliardi *et alii*, 2012; Agliardi *et alii*, 2013; Crosta *et alii*, 2013; Pedrazzini *et alii*, 2016), Scottish Highland (Jarman, 2006), Sicily (Agnesi *et alii*, 2000; Di Maggio *et alii*, 2014), and Western Carpathians (Nemčok, 1982; Alexandrowicz & Alexandrowicz, 1988; Pánek *et alii,* 2017, 2019). Others were made for different parts of the world, such as Japan (Kaneda & Kono, 2017), New Zealand (McLean *et alii*, 2015), Patagonian Andes (Pánek *et alii,* 2021), and Taiwan (Tsou *et alii,* 2015).

In addition to Earth, DSGSDs were recognized on other planets of the Solar System, such as Mars (Mège & Bourgeois, 2011; Guallini *et alii*, 2012; Gourronc *et alii,* 2014; Makowska *et alii*, 2016; De Blasio & Martino, 2017; Crosta *et alii*, 2018; Kromuszczyńska *et alii*, 2019; Discenza *et alii*, 2021). Like terrestrial counterparts, Martian gravitational deformations are characterized by geomorphic features similar to those common on the Earth (Mège & Bourgeois, 2011; Gourronc *et alii*, 2014), but have significantly larger dimensions, at least one order of magnitude higher (Kromuszczyńska *et alii*, 2019). The state of the art and the complete review of the Martian DSGSDs is reported in Discenza *et alii* (2021).

Mechanisms and controlling factors

The onset and the development of DSGSDs are closely related to specific geological-structural, geomorphological, and geomechanical conditions (Agliardi *et alii*, 2001; Di Luzio *et alii*, 2004b; Agliardi *et alii,* 2012; Esposito *et alii*, 2014; Mariani & Zerboni, 2020), that directly influence the kinematics of the processes (Pánek & Klimeš, 2016). The works by Crosta (1996), Jaboyedoff *et alii* (2011), and Agliardi *et alii* (2012), with their related bibliography, provides a complete discussion of the topic.

Without prejudice to the complexity of the phenomena and the absence of a univocal classification, it is possible to divide the DSGSDs into two large macro-categories: sackung and spreading (Fig. 4). The sackung is characterized by a significant vertical component of the deformation in the upper part of the slope, which is also associated with horizontal displacements in the middle-lower portion of the relief (Zischinsky, 1966; Hutchinson, 1988; Agliardi *et alii*, 2012). The spreading is characterized by a prevalent horizontal component (Jahn, 1964; Varnes, 1978). From a morphological and kinematic point of view, further types of deformations, such as toppling and sliding, can be included in the macro-category of sackung, while rock block slide can be included in spreading (Hutchinson, 1988; Hungr *et alii*, 2014).

Sackung typically occurs in mountainous areas and slopes characterized by the presence of jointed rock masses (Agliardi *et alii*, 2012). In these cases, inherited structures such as faults, folds, bedding planes, and joints strongly control the process (Chigira, 1992; Agliardi *et alii,* 2001; Bianchi Fasani *et alii,* 2004; Scarascia Mugnozza *et alii*, 2006a; Brideau *et alii,* 2009; Reitner & Linner, 2009; Jaboyedoff *et alii,* 2013; Esposito *et alii*, 2021). The role played by pre-existing structures on the evolution of DSGSDs was demonstrated by several studies, that highlighted not only the importance of main bedrock anisotropies acting as preferential weakness planes (or zones) for the movement to occur, but also the implications in terms of overall geomechanical properties of the material at the slope scale (Ambrosi & Crosta, 2006; Brideau *et alii*, 2009; Jaboyedoff *et alii*, 2009; Ambrosi & Crosta, 2011; El Bedoui *et alii*, 2011; Bozzano *et alii,* 2012; Makowska *et alii,* 2016; Della Seta *et alii*, 2017).

Sackung is mainly controlled by time-dependent deformations (Ter-Stepanian, 1966; Zischinsky, 1969; Nemčok, 1972; Mahr, 1977; Mahr & Nemčok, 1977; Radbruch-Hall, 1978; Savage & Varnes, 1987; Chigira, 1992; Martino *et alii*, 2004; Apuani *et alii*, 2007; Esposito *et alii,* 2007; Discenza *et alii*, 2011; Bozzano *et alii*, 2012, 2016; Della Seta *et alii,* 2017), which are spread over very long time intervals (Dramis & Sorriso-Valvo, 1994; Agliardi *et alii,* 2012, 2013; Della Seta *et alii*, 2017), i.e. up to hundreds of thousands years. The deformation of rock mass occurs mainly for viscous deformations connected to deep creep phenomena (Ter-Stepanian, 1966; Zischinsky, 1966; Feda, 1973; Mahr, 1977; Radbruch-Hall, 1978; Savage & Varnes, 1987; Hutchinson, 1988; Chigira, 1992), even if there are ductile and visco-plastic deformations along shear planes and sliding surfaces (Agliardi *et alii,* 2001; Ambrosi & Crosta, 2006; Jaboyedoff *et alii,* 2013).

Creep phenomena are driven by various factors, such as the mechanical and rheological characteristics of the involved rocks, the structural setting of the relief, and the jointing state of rock masses (Chigira, 1992; Ambrosi & Crosta, 2011; Jaboyedoff *et alii,* 2013; Martino *et alii,* 2017; Discenza *et alii,* 2020). Local the weathering, especially of igneous and metamorphic rocks, can play an important role in the deterioration of the mechanical properties and in the variation in viscosity of rock masses (Genevois & Prestininzi, 1979; Prestininzi, 1984; Pellegrino & Prestininzi, 2007; Bozzano *et alii,* 2012). As demonstrated by Discenza *et alii* (2020), the rock mass jointing condition and the geometrical characteristic of the discontinuities greatly influence the rheological properties of the deformed masses and the creep processes.

Spreading, on the other hand, is characteristic of slopes with overlapping of rigid rocks on ductile and highly deformable bedrock (Nemčok *et alii,* 1972; Pašek, 1974; Záruba & Mencl, 1976; Varnes, 1978; Hutchinson, 1988; Agliardi *et alii,* 2012; Bozzano *et alii,* 2013; Pasuto & Soldati, 2013; Di Maggio *et alii*, 2014). This process is essentially controlled by the slope setting, the geometry of the contact between stiff and ductile materials, as well as by the thickness of the rigid rocks (Esposito *et alii,* 2007; Alfaro *et alii*, 2019). In some specific cases spreading can affect jointed rock masses without an evident rheological contrast (Jahn, 1964; Martino *et alii,* 2004; Discenza *et alii,* 2011; Pasuto & Soldati, 2013). This kind of rock mass spreading is strictly related to the stress-strain state of the mass and the unloading stress processes, that favor the expansion of the mass through the formation of sub-vertical deformational bands (Martino *et alii,* 2004; Discenza *et alii,* 2011).

The kinematics of spreading is controlled by slow and deep deformational processes, which determine the expansion of the slope towards the valley floor (Varnes, 1978; Cruden & Varnes, 1996; Pasuto & Soldati, 2013; Hungr *et alii,* 2014). The mass deformation occurs through creep processes and visco-plastic deformations associated with tensile regime, both in rock mass and along discrete planes (Varnes, 1978; Crosta, 1996). Visco-plastic strain develop along sub-vertical bands of deformation decreasing with depth, which do not give rise to continuous shear zone (Jahn, 1964; Martino *et alii,* 2004). Locally, the expansion can also take place through one or more slides with a predominantly horizontal component (Bozzano *et alii*, 2013; Hungr *et alii,* 2014; Bois *et alii,* 2018).

