A Global Database of Giant Landslides on Volcanic Islands

Matt Rowberry, Jan Klimeš, Jan Blahůt, Jan Balek, and Michal Kusák

Abstract

This paper describes a comprehensive online database of giant landslides on volcanic islands compiled by researchers from the Institute of Rock Structure and Mechanics, Czech Academy of Sciences, in the framework of IPL Project 212. The database was constructed from 2016 to 2018. It comprises a total of seventy-five events from the Atlantic Ocean and Mediterranean Sea, sixty-seven events from the Pacific Ocean, and forty events from the Indian Ocean. In this paper some of the main benefits of landslide inventories and thematic databases are outlined and the global distribution of giant landslides on volcanic islands is described in depth. The database is hosted on the website of the Institute of Rock Structure & Mechanics and records can be downloaded as a spreadsheet or kml file for integration in a number of geospatial programs including ArcGIS and Google Earth. However, since completion of the database in 2018, a number of potentially significant studies of giant landslides on volcanic islands have been published from archipelagos in the Atlantic and Pacific Oceans while outstanding modern analogues for past events are represented by the collapse of Anak Krakatau on 22 December 2018 and the collapse of Hunga Tonga-Hunga Haʻapai on 15 January 2022. Consequently, the recent literature will be scrutinized with the aim of updating information already contained in the database while two new layers are planned: the first of these will provide information about recent volcanic collapses and the second will provide information about the long-term instrumental monitoring of giant landslides. It is intended that the second release of the database will be available online in early 2023.

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Keywords

Giant landslides • Landslide inventories • Thematic databases • Debris avalanches • Slumps • Volcanic islands

1 Introduction

In the 1960s it was shown that the Hawaiian Ridge hosted a pair of giant landslides (Moore 1964) but the geomorphological evidence used to document these events was not greeted with universal enthusiasm (Langford and Brill 1972). Not only were the original observations corroborated by later research but it has become clear that the vast majority of volcanoes are prone to episodes of slope instability and subsequent structural failure (McGuire 1996). Indeed it is now known that the structural failure of a volcano can create some of the largest landforms generated in a single geological moment (Whelan and Kelletat 2003). Instability may be caused by magma emplacement, peripheral erosion, the overloading of slopes, or the oversteepening of slopes while subsequent failure may be triggered by a suite of climatic, magmagenic, or seismogenic processes (McGuire 1996). The potential for instability may be increased on oceanic island volcanoes due to edifice spreading along weak sedimentary horizons or in response to seaward creeping masses of olivine cumulate (Fig. 1). In many instances, it is probable that more than one preparatory factor is operating prior to the initiation of a specific trigger.

The seafloors and subsurfaces of numerous volcanic archipelagos have now been imaged in unprecedented detail thanks to advances in a range of geophysical techniques such as single and multibeam echo sounders, sidescan sonar, and reflection and refraction seismic surveys (e.g. Crutchley and Kopp 2018; Hughes Clark 2018; Klaucke 2018). Giant landslides on volcanic islands transport hundreds of thousands of cubic metres to hundreds of cubic kilometres of

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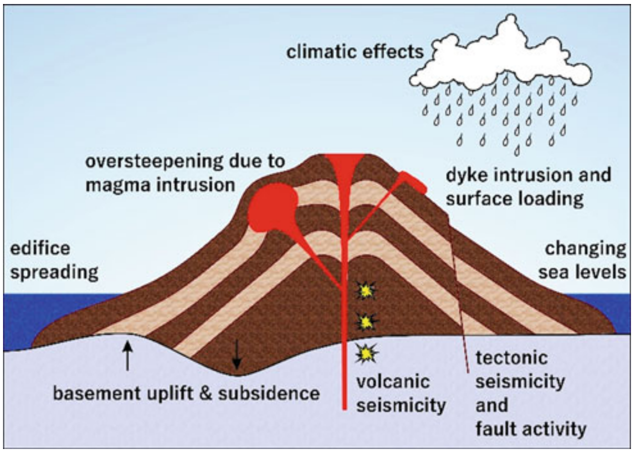

Fig. 1 Factors contributing towards the development of structural instability at active volcanoes (modified from McGuire 1996)

material and create arcuate embayments and steep cliffs (Fig. 2). Through time these features are degraded by erosion and partially or completely hidden by further volcanism. Their deposits can be transported for hundreds of kilometres and can extend over areas of many hundreds of square kilometres (Masson et al. 2002). In the sea, these accumulations are often well preserved but they tend to lie at considerable depths so investigating their internal structure requires access to—usually proprietary—borehole data. Consequently, giant landslides on volcanic islands remain among the most poorly studied types of terrestrial landslide despite their global distribution and potential to generate catastrophic failures and tsunamis (Day et al. 2015; Ramalho et al. 2015).