In general terms, the development of DSGSDs is governed by different control factors (Agliardi *et alii*, 2012; Jaboyedoff *et alii,* 2013; Bozzano *et alii,* 2016; Pánek & Klimeš, 2016; Martino *et alii,* 2017): (*i*) inherited and invariant factors (e.g., anisotropies, deformability contrasts, morpho-structural conditions, tectonic elements, karst); (*ii*) factors related to the morpho-dynamics of the relief that induce significant variations of the local stress regime in short to mid-term time spans (e.g., post-glacial debuttressing, river dynamics, erosional processes, changes in water table level, tectonic stresses, earthquakes), if

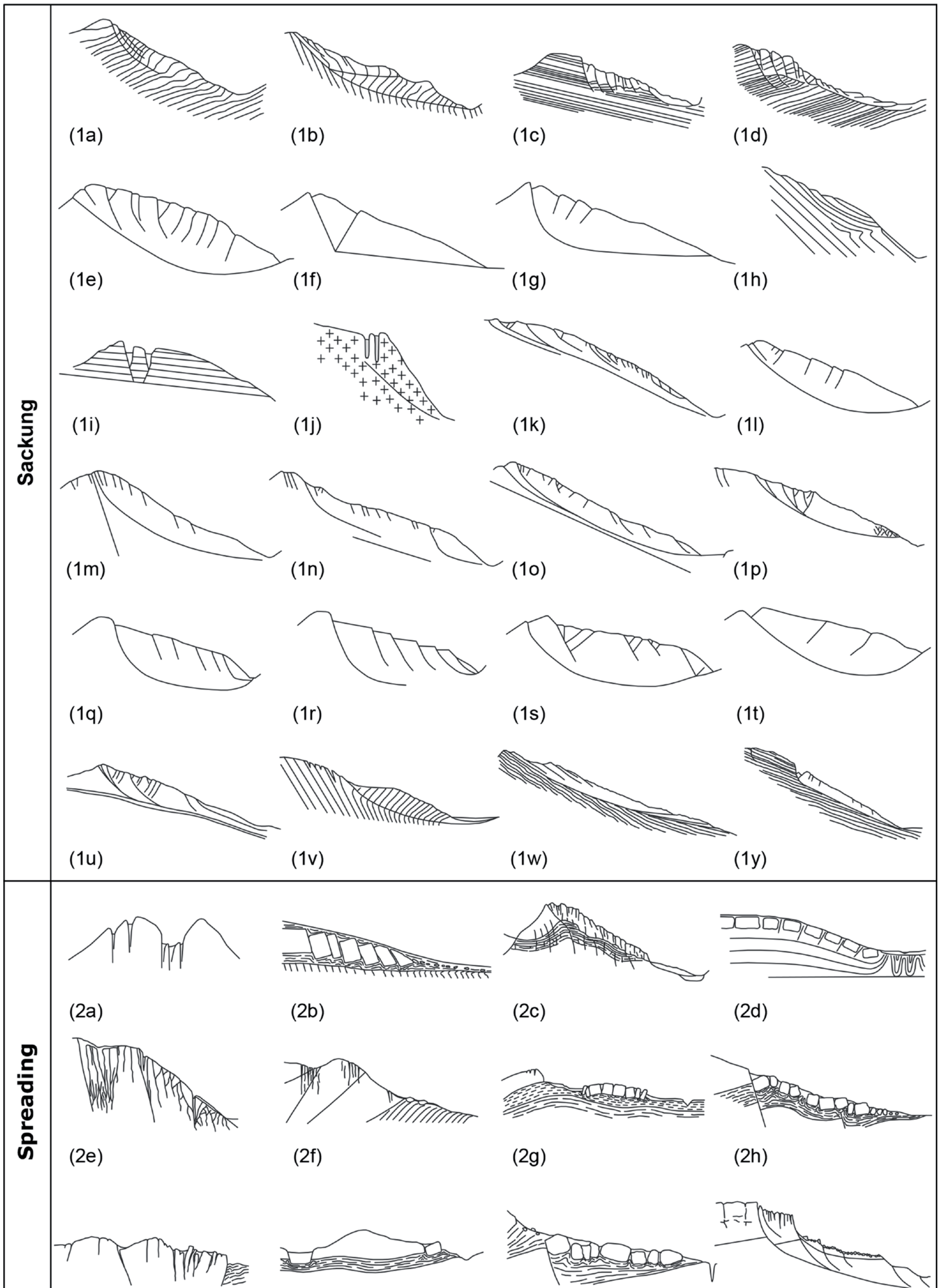

Fig. 4 - Examples of DSGSDs proposed in the literature, divided on the basis of general typology (sackung and spreading) and ordered on the basis of year of publications (modified after Agliardi et alii, 2012). Sackung: (1a), (1b) Zischinsky (1966); (1c), (1d) Nemčok (1972); (1e) Mahr (1977); (1f), (1g) Hutchinson (1988); (1h), (1i), (1j) Chigira (1992); (1k) Agliardi et alii (2001); (1l), (1m), (1n), (1o) Ambrosi & Crosta (2006); (1p) Apuani et alii (2007); (1q), (1r), (1s), (1t) Bois et alii (2008); (1u) Agliardi et alii (2009); (1v) Martino et alii (2020); (1w), (1y) Vick et alii (2020). Spreading: (2a) Jahn (1964); (2b) Záruba & Mencl (1969); (2c) Nemčok (1982); (2d) Hutchinson (1988); (2e) Martino et alii (2004); (2f) Esposito et alii (2007); (2g), (2h), (2i), (2j), (2k) Di Maggio et alii (2014); (2l) Pánek & Klimeš (2016)

compared to the time scale featuring such slope deformational processes. These factors fundamentally control both the development of slope-scale deformational processes and the subsequent evolution of large landslides and slope collapses (Hungr & Evans, 2004; Pánek & Klimeš, 2016; Della Seta *et alii,* 2017; Delchiaro *et alii, 2*019).

Among the inherited and pre-existing factors, the geological-structural and geomechanical conditions described above are of particular importance (Agliardi *et alii,* 2001; Di Luzio *et alii,* 2004b; Agliardi *et alii*, 2012; Esposito *et alii,* 2014; Pánek *et alii,* 2021), in addition to the morphological features of relief (Swolf & Savage, 1986; Amadei *et alii*, 1988; Ambrosi & Crosta, 2011). Tectonic structures such as folds and faults should certainly be included among the most important inherited elements (Chigira, 1992; Crosta & Zanchi, 2000; Agliardi *et alii,* 2001; Bianchi Fasani *et alii,* 2004; Hippolyte *et alii,* 2006; Scarascia Mugnozza *et alii*, 2006a; Brideau *et alii,* 2009; Reitner & Linner, 2009; Ambrosi & Crosta, 2011; Bozzano *et alii*, 2012; Crosta *et alii*, 2013; Jaboyedoff *et alii,* 2013; Stead & Wolter, 2015; Pedrazzini *et alii,* 2016; Martino *et alii,* 2017; Alfaro *et alii,* 2019; Teshebaeva *et alii,* 2019; Mariani & Zerboni, 2020; Vick *et alii,* 2020; Esposito *et alii,* 2021), in addition of course to bedding planes or schistosity with peculiar geometric characteristics (Kieffer, 1998; Ambrosi & Crosta, 2011; Della Seta *et alii,* 2017; Discenza *et alii,* 2020; Vick *et alii,* 2020).

Under particular conditions, large-scale deformational processes can originate from karst of carbonate rocks (Apuani & Corazzato, 2009; Pánek *et alii,* 2009b; Lenti *et alii,* 2012) or from dissolution of evaporitic rocks (Martinotti *et alii,* 2011; Gutiérrez *et alii*, 2012a; Carbonel *et alii*, 2013). In the Italian Apennines there are several examples of DSGSDs related to karst phenomena, such as Mt. Nuria (Martino *et alii*, 2004; Maffei *et alii*, 2005; Casini *et alii*, 2006, Lenti *et alii,* 2012) and Mt. Rocchetta (Discenza *et alii,* 2009, 2011).

The structural and morpho-climatic evolution of the area (Agliardi *et alii,* 2009; Bianchi Fasani *et alii,* 2011; Crosta *et alii,* 2013; Della Seta *et alii,* 2017; Jarman & Harrison, 2019), the topographic and tectonic stresses (Varnes *et alii*, 1989; Crosta, 1996; Ambrosi & Crosta, 2011), the river erosion at the slope toe (Crosta & Zanchi, 2000; Hou *et alii,* 2014; Bozzano *et alii*, 2016; Delchiaro *et alii,* 2019; Esposito *et alii*, 2021), the changes in groundwater level (Agliardi *et alii,* 2001; Jaboyedoff e*t alii,* 2009), and the tectonic deformations (Discenza *et alii*, 2011; Alfaro *et alii,* 2019) must also be considered. Recent studies showed that gravitational slope deformations are quite widespread in tectonically active areas (Crosta & Zanchi, 2000; Agliardi *et alii,* 2009; Ambrosi & Crosta, 2011; Pedrazzini *et alii,* 2016; Teshebaeva *et alii,* 2019) and in correspondence with active faults (Agliardi *et alii,* 2009; Moro *et alii,* 2012; Pánek & Klimeš, 2016). In this case, seismic shaking can represent a real trigger/onset factor for new phenomena (Jibson *et alii,* 2004; Tibaldi *et alii,* 2015) or lead to an acceleration of pre-existing ones (Moro *et alii*, 2007; Amato *et alii*, 2018; Agliardi *et alii*, 2019).

Among the morpho-dynamic processes, glaciation and deglaciation periods often play a significant role and represents one of the main triggering factors of DSGSDs in the alpine environment (Agliardi *et alii,* 2012; Pánek & Klimeš, 2016). Since the first works on glacier withdrawal (Beck, 1968), several studies have linked the development of large-scale gravitational processes with post-glacial effect (Bovis, 1990; McCalpin & Irvine, 1995; Bovis & Stewart, 1998; Ballantyne, 2002; Hippolyte *et alii*, 2006; Jarman, 2006; Agliardi *et alii*, 2009; Hippolyte *et alii*, 2009; McColl *et alii*, 2010; McColl, 2012; Agliardi & Crosta, 2014; Ballantyne *et alii*, 2014; Baroni *et alii*, 2014; Leith *et alii,* 2014; Grämiger *et alii,* 2017; Agliardi *et alii*, 2019; Jarman & Harrison, 2019). Different triggering factors of DSGSDs may be associated to glacier retreat, such as slope debuttressing, glacial rebound, stress redistribution, valleys erosion, changes in slope hydrology, and rock jointing (Ballantyne, 2002; McColl, 2012; Crosta *et alii*, 2013; Ballantyne *et alii*, 2014; Jarman & Harrison, 2019). The role of post-glacial effects in the development of DSGSDs was invoked by several authors even for the gravitational phenomena present on Mars in Valles Marineris (Mège & Bourgeois, 2011; Gourronc *et alii*, 2014; Makowska *et alii*, 2016; Kromuszczyńska *et alii,* 2019).

DSGSDs and related slope failures

DSGSDs represent a risk factor not only for their related induced strain (Záruba & Mencl, 1969; Dramis & Sorriso-Valvo, 1994; Discenza *et alii*, 2011; Frattini *et alii*, 2013; Pánek & Klimeš, 2016) but also for the overcoming of the plasticity threshold in all or part of the slope (Fig. 5). The plasticization can lead the formation of collapses (Evans *et alii,* 2006) featured by different types of landslides *s.s.*: from slow to extremely rapid kinematics (Hungr & Evans, 2004; Pánek & Klimeš, 2016). In particular, catastrophic collapses or massive Rock Slope Failures (RSFs) represent the most important effect for society in terms of risk to life and infrastructures, as they are characterized by high volumes and travel at high speeds (Hungr & Evans, 2004; Evans *et alii*, 2006; Chigira *et alii,* 2010).

The possibility that a gravitational deformation may evolve into a large landslide can be the consequence of several factors such as: (*i*) evolution of the creep processes up to the failure or tertiary creep (Genevois & Prestininzi, 1979; Martino *et alii*, 2017; Discenza *et alii*, 2020); (*ii*) variation of the mechanical characteristics of the mass and strength reduction (Chigira

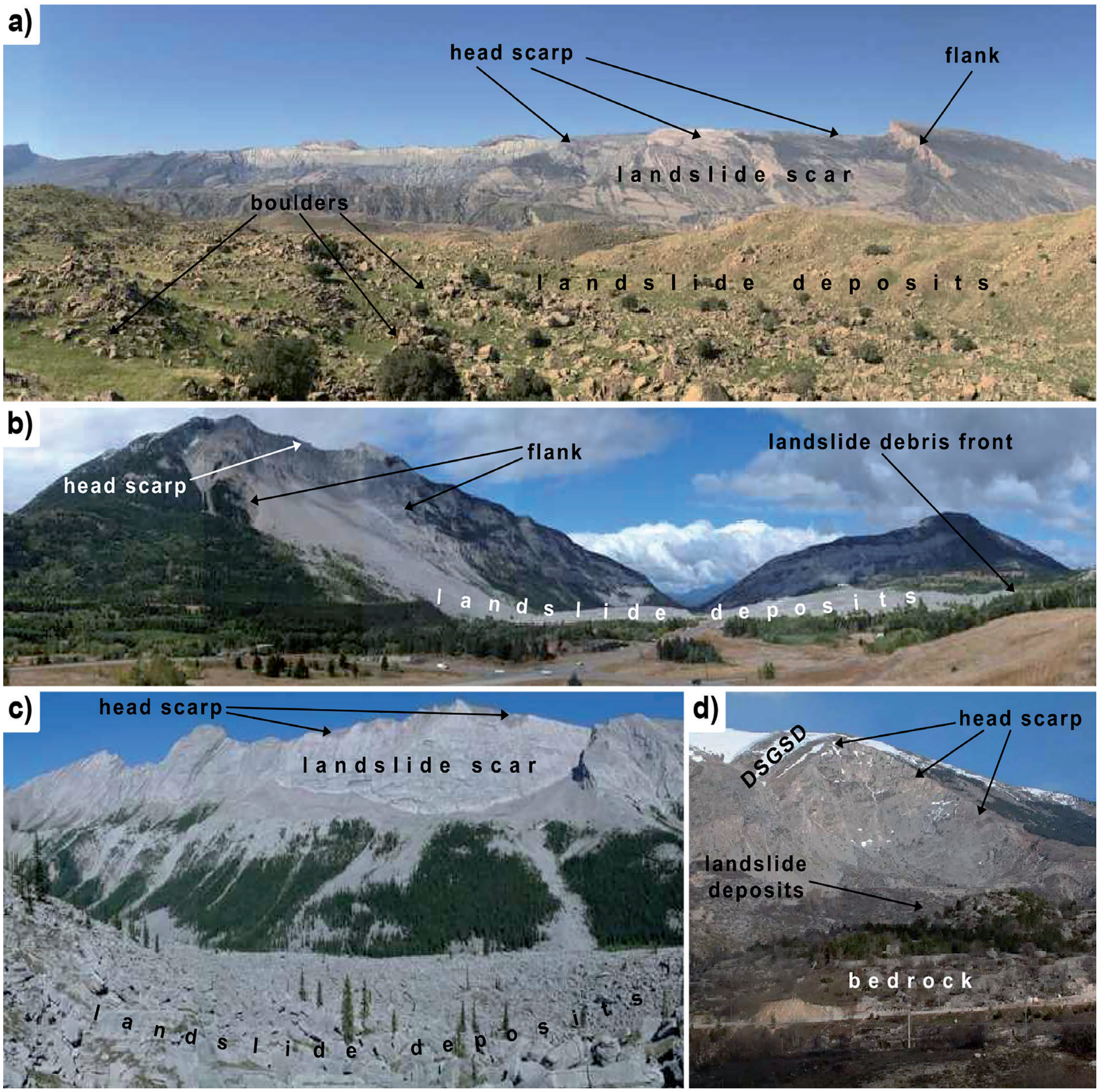

Fig. 5 - Some examples of massive Rock Slope Failures (RSFs) related to DSGSDs evolution: a) the gigantic Seymareh landslide, Zagros Mountains, Iran (photo courtesy of Dr. Javad Rohui); b) the Frank rock avalanche, Turtle Mountain, Canada; c) the Mount Elizabeth rock avalanche, Canadian Rockies, Canada; d) the Scanno rock avalanche, Central Apennines, Italy

& Kiho, 1994; Bisci *et alii*, 1996; Pánek *et alii,* 2009a); (*iii*) modification of slope topography (Wilson *et alii*, 2003; Crosta *et alii,* 2014; Della Seta *et alii*, 2017); (*iv*) sudden changes in the stress condition due to events as earthquakes and extreme rainfalls (Chigira *et alii,* 2010, 2013b; Delchiaro *et alii,* 2019; Francioni *et alii*, 2019).