Insufficient information pertaining to the internal structure of giant landslides on volcanic islands means that such events are poorly defined. They are usually interpreted as either debris avalanches or slumps; debris avalanches are thought to reflect a sudden single catastrophic event while slumps are thought to reflect protracted slope deformation. Evidence for both of these end members are sometimes found in a single archipelago, occasionally even on a single volcanic edifice, such as on the main island of Hawai‘i and on El Hierro in the Canary Islands. Furthermore, some debris avalanches have been reinterpreted as multistage collapses (Hunt et al. 2013) while some slumps present evidence for recurring periods of rapid slip (Blahůt et al. 2020). It is also possible that structural failure then triggers an eruption in much the same way as was seen on Mount Saint Helens in May 1980. In such a scenario, evidence for the initial structural failure could disappear almost instantaneously. There is also the possibility that slumps transition into catastrophic debris avalanches but no unequivocal evidence for this has yet been recognised.

Until recently, information about giant landslides on volcanic islands had not been rationalised into a single online resource. Here an outline of the first comprehensive global database of giant landslides on volcanic islands is presented. The database was compiled over a three year period from 2016 to 2018: the first year concentrated on investigating events in the Atlantic Ocean; the second year concentrated on investigating events in the Pacific Ocean; and the third year concentrated on investigating events in the Indian Ocean. In this paper, attention focuses, first, on the benefits of landslide inventories and thematic databases, second, on the global distribution of giant landslides on volcanic islands and, third, on plans to update the database and implement some changes. It is hoped that the database will be used by the research community to investigate the spatial and temporal distribution of such landslides, to investigate their morphometric characteristics in more detail, and to assess the hazard and potential risks posed by future events. The complete database is available at: https://www.irsm.cas.cz/ext/giantlandslides.

Fig. 2 An example of an arcuate embayment and steep cliffs formed by a giant landslide on a volcanic island: the Las Playas debris avalanche on El Hierro in the Canary Islands (photograph by Jan Klimeš)

2 Landslide Inventories and Thematic Databases

Landslide inventories and thematic databases provide essential information needed to assess the spatial and temporal distribution of landslides, their preparatory factors and triggers, and their negative societal impacts (Guzzetti et al. 2012). The scope of such inventories and databases can be regional (Blahůt et al. 2012; Strozzi et al. 2018) or global (Kirschbaum et al. 2010; Froude and Petley 2018) or it can extend beyond the Earth to cover extraterrestrial bodies such as Mars (Brunetti et al. 2014; Crosta et al. 2018). Despite their importance, it is sometimes difficult to access information about landslide databases in terms of, for example, their completeness, format, and structure and such information is necessary in order to be able to generate reliable susceptibility, hazard, and risk assessments (Van Den Eeckhaut and Hervás 2012). Nonetheless, in many instances the rapid preparation of more reliable and relevant landslide inventories is being facilitated by advancing technologies coupled with data mining from media reports (e.g. Kreuzer and Damm 2020; Franceschini et al. 2022) or social networks (e.g. Pennington et al. 2015; Juang et al. 2019).

There is still the fundamental issue that landslide inventories have only been prepared for a small proportion of the globe. In terrestrial settings, it has been estimated that inventory mapping covers only around one percent of the total land surface (Guzzetti et al. 2012). In submarine settings, this figure is thought to be lower, in light of the fact that more than three quarters of the seafloor is still not mapped at a resolution of 1 km (Jakobsson 2020). However, there are an increasing number of inventories and databases that have focused on compiling information about submarine landslides (Camerlenghi et al. 2010; Urlaub et al. 2013; Gamboa et al. 2021). These are particularly useful because such landslides have the potential to cause devastating tsunamis in coastal regions far from the triggering event. However, due to the financial and time constraints associated with seafloor mapping, there is a tendency for submarine landslide inventories to come from regions of high economic importance (Chaytor et al. 2009; Katz et al. 2015). It is anticipated that in the future an increasing number of giant landslides will be recognised in more remote, less prosperous volcanic islands such as those in the Subantarctic.

3 Database Structure

The term giant landslide is used here to refer to any mass movement whose main body can be defined with some degree of confidence and whose volume is in the order of cubic kilometres while the term volcanic island is restricted

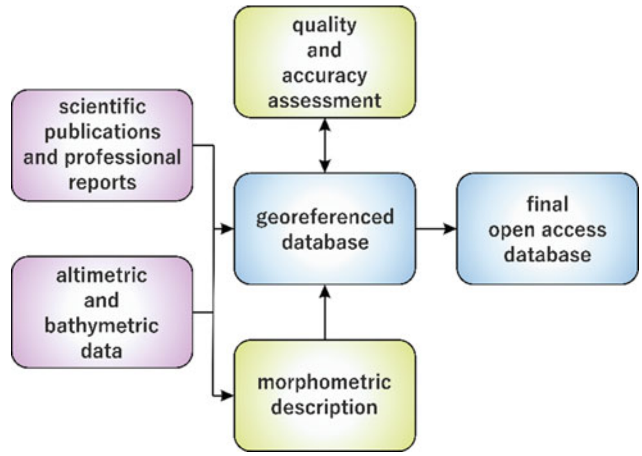

Fig. 3 Flow diagram outlining our approach to construction of the giant landslides on volcanic islands database (modified from Blahůt et al. 2018a)

to only those islands whose origins are entirely volcanic (Blahůt et al. 2018a, 2019). The majority of the information found in the database has been sourced from peer reviewed scientific publications—both manuscripts and book chapters—while a small proportion comes from other sources such as professionals reports and technical documents. This information has been supplemented by insights gleaned from altimetric and bathymetric models. For the European islands—including those that comprise the autonomous community of Spain, the Canary Islands, and those that comprise the two autonomous regions of Portugal, Azores and Madeira—altimetric data were obtained from the Shuttle Radar Topography Mission (SRTM 2019) and bathymetric data were obtained from the European Marine Observation & Data Network (EMODNET 2019). In all other cases—including the French overseas department of La Réunion—the altimetric data and the bathymetric data were obtained from the Global Multi Resolution Topography (GMRT 2019). To define the spatial characteristics of each giant landslide it has been necessary to georeference published maps using ArcGIS. The georeferenced maps have been subjected to rigorous accuracy assessments prior to inclusion of the data in the database (Fig. 3). A complete list of all the parameters included in the database is presented on Table 1.

4 Global Distribution

4.1 North Atlantic Ocean

In the North Atlantic Ocean, giant landslides have been recognised in the archipelagos of Madeira, the Azores, the Canary Islands, the Cape Verde Islands, and the Lesser Antilles (Fig. 4). The database includes eight events from the

Table 1 Data compiled in the giant landslide on volcanic island database. Uncertainties in these data are described in more detail elsewhere (Blahůt et al. 2019)

Name	The name of the giant landslide
Island	The name of the volcanic island hosting the landslide
Archipelago	The name of the archipelago to which the island belongs
Type	The type of mass movement according to the source document
Island age	The age—often given as a range—ascribed to the volcanic edifice
Island age: mean	The mean of the age range ascribed to the volcanic edifice
Source	Source document or documents used for georeferencing the landslide
Bathymetric method	Method used to create the maps in the source document(s)
Landslide age	The age—often given as a range—ascribed to the landslide
Landslide age: mean	The mean of the age range ascribed to the landslide
Total volume	The volume—often given as a range—ascribed to the landslide
Volume: mean	The mean of the volume range ascribed to the landslide
Area	The area of the landslide derived from the georeferenced map
Width	The width of the landslide derived from the georeferenced map
Length	The length of the landslide derived from the georeferenced map
Perimeter length	The perimeter length of the landslide derived from the georeferenced map
W—gHM (J)	The potential energy of the landslide (see Blahůt et al. 2019)
Hmax	Maximum elevation of the landslide derived from the georeferenced map
Hmin	Minimum elevation of the landslide derived from the georeferenced map
ΔH	The fall height of the landslide derived from the georeferenced map
Complete	Is a complete outline of the areal extent of the landslide defined
H/L	The apparent friction coefficient of the landslide
Mean slope	The mean gradient of the landslide
L/H	The relative runout of the landslide