The large slope collapses that can result from DSGSDs have volumes in the order of tens or hundreds of millions of cubic meters and are characterized by considerable elongations (Evans *et alii*, 2006; Hermanns & Longva, 2012; Hungr *et alii,* 2014; Strom, 2021), up to 30 times the initial height of fall. Heim (1932) defined these phenomena with the term *sturzstrom*, the German equivalent of rock fall stream. This term was later taken up by Hsü (1975), while Howard (1973) and Varnes (1978) define these phenomena as rock-debris flow or rock avalanche.

Recent cases of rock avalanches connected to DSGSDs have been described from different parts of the world (Azzoni *et alii*, 1992; Semenza & Ghirotti, 2000; Crosta, 2001; Crosta *et alii*, 2004; Boultbee *et alii*, 2006; Hewitt *et alii,* 2008; Chigira, 2009; Jaboyedoff *et alii,* 2009; Chigira *et alii,* 2010, 2013b; Crosta *et alii,* 2014; Del Ventisette *et alii,* 2015). More ancient RSFs are also widespread, ranging from the British Mountains (Jarman & Harrison, 2019), Carpathians (Pánek *et alii*, 2009a), Central Andes (Hermanns & Longva, 2012), Eastern Pyrenees (Jarman *et alii*, 2014), European Alps (Korup, 2006b; Pedrazzini *et alii*, 2013), Karakoram Himalaya (Hewitt, 2006), Norway (Blikra *et alii*, 2006; Böhme *et alii,* 2013), Scottish Highland (Jarman, 2006; Ballantyne *et alii*, 2014), Southern Alps of New Zealand (Barth, 2014), Zagros Mountains (Delchiaro *et alii,* 2019), and especially Italian Apennines (Nicoletti *et alii*, 1993; Bianchi Fasani *et alii,* 2004; Di Luzio *et alii,* 2004a; Galadini, 2006; Scarascia Mugnozza *et alii*, 2006a, 2006b; Bianchi Fasani *et alii*, 2014; Esposito *et alii,* 2014; Gori *et alii,* 2014; Antonielli *et alii,* 2020).

MORPHOLOGICAL FEATURES AND DEFORMATIONAL STRUCTURES

The DSGSDs determine the formation of a large number of characteristically elements, both shallow and deep, distributed along the slope, from the ridge top to the valley bottom (Agliardi *et alii,* 2001, 2012; Jaboyedoff *et alii,* 2013).

These elements show different characteristics depending on the type of deformational process, its mechanisms, and the stratigraphical, structural, and geomorphological context of relief (Pánek & Klimeš, 2016). More information on superficial and deep structures of DSGSDs are reported in the papers by Chigira (1992), Agliardi *et alii* (2001, 2012) and Jaboyedoff *et alii* (2013), and the references therein.

Surface features

There are a wide variety of different surface morphological features connected to DSGSDs (Fig. 6), although some are perhaps similar to those of a purely tectonic nature (Jaboyedoff *et alii,* 2013). However, unlike the tectonic-associated features, the geomorphic evidence of DSGSDs show a characteristic distribution along the relief, as well as being less persistent than the tectonic ones, even if they often coincide with them (Agliardi *et alii,* 2001, 2012). In fact, often the existing tectonic structures represent weakness zones exploited and "gravitationally re-activated" by the DSGSD.

At the top of the relief, elements such as double ridges, downhill-facing scarps, normal faults, uphill-facing (or counterslope) scarps, trenches, tension cracks, closed depressions, and grabens are found (Radbruch-Hall *et alii*, 1976; Mahr, 1977; Bovis, 1982; Savage & Varnes, 1987; Chigira, 1992; Dramis & Sorriso-Valvo, 1994; Agliardi *et alii*, 2001; Hürlimann *et alii*, 2006; Agliardi *et alii*, 2009, 2012; Jaboyedoff *et alii*, 2013). At the finer scale, uphill-facing scarps or uphill-facing scarps systems often play an important structural control (Jaboyedoff *et alii*, 2013) and are clear kinematic indicators, in that they represent the junctions between the active and passive blocks of the deformed masses (Hutchinson, 1988).

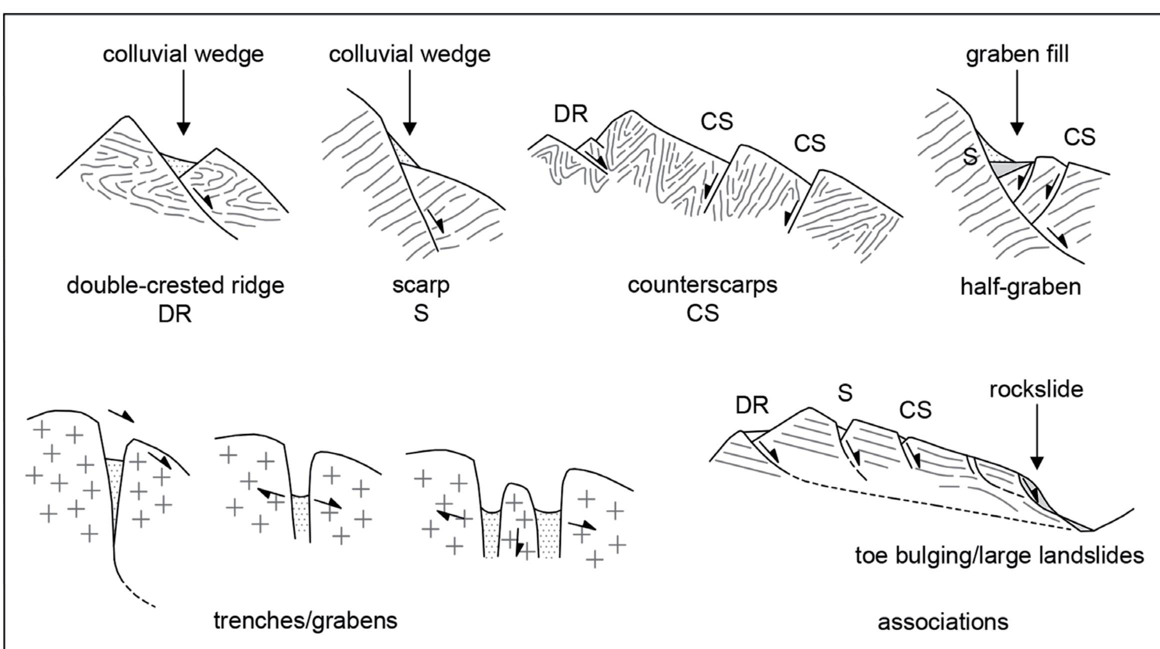

Fig. 6 - Morpho-structural features characteristic of DSGSD phenomena, related kinematic significance, and typical associations (redrawn after Agliardi *et alii, 2012)*

In the middle portion of the slope, numerous morphological structures of transition between the upper and the lower part are found, such as scarps, uphill-facing scarps, trenches, tension cracks, and grabens (Zischinsky, 1969; Savage & Varnes, 1987; Chigira, 1992; Agliardi *et alii,* 2001, 2012; Jaboyedoff *et alii,* 2013). The morphological elements are either newly-generated or set on the pre-existing discontinuities. The flanks of the deformation can frequently coincide with tributary streams (Agliardi *et alii*, 2012) or normal faults (Jaboyedoff *et alii,* 2013). In the case of slopes with sub-vertical joints, deformations lead to the development of toppling structures (Bovis & Evans, 1996; Nichol *et alii,* 2002; Reitner & Linner, 2009).

At the toe of DSGSDs, in the lower part of the slope, compression and shortening mechanisms are typical, leading to the formation of folds (Zischinsky, 1969; Mahr & Nemčok, 1977; Záruba & Mencl, 1982; Chigira, 1992; Hermann *et alii*, 2000; Hippolyte *et alii,* 2006) and reverse faults (Mahr, 1977; Savage & Varnes, 1987). In such settings, bulging (Agliardi *et alii*, 2001; Discenza *et alii*, 2011; Agliardi *et alii,* 2012) and large secondary landslides (Crosta, 1996; Agliardi *et alii,* 2001, 2012; Pánek & Klimeš, 2016; Crippa *et alii*, 2020) are often encountered.

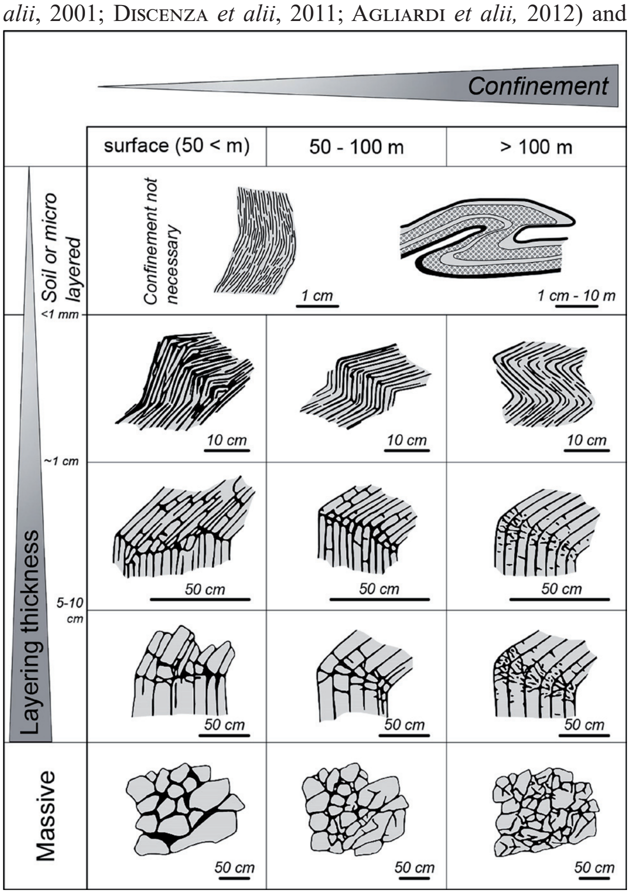

Fig. 7 - Schematic sketches of mesoscopic features and fold styles induced by mass rock creep, depending on rock fabric (layering, massive and soil material) and confinement (redrawn after Jaboyedoff *et alii, 2013). Black areas represent openings, while grey areas represent rock and soil material*

Deep structures

The DSGSDs produce significant deformations within the rock masses and soils involved in the instability, of both brittle and ductile nature (Chigira, 1992; Jaboyedoff *et alii*, 2013). The surface morphological features and the related structures produced by the DSGSDs are very similar to those of a pure tectonic nature (Chigira, 1992; Jaboyedoff *et alii*, 2011; Agliardi *et alii,* 2012; Jaboyedoff *et alii*, 2013). Deformational structures such as folds, faults, shear zones, and cataclastic bands have been described by various authors for large-scale gravitational phenomena (Zischinsky, 1969; Nemčok *et alii*, 1972; Mahr & Nemčok, 1977; Fleming & Johnson, 1989; Chigira, 1992; Braathen *et alii,* 2004). These mass deformations are indicative of slope collapse mechanisms (Jaboyedoff *et alii,* 2011) and are found on slopes with extremely different dimensions (Fig. 7), from a few tens to thousands of meters (Chigira, 1992).

As regards the deep structures, the distinctive features of DSGSDs have not yet been fully understood, due to both the complexity of processes and the difficulties in directly analyzing these portions of the involved rock mass. Generally, the shear planes, clearly evident on the surface, do not extend in depth in the entire rock mass (Mencl, 1968; Hutchinson, 1988). In this cases, in the inner portion of slope, creep processes determine the progressively decreasing of deformations with depth (Jahn, 1964; Zischinsky, 1966; Mencl, 1968; Nemčok, 1972; Mahr & Nemčok, 1977; Varnes, 1978; Nemčok, 1982; Dramis & Sorriso-Valvo, 1994; Cruden & Varnes, 1996; Martino *et alii,* 2004; Esposito *et alii,* 2007; Discenza *et alii,* 2011; Martinotti *et alii*, 2011; Di Maggio *et alii,* 2014; Della Seta *et alii,* 2017), without the development of a continuous sliding plane or basal shear zone. Locally, deep creep processes can lead to the volumetric decrease of rock mass (density increase), forming a thick but not continuous contractant shear zone (Feda, 1973; Mahr, 1977; Radbruch-Hall, 1978).

Sometimes, the progression of deformations or the presence of inherited structures, favor the development of a well-defined sliding plane or basal shear zone, extended continuously below the deformed rock mass (Chigira, 1992; Agliardi *et alii,* 2001; Strauhal *et alii*, 2017). This element, often invoked as a discriminating between landslides and slope-scale deformational processes (Dramis & Sorriso-Valvo, 1994), have been recognized (or hypothesized/inferred) in DSGSD phenomena by numerous authors (Gignoux & Barbier, 1955; Crosta & Zanchi, 2000; Agliardi *et alii*, 2001; Ambrosi & Crosta, 2006; Bonzanigo *et alii,* 2007; Madritsch & Millen, 2007; Agliardi *et alii*, 2009; Moro *et alii*, 2009; Barla *et alii*, 2010; Zangerl *et alii*, 2010; GHIROTTI *et alii*, 2011; AGLIARDI *et alii*, 2012; MORO *et alii*, 2012; STRAUHAL *et alii,* 2017; AGLIARDI *et alii*, 2019; MARIANI & ZERBONI, 2020; VICK *et alii*, 2020). The basal shear zone generally present thickness between few meters and some ten of meters and is composed by cataclastic breccias with abundant fine matrix (CROSTA & ZANCHI, 2000; MADRITSCH & MILLEN, 2007; CROSTA *et alii,* 2013).

TIME SPAN AND DIMENSIONS OF DSGSDs

As suggested by many authors, characteristic features of DSGSDs are the spatial and temporal scales on which they act (DRAMIS & SORRISO-VALVO, 1994; AGLIARDI *et alii,* 2001, 2012; JABOYEDOFF *et alii,* 2013; PÁNEK & KLIMEŠ, 2016). These aspects are fundamental in the study of DSGSDs and in the discriminating with respect to other gravitational processes. The main data available in literature are summarized below, in order to analyze and quantify the spatial and temporal characteristic of these phenomena.

Regarding the time scale, many methods (e.g., dendrochronology, tephrochronology, TCN, U-series, radiocarbon) have been used in last decades to study the age and the evolution of DSGSDs (PÁNEK & KLIMEŠ, 2016).