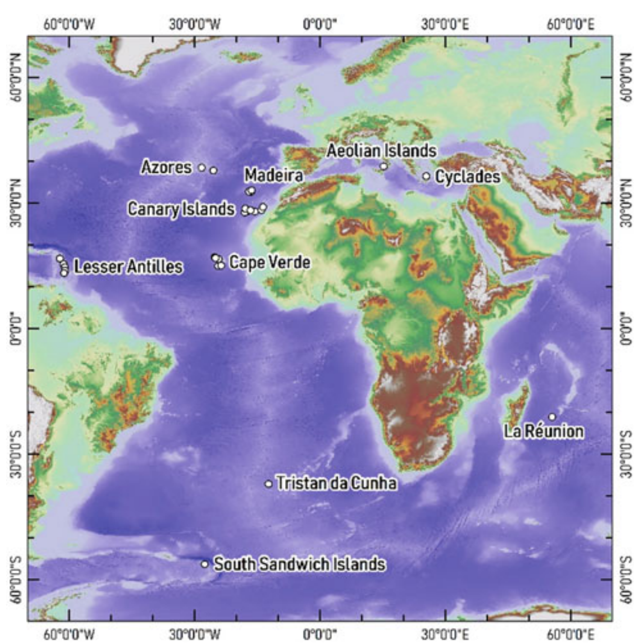

Fig. 4 Distribution of giant landslides on volcanic islands from the Atlantic and Indian Oceans. Global relief model derived from Global Bathymetry and Topography at 15 Arc Sec: SRTM15 + V2.1 (Tozer et al. 2019)

volcanoes of Madeira. Seafloor mapping of this region has been performed using multibeam echosounder. Four giant landslides are known from the main island of Madeira while two are known from each of the islands of Desertas and Porto Santo (Quartau et al. 2018). The database includes five events from the volcanoes of the Azores. Seafloor mapping of this region has also been performed using multibeam echosounder. Four giant landslides are known from the island of Pico (Costa et al. 2014; Omira et al. 2016) and one is known from the island of São Miguel (Sibrant et al. 2015).

The database includes thirty two events from the volcanoes of the Canary Islands. Seafloor mapping of this region has been performed using side scan sonar and multibeam echosounder. Nine giant landslides are known from the island of La Gomera, seven are known from El Hierro, seven are known from Tenerife, four are known from Gran Canaria, three are known from La Palma, and one is known from each of the islands of Fuerteventura and Lanzarote (Carracedo et al. 1999; Urgeles et al. 1999; Gee et al. 2001; Krastel et al. 2001; Masson et al. 2002; Acosta et al. 2003; Ancochea et al. 2006; Casillas et al. 2010; Dávila Harris et al. 2011; Hunt et al. 2011; Boulesteix et al. 2013; Hunt et al. 2014; Becerril et al. 2016; León et al. 2017).

The database incorporates twelve events from the volcanoes of Cape Verde. Seafloor mapping of this region has been performed using multibeam echosounder. Four giant landslides are known from each of the Barlavento Islands of Santo Antão and São Nicolau, two are known from the Sotavento Island of Fogo, one is known from the Barlavento Island of São Vicente, and one is known from the Sotavento Island of Santiago (Le Bas et al. 2007; Masson et al. 2008). In addition, the database incorporates thirteen events from the volcanoes of the Lesser Antilles. Seafloor mapping of this region has also been performed using multibeam echosounder. Seven giant landslides are known from the Leeward Island of Montserrat, three are known from the Windward Island of Martinique, and one is known from each of the Windward Islands of Dominica, Santa Lucia, and St Vincent (Deplus et al. 2001; Brunet et al. 2016; Coussens et al. 2016).

4.2 Mediterranean Sea

In the Mediterranean Sea giant landslides have been recognised in the Aeolian Islands and the Cyclades (Fig. 4). Seafloor mapping around the Aeolian Islands has been performed using side scan sonar and multibeam echosounder while it has been performed using multibeam echosounder around the Cyclades. From the Aeolian Islands, one giant landslide is known from the island of Stromboli (Romagnoli et al. 2009). From the Cyclades, two giant landslides are known from the island of Santorini (Hooft et al. 2017).