DSGSD location / region	Age (ka)	Dating method	References
Mt. Scincina / Alps (Italy)	> 120	^{14}C, OSL + relative dating	TIBALDI *et alii* (2004)
Foros / Crimean Mountains (Ukraine)	> 110	Uranium-series, ^{14}C	PÁNEK *et alii* (2009b)
Perecalç / Pyrenees (Spain)	> 45	^{14}C, OSL	GUTIÉRREZ *et alii* (2012b)
Mt. Quoshadagh / Quoshadagh Range (Iran)	> 42	^{14}C, OSL	BAROŇ *et alii* (2013)
Mt. Morrone / Apennines (Italy)	> 41	^{14}C	GORI *et alii* (2014)
Bregaglia Valley / Alps (Switzerland and Italy)	> 29-16	^{14}C, OSL + relative dating	TIBALDI & PASQUARÈ (2008)
Mt. Rognier / Alps (France)	~ 17	^{10}Be	HIPPOLYTE *et alii* (2012)
El Ubago / Pyrenees (Spain)	~ 16.9	^{14}C	GUTIÉRREZ *et alii* (2008)
Horvatov Yrch Ridge / Tatra Mountains (Slovakia and Poland)	~ 15.7–4.4	^{10}Be, ^{36}Cl	PÁNEK *et alii* (2017)
Val Venosta / Alps (Italy)	~ 14.2	U/Th	KOLTAI *et alii* (2018)
Zenzano Fault / Iberian Chain (Spain)	> 13.6	^{14}C	CARBONEL *et alii*. (2013)
Polska Tomanova Ridge / Tatra Mountains (Slovakia and Poland)	~ 12.4–8.4	^{10}Be	PÁNEK *et alii* (2017)
Aspen Highlands / Colorado (USA)	~ 11.5–11	^{14}C	MCCALPIN & IRVINE (1995)
Arcs / Alps (France)	~ 11.5	^{10}Be	HIPPOLYTE *et alii* (2009)
Kagel Mountain / San Gabriel Mountains (California, USA)	~ 10.7	^{14}C	MCCALPIN & HART (2003)
La Clapière / Alps (France)	10.3	^{10}Be	BIGOT-CORMIER *et alii* (2005) EL BEDOUI *et alii* (2009)
Salatín Ridge / Tatra Mountains (Slovakia and Poland)	~ 10.3–4.2	^{10}Be	PÁNEK *et alii* (2017)
Mt. Kushtaka / Yakutat Microplate (Alaska, USA)	> 10.2	^{14}C, OSL	MCCALPIN *et alii* (2011)
Mt. Watles / Alps (Italy)	~ 10	^{14}C	AGLIARDI *et alii* (2009)
Mt. Serrone / Apennines (Italy)	~ 9.6	^{14}C	MORO *et alii* (2012)
Vallibierna and Estós sackungen / Pyrenees (Spain)	~ 7.8–5.9	^{14}C	GUTIÉRREZ-SANTOLALLA *et alii* (2005)
Hlinske Saddle / Tatra Mountains (Slovakia and Poland)	~ 6.0–4.0	^{10}Be	PÁNEK *et alii* (2017)
Mt. Ondřejník / Western Carpathians (Czech Republic)	> 5.9	OSL	PÁNEK *et alii* (2011)
Moravskoslezske Beskydy Mts. / Western Carpathians (Czech Republic)	4.2-3.6	^{10}Be	BŘEŽNÝ *et alii* (2018)
Blue Ridge and Lytle Creek sackungen / San Gabriel Mts. (California, USA)	4.2–0.8	^{14}C	MCCALPIN & HART (2003)
Teruel Graben / Iberian Chain (Spain)	3.5	^{14}C	GUTIÉRREZ *et alii* (2012a)
Affliction Creek / Coast Mountains (British Columbia, Canada)	Onset of activity between AD 1865–1875	lichenometry	BOVIS (1982)

Tab. 1 - Time span of some characteristic DSGSDs, constrained by absolute dating and relative methods (modified after PÁNEK & KLIMEŠ, 2016)

The available data (Tab. 1) show that the evolution of these phenomena occurs (generally) over time intervals of thousands (Bovis, 1982; Mccalpin & Hart, 2003; Gutiérrez-Santolalla *et alii*, 2005; Pánek *et alii*, 2011; Gutiérrez *et alii,* 2012a; Moro *et alii*, 2012; Pánek *et alii*, 2017; Břežný *et alii*, 2018) or tens of thousands of years (McCalpin & Irvine, 1995; McCalpin & Hart, 2003; Bigot-Cormier *et alii,* 2005; Gutiérrez *et alii,* 2008; Tibaldi & Pasquarè, 2008; Agliardi *et alii,* 2009; El Bedoui *et alii*, 2009; Hippolyte *et alii*, 2009; McCalpin *et alii,* 2011; Gutiérrez *et alii*, 2012b; Hippolyte *et alii*, 2012; Baroň *et alii,* 2013; Carbonel *et alii*, 2013; GORI *et alii,* 2014; Pánek *et alii,* 2017; Koltai *et alii*, 2018), sometimes hundreds of thousand years (Tibaldi *et alii*, 2004; Pánek *et alii,* 2009b).

These results are fully compatible with the indirect deductions deriving from geomorphological analyzes (Agliardi *et alii,* 2001) and time-dependent numerical modelling (Discenza *et alii,* 2011; Della Seta *et alii*, 2017), which show similar evolution times. As suggested by Pánek & Klimeš (2016), the lifespans are significantly different for the DSGSDs located in formerly glaciated terrain later the final deglaciation (onset after ~18–10 ka), and for the phenomena locate in non-glaciated setting, often predating global Last Glacial Maximum (~23–19 ka).

The DSGSDs are characterized by considerable dimensions, with thickness of many tens or hundreds of meters (Pánek & Klimeš, 2016) and surface up to hundreds of km^2 (Ambrosi & Crosta, 2006; Agliardi *et alii,* 2013; Crosta *et alii*, 2013). While there is a great deal of information in the literature on the surface and depth of these phenomena, less data is available on the volumes, as the diffuse margins and the complexity of the processes make the evaluation of this parameter very difficult. In particular, the data collected in the present study (Tab. 2) show that the volumes of these phenomena are generally variable between 10^6 m^3 (Jarman, 2006; Discenza *et alii,* 2011) and 10^9 m^3 (Tibaldi *et alii,* 2015; Agliardi *et alii,* 2019;

DSGSD location / region	Maximum depth (m)	Surface (km^2)	Volume (m^3)	References
Mt. Quoshadagh / Quoshadagh Range (Iran)	800	~ 220	$8.3\cdot10^{10}$ - $1.1\cdot10^{11}$	Baroň *et alii* (2013)
Sinne Valley / Alps (France)	n.a.	n.a.	$9.5\cdot10^{9}$	Drouillas *et alii* (2020)
Piz Dora / Val Müstair (Switzerland)	400	12	$1.85\cdot10^{9}$	Agliardi *et alii* (2019)
Talas–Fergana Fault / Tien Shan (Kyrgyzstan)	250	4	$1\cdot10^{9}$	Tibaldi *et alii* (2015)
El Ubago / Pyrenees (Spain)	> 300 ?	4.4	$6.0\cdot10^{8}$	Gutiérrez *et alii* (2008)
Celentino / Alps (Italy)	80 - 100	5	$3.5\cdot10^{8}$ - $4.0\cdot10^{8}$	Ghirotti *et alii* (2011)
Vollan / Sunndal Valley (Norway)	200	~ 2.5	$2.6\cdot10^{8}$	Oppikofer *et alii* (2017)
Mount Breakenridge / Lillooet Ranges (British Columbia, Canada)	n.a.	n.a.	$2\cdot10^{8}$	Nichol *et alii* (2002)
Beinn Fhada / Scottish Highlands (Scotland)	100 ?	3.0	$1.12\cdot10^{8}$	Jarman (2006)
Encampadana / Central–Eastern Pyrenees (Andorra)	300	1.5	$1\cdot10^{8}$	Hürlimann *et alii* (2006)
Moosfluh / Alps (Switzerland)	170	1.3	$7.5\cdot10^{7}$	Glueer *et alii* (2019)
Sgurr Bhreac / Scottish Highlands (Scotland)	n.a.	0.82	$3.6\cdot10^{7}$?	Jarman (2006)
An Sornach / Scottish Highlands (Scotland)	n.a.	0.75	$1.3\cdot10^{7}$?	Jarman (2006)
Sgurr na Ciste / Scottish Highlands (Scotland)	80	1.25	$5\cdot10^{6}$ - $1\cdot10^{7}$	Jarman (2006)
Tino / Apennines (Italy)	50	~ 0.25	$1\cdot10^{6}$ - $1\cdot10^{7}$	Martino *et alii* (2020)
Grisciano / Apennines (Italy)	50	~ 0.18	$1\cdot10^{6}$ - $1\cdot10^{7}$	Martino *et alii* (2020)
Mt. Rocchetta / Apennines (Italy)*	300-350	0.25	$8.0\cdot10^{6}$	Discenza *et alii* (2011)
Sgurr na Lapaich / Scottish Highlands (Scotland)	100 ?	0.3	$7\cdot10^{6}$?	Jarman (2006)
Hell's Glen / Scottish Highlands (Scotland)	60	0.52	$1.75\cdot10^{6}$	Jarman (2006)

*Tab. 2 - Dimensions of some characteristics DSGSDs (maximum depth, surface, volume); * indicate phenomena for which the volume is not present in the original publication but was determined through the analyzes of surface and depth*

Drouillas *et alii*, 2020), although locally they can reach 10^{10} - 10^{11} m^3 (Baroň *et alii,* 2013). Many DSGSDs are included in this range, with volumes varying between 10^7 and 10^8 m^3 (Nichol *et alii,* 2002; Hürlimann *et alii,* 2006; Jarman, 2006; Gutiérrez *et alii,* 2008; Ghirotti *et alii*, 2011; Oppikofer *et alii,* 2017; Glueer *et alii*, 2019; Martino *et alii,* 2020).

DISCUSSION AND CONCLUSIONS

Deep-Seated Gravitational Slope Deformations (DSGSDs *Auct*.) are phenomena of great importance from a scientific point of view, both for the role they play in the evolution of relief and for the significant social impact should they occur in proximity to peoples and infrastructures (Záruba & Mencl, 1969; Dramis & Sorriso-Valvo, 1994; Pánek & Klimeš, 2016; Martino *et alii,* 2020). In fact, they often produce significant interferences with anthropic elements and constitute a great potential risk factor (Záruba & Mencl, 1969; Dramis & Sorriso-Valvo, 1994; Discenza *et alii*, 2011; Frattini *et alii,* 2013; Pánek & Klimeš, 2016), both directly (e.g., related slope deformations) and indirectly (e.g., for the possible catastrophic evolution). Large landslides with rapid kinematics were recognized in many parts of the world in association with DSGSD phenomena (Hungr & Evans, 2004; Pánek & Klimeš, 2016), both in historical and recent times.

It is worth highlighting the predisposing role of the morpho-evolutionary context as a factor (often necessary and sufficient) that controls the stress regime variations acting on the slopes over different time spans (Agliardi *et alii,* 2009; Della Seta *et alii,* 2017). In fact, significant changes of the stress-strain conditions can occur over larger time spans (Chigira, 1992; Discenza *et alii,* 2011; Pánek & Klimeš, 2016), due to the morpho-evolutionary context and/or geodynamic regime modifications. The significance of such variations in terms of slope stability is then related to (Martino *et alii,* 2017): (*i*) the amount and temporal rate of changes in deviatoric stress; (*ii*) the rheology of the slope materials as long as more or less prominent viscous deformation alternate with and superimpose on elastic-plastic strain.

In the last decades, several studies were conducted on these phenomena, with extremely different purposes and methodology. At present, there are many terminologies and definitions in literature, from which derives a considerable complexity in the systematic approach to DSGSDs. One of the main issues is the definition of the limit (and, thus, distinction) between slow-moving large landslides, DSGSDs, and gravitational tectonics, as they all produce some similar deformative effects and geomorphic features.

Like the tectonic processes *s.s.*, the DSGSDs produce deformations of the involved mass such as folds, faults, and shear zones (Zischinsky, 1969; Nemčok *et alii,* 1972; Mahr & Nemčok, 1977; Fleming & Johnson, 1989; Chigira, 1992; Braathen *et alii*, 2004). The similarities between the effects produced by the two processes (Chigira, 1992; Jaboyedoff *et alii*, 2011; Agliardi *et alii*, 2012; Jaboyedoff *et alii,* 2013) make their distinction particularly complex, even more if we consider that many slope deformations exploit pre-existing tectonic elements as kinematic release planes (Agliardi *et alii*, 2001; Di Luzio *et alii,* 2004b; Agliardi *et alii,* 2012; Esposito *et alii,* 2014). In this case, the identification of the dominant process and the real cause of the deformation elements present on slope must be made not so much on the individual identified elements, but rather on the spatial distribution of the same and on the relative extension within the slope (Agliardi *et alii,* 2012).

In differentiating DSGSDs from conventional landslides, many elements have been considered over time by various authors. Some workers consider the absence of a continuous sliding surface or basal shear zone (Dramis & Sorriso-Valvo, 1994), but the recognizing (or hypothesizing/inferring) of this element in numerous DSGSDs leads today to consider this condition as non-discriminatory between the two processes (Agliardi *et alii,* 2001; Pánek & Klimeš, 2016). Other authors consider the absence of clear and well-defined external limits (Fig. 8) as discriminatory (Agliardi *et alii,* 2001; Jarman, 2006; Agliardi *et alii,* 2012; Crosta *et alii,* 2013; Jarman & Harrison, 2019) but, even if this is a very common condition in DSGSD phenomena, it depends on local geological conditions and the evolutionary stage of the process.

Starting from an initial study (Sorriso-Valvo, 1984), some years later Sorriso-Valvo (1995) proposed a differentiation between landslides and gravitational deformations according to the size of the phenomena and the effects produced by the scale factor; conventional landslides are divided into two classes depending on whether the scale effect is influential or not on the development of the phenomenon, while gravitational deformations are distinguished from gravitational tectonics both in relation to the size of the DSGSDs and the extension on the mountain relief. Jaboyedoff *et alii* (2011) divide the instability phenomena into three dimensional orders; conventional landslides correspond to the 3rd order (or at most to the 2nd in the case of large rock avalanches), while gravitational deformations correspond to the 2nd order if they concern only the slope or to the 1st order if they concern entire mountainous relief. Finally, Hungr *et alii* (2014) divide the DSGSDs into two different types, the mountain slope deformations and the rock slope deformations; the first concern entire mountain relief, with a height in the order of 1 km or more, while the latter concern rock slope with a height of a few tens or hundreds of meters.

A characteristic aspect of DSGSDs is represented by the

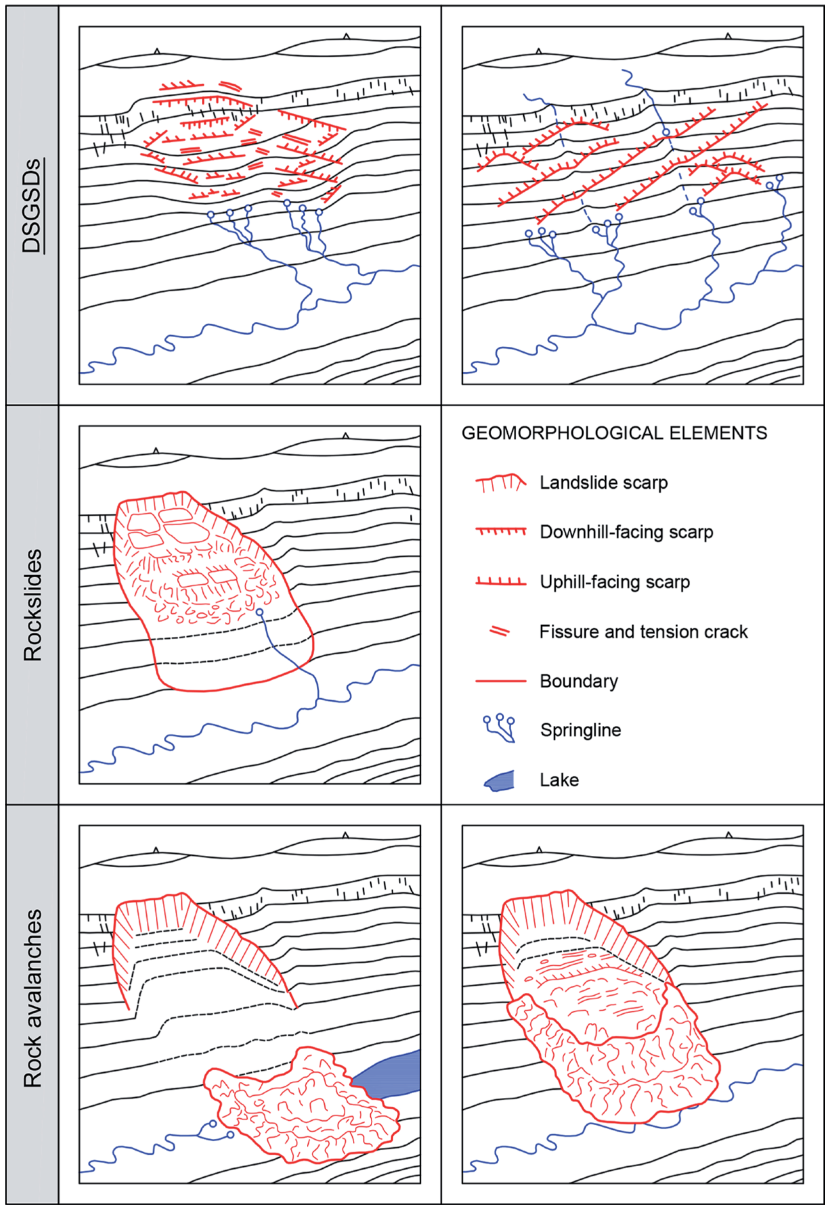

Fig. 8 - Scheme for the distinction between different large-scale gravitational phenomena (i.e., DSGSDs, Rockslides, Rock avalanches) based on the morphological characteristics along the slope (modified after Jarman & Harrison, 2019). DSGSDs are characterized by diffuse boundaries (or margins) and numerous morphological features with peculiar assemblage (scarps, uphill-facing scarps, fissures)