4.3 South Atlantic Ocean

In the South Atlantic Ocean, giant landslides have been recognised in the archipelagos of Tristan da Cunha and the South Sandwich Islands (Fig. 4). Seafloor mapping around Tristan da Cunha has been performed using side scan sonar while multibeam echosounder has been used around the South Sandwich Islands. From Tristan da Cunha, one giant landslide is known from the main island of Tristan da Cunha (Holcomb and Searle 1991). From the South Sandwich Islands, one giant landslide is known from the Traversay Island of Zavodovski (Leat et al. 2010).

4.4 Indian Ocean

In the Indian Ocean giant landslides have been recognised in the Mascarenhas Archipelago (Fig. 4). The database includes forty events from the island of La Réunion (Oehler et al. 2008). Seafloor mapping of this region has been performed using deep tow side scan sonar and multibeam echosounder. No other volcanic edifice is thought to have hosted so many giant landslides and yet these are the only events hitherto identified in the Indian Ocean.

4.5 Northern Pacific Ocean

In the northern Pacific Ocean giant landslides have been recognised in the Aleutian Arc—including Alaska—and in the Hawaiian Islands (Fig. 5). The database includes four events from Alaska and nine events from the volcanoes of the Aleutian Arc. Seafloor mapping around Alaska has been performed using multibeam echosounder while side scan sonar and multibeam echosounder has been used around other parts of the Aleutian Arc. From Alaska, four giant landslides are known from Augustine Island (Begét and Kienle 1992; Waythomas et al. 2006). From the Aleutian Arc, three giant landslides are known from the Delarof Island of Gareloi, one is known from each of the Rat Islands of Kiska and Segula, and one is known from each of the Andreanof Islands of Great Sitkin, Bobrof, Kanaga, and Tanaga (Coombs et al. 2007).

The database includes nineteen events from the volcanoes of the Hawaiian Islands. Seafloor mapping in this region has been performed using side scan sonar. Eleven giant landslides are known from the main island of Hawai‘i, three are known from the island of O‘ahu, two are known from the island of Kaua‘i, and one is known from each of the islands

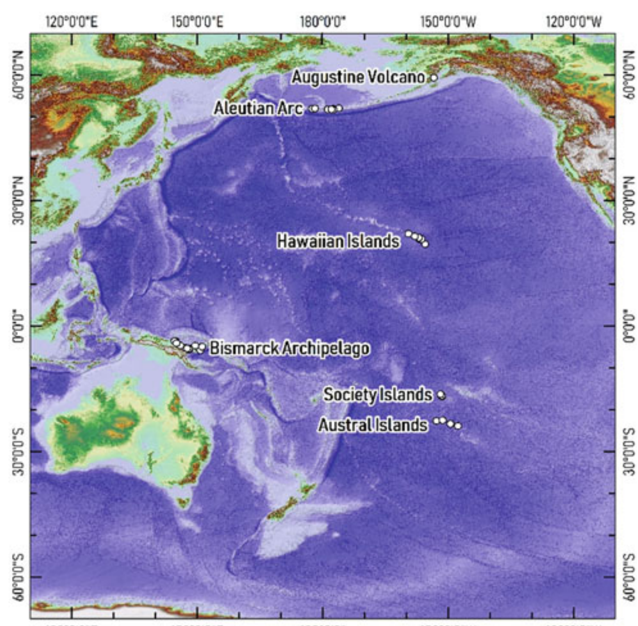

Fig. 5 Distribution of giant landslides on volcanic islands from the Pacific Ocean. Global relief model derived from Global Bathymetry and Topography at 15 Arc Sec: SRTM15 + V2.1 (Tozer et al. 2019)

of Lanaʻi, Maui, and Molokaʻi (Lipman et al. 1988; Moore et al. 1989, 1994; McMurtry et al. 2004). The inventory of giant landslides on the Hawaiian Islands is exceptional in the sense that it includes the only instance of a sandrubble flow—from the island of Hawaiʻi—as well as seven slumps from three different islands—five from the island of Hawaiʻi, one from Maui, and one from Oʻahu.