high spatial and temporal scales on which they act. Over the years, a lot of authors have provided indications to describe the spatial scale of these phenomena (Dramis & Sorriso-Valvo, 1994; Agliardi *et alii*, 2001, 2012; Jaboyedoff *et alii,* 2013; Pánek & Klimeš, 2016), taking as a reference the extent of the phenomenon with respect to the relief. The numerous existing bibliographic data, described in the previous paragraphs, made it possible to define the characteristic intervals of time span and volume for DSGSDs. These phenomena commonly have dimension of 10^6 - 10^9 m^3, locally up to 10^{10} - 10^{11} m^3, and develop over time intervals on the order of 10^3 - 10^4 years, sometimes up to 10^5 years.

This study proposes a new reference scheme which, starting from the state of the art, integrates the concept of time scale in defining slope deformational processes (Fig. 9). The scheme is based on two main aspects: (*i*) volume; (*ii*) time scale. The volume regulates short-term geostatic load and elastic-plastic equilibrium on and refers to a given

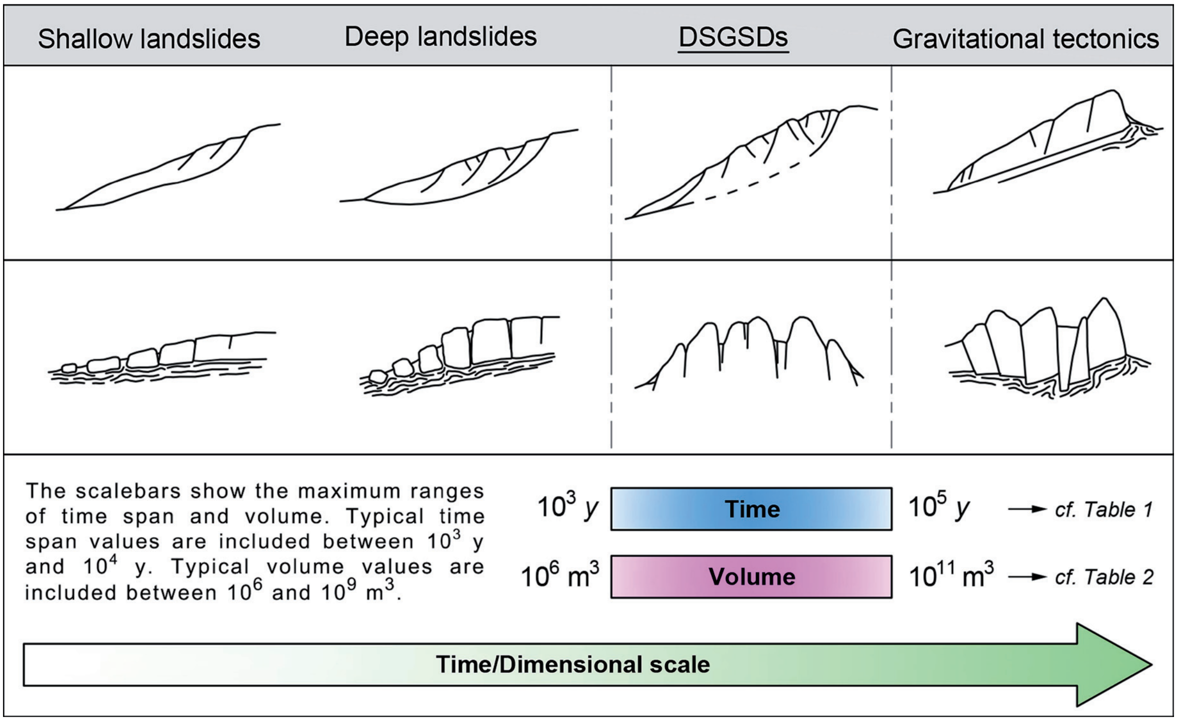

Fig. 9 - Simplified scheme representing dimensional and temporal scales (in terms of orders of magnitude) characterizing the DSGSDs, as defined by the available literature studies

morpho-structural setting, the related relief energy, as well as geodynamic regime. The time scale introduces the relevance of the time-dependent mechanical parameters of the slope materials as long as the time span "fits" the viscosity of slope materials and the related creep behavior. Obviously, the boundary conditions of the different processes are not sharp but are indicative (i.e., there is some uncertainty) and so they should always be considered in relations to the geological context.

The review of the main existing studies has made it possible to fully define all the aspects that characterize the DSGSDs and that allow them to be distinguished from conventional landslides and gravitational tectonics. Among these, particular importance assumes the high space-time scales on which they act. In summary, the main characteristics of the DSGSDs are:

- dimensions comparable with those of the entire slope (or larger portion of it);
- diffuse, discontinuous or not well-defined external boundaries (or limits/margins), with flanks often coinciding with tributary streams or tectonic elements;
- peculiar assemblage of typical morphological features (e.g., double ridges, ridge top depressions, trenches, scarps, counterscarps, tension cracks, toe bulging), generally distributed along the entire ridge-slope-valley floor system;
- very small deformation rates (in the order of mm per years);
- large spatial and temporal scales (volumes between 10^6 - 10^{11} m^3 and time span between 10^3 - 10^5 years);
- complex deformational processes (brittle, ductile, and viscous-plastic deformation, in mass or along discrete zones and surfaces);
- heavily jointed and deformed rock masses (not completely disturbed, with original structures still recognizable, except for discrete shear zones);
- presence of secondary landslides and large Rock Slope Failures (in all or part of the slope).

For specific bibliographical references and the description of the individual aspects, please refer to the contents of the previous paragraphs.

Above all, the concept of "depth" should be less constraining in favor of a more appropriate reference to the coupling of spatial and temporal scale factors, which better reflect the morpho-evolutionary characteristics of the process and its rheological behavior. Depth is not considered as a distinctive element of these processes, as there are landslides and tectonic processes with depths comparable with those of DSGSDs, but rather a direct consequence of the scale on which they act, which requires a stress field that can only form in large rock volumes.

In addition to commonly used terms such as Deep-Seated Gravitational Slope Deformation (DSGSD *Auct.*), other terminologies such as Slope Tectonics (ST – Jaboyedoff *et alii,* 2011), Mass Rock Creep (MRC - Radbruch-Hall, 1978; Chigira, 1992) or Rock Slope Deformation (RSD – Hungr *et alii*, 2014; Jarman & Harrison, 2019) exists in literature. These terms have the advantage of not referring to the concept of depth, by introducing significant elements that refer to spatial scale or the rheology of the slope material. At the end of the present study, alternative terms such as Slope-Scale Gravitational Deformation (SSGD) or Large-Scale Gravitational Slope Deformation (LSGSD) are proposed, which further detach themselves from the concept of depth by making direct and explicit reference to the scale of the processes.

Finally, it is emphasized that the absence of a uniformly accepted classification and terminology in the scientific field represents a significant problem in the treatment of these deformational processes. In fact, it is often difficult to correlate the different case studies and frame them in a unique and complete way. A fundamental aspect of future research will therefore be the introduction of comprehensive classification system, which should refer to the kinematic, the morpho-structural setting, and the geological/geomechanical features of the slope, that are proxies of the mechanical properties.

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