4.6 Southern Pacific Ocean

In the southern Pacific Ocean giant landslides have been recognised in the Bismarck Archipelago and in French Polynesia (Fig. 5). The database incorporates thirteen events from the volcanoes of the Bismarck Archipelago. Seafloor mapping in this region has been performed using side scan sonar and multibeam echosounder. Two giant landslides are known from each of the Madang Province islands of Crown and Karkar, one is known from the Madang Province island of Manam, one is known from each of the East Sepik Province islands of Bam and Kadovar, one is known from each of the Morobe Province islands of Ritter, Sakar, Tolokiwa, one is known from each of the West New Britain Province islands of Garove, Lolobau, and New Britain (Silver et al. 2009; Day et al. 2015).

The database includes twenty-two events from the volcanoes of French Polynesia. Seafloor mapping in this region has been performed using single beam and multibeam echosounder. From the Austral Islands, four giant landslides are known from Rūrutu Island, three from Tupuaʻi Island, three from Ra'ivāvae Island, and two from Rimatara Island (Clouard and Bonneville 2004). From the Society Islands, three giant landslides are known from the Leeward Island of Bora Bora, two from the Leeward Island of Raiatea, two from the Leeward Island of Taha'a, one from the Leeward Island of Tupai (Clouard and Bonneville 2004) along with two from the Windward Island of Tahiti (Clouard et al. 2001; Hildenbrand et al. 2006).

5 Future Plans for the Database

More than three years have passed since the full database of giant landslides on volcanic islands first appeared as an online resource. On the basis of information contained in the database, it has been possible to investigate the basic morphometric characteristics of the giant landslides and the relationships that exist between these characteristics (Blahůt et al. 2019). Until now, the database has not helped to shed any light on the association between giant landslides and megatsunamis, while the information contained in the database has not yet been used as part of a susceptibility, hazard, and risk assessment.

In the intervening period, important new research on giant landslides has been published from many parts of the Atlantic Ocean including Cape Verde (Martínez-Moreno et al. 2018; Barrett et al. 2020; Cornu et al. 2021), the Azores (Hildenbrand et al. 2018; Marques et al. 2020, 2021), the Canary Islands (Coello-Bravo et al. 2020), and the Lesser Antilles (Solaro et al. 2020) as well as the Bismarck Archipelago in the Pacific Ocean (Watt et al. 2019). Moreover, the collapse of Anak Krakatau on 22 December 2018 stimulated much research (Williams et al. 2019; Grilli et al. 2019, 2021; Hunt et al. 2021; Cutler et al. 2022) and it is anticipated that the collapse of Hunga Tonga-Hunga Haʻapai on 15 January 2022 will provide the impetus for many new studies. Consequently, this feels like an auspicious time to update the global giant landslides on volcanic islands database.

First, the recent literature will be scrutinised with the aim of updating the information already contained in the database. Second, two new layers will be added. The first of these layers will provide information about recent volcanic collapses such as those of Anak Krakatau and Hunga Tonga-Hunga Haʻapai. Synthesising information about these events is important because they represent outstanding analogues for past collapses. The second of these layers will provide information about the long term monitoring of giant landslides on volcanic islands through direct instrumental methods such as dilatometric gauges (Blahůt et al. 2017, 2018b) and GNSS (Owen et al. 2000; Hildebrand et al. 2012). Such monitoring is important because it serves to verify remote sensing observations, which could be especially helpful in relation to hazard assessment. It is intended that the second release of the giant landslides on volcanic islands database will be available online in early 2023.

6 Conclusions

Landslide inventories and thematic databases provide essential information needed to assess the spatial and temporal distribution of landslides, their preparatory factors and triggers, and their negative societal impacts. In this paper, an online database of giant landslides on volcanic islands has been described. The database was constructed from 2016 to 2018 and comprises a total of seventy-five events from the Atlantic Ocean and Mediterranean Sea, sixty-seven events from the Pacific Ocean, and forty events from the Indian Ocean. However, there is now a clear need to update the existing database in light of potentially significant recent research from archipelagos in the Atlantic and Pacific Oceans coupled with major collapses on Anak Krakatau and Hunga Tonga-Hunga Haʻapai. Two new layers will provide information about recent volcanic collapses and the long-term instrumental monitoring of giant landslides. The second release of the database should be available online in early 2023.

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