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Harmonising the lithostratigraphic nomenclature: towards a uniform geological dataset of Switzerland

Stefan Strasky[1] · Alain Morard[1] · Andreas Möri[1]

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Abstract Uniform geological datasets are a prerequisite for geological GIS analyses. Although the Geological Atlas of Switzerland 1:25,000 aims to supply spatial geological information nationwide, little effort has been undertaken in the past to harmonise this map series and its vector datasets. In the course of the HARMOS project, lithostratigraphic nomenclature was harmonised and standard map legends for a target scale of 1:25,000 were produced. This allows representing the lithostratigraphic units of Switzerland in a homogeneous way and sets a new reference in the lithostratigraphy of Switzerland. More than 40 experts in the field of regional stratigraphy contributed their knowledge to the project and, together with the Swiss Committee on Stratigraphy, guaranteed a high quality level. All results are presented in the Lithostratigraphic Lexicon of Switzerland, available cost-free online at http://www.strati.ch. By improving quality and accessibility of lithostratigraphic information, we supply a fundamental basis for the Swiss geological community and further research.

Keywords Regional stratigraphy · Lithostratigraphy · Geological maps · GIS

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✉ Stefan Strasky
stefan.strasky@swisstopo.ch

1 Swiss Geological Survey, Federal Office of Topography swisstopo, Seftigenstrasse 264, 3084 Wabern, Switzerland

1 Introduction

During the last 20 years, the demand for geological vector datasets in geographic information system (GIS) format has risen steadily. The benefits and the fields of applications of uniform, well-structured geological datasets are diverse (e.g. Heitzmann and Phillipp 1999; Beer et al. 2005; Asch et al. 2012). Their use still has an enormous potential in various fields such as subsurface and land-use planning, civil engineering, natural hazard assessment or 3-dimensional (3D) geological modelling.

Long before the digital age, Maurice Lugeon was aware of the significance of uniform nationwide geological maps by initiating the production of the Geological Atlas of Switzerland 1:25,000 (GA25) in 1924 (protocol of the Swiss Geological Commission, May 10, 1924). Albert Heim, the president of the Swiss Geological Commission at that time, criticised the new approach of a sheetwise geological map production based on divisions of the topographic map series. He worried about a senseless division of Switzerland's geology into rectangles and a loss of meaning by abandoning the conventional approach of limiting the map extent to scientifically reasonable, natural geological boundaries. Furthermore, he argued that a uniform map legend cannot be constructed in advance and must succeed the mapping process in any case. Consequently, A. Heim announced his resignation from the Swiss Geological Commission (Heim 1924) and the way was paved for the production of the GA25. M. Lugeon and others created the first standard map legend for the GA25. The Swiss Geological Commission approved this basic map legend and the first map sheet of the GA25 was published in 1930 (Keller and Liniger 1930). Since then, 149 further map sheets, covering approximately 68 % of Switzerland's territory, have been published by the Swiss

Geological Commission and later by the Swiss Geological Survey (e.g. SGC 1985; FOWG 2002) and subsequently transferred into GIS datasets, which are now available at swisstopo under the name of GeoCover (SGS 2012a).

Despite the initial uniform concept, map legends of the GA25 differ significantly from each other in many cases, especially with regard to lithostratigraphic nomenclature. This is due to the long production period of the GA25 of over 85 years and the missing lithostratigraphic standards on the one hand, and scientific progress in lithostratigraphy on the other hand. The publication of the Swiss fascicles of the International Stratigraphic Lexicon set a first important standard (Waibel and Burri 1960; Rutsch 1964; Habicht 1987). Further publications by the Swiss Committee on Stratigraphy (SCS) regarding the use of lithostratigraphic nomenclature in Switzerland followed (SGC 1973; Remane et al. 2005). However, the differing individual application of lithostratigraphic nomenclature by the authors as well as the regional or historical preferences remain obvious in the legends of the different GA25 map sheets (Fig. 1) and considerably limit the power of digital datasets of this map series. GIS analyses involving several GA25 map sheets are thus very restricted. Therefore, the Swiss Geological Survey initiated the HARMOS project in 2011 with the aim of harmonising the lithostratigraphic nomenclature of the GA25 map units and developing standard map legends in order to complete the Swiss geological data model (SGS 2012b) and to uniformly describe the geology of Switzerland at a scale of 1:25,000.

The present work shows the procedure towards the new standard map legends and summarises the most important results from the HARMOS project.

2 Procedure

Lithostratigraphy is the primary means of subdividing, classifying and naming rock bodies based on observable field criteria (petrography, mineral and fossil content, geomorphology) and mutual geometric relationships. Although the determination of lithostratigraphic boundaries often remains somewhat arbitrary both vertically and laterally, it still provides a stable, objective framework for further geological investigations. Lithostratigraphy thus has to be clearly distinguished from interpretative approaches such as chronostratigraphy, biostratigraphy or sequence stratigraphy. The fundamental unit of lithostratigraphy (and of geological mapping at a scale of 1:25,000) is the formation, which is defined as «a rock unit whose lithological characteristics differ from surrounding formations and/or which is bounded by mappable discontinuities» (Remane et al. 2005). The SCS suggests applying the lithostratigraphic procedure to all rock types, from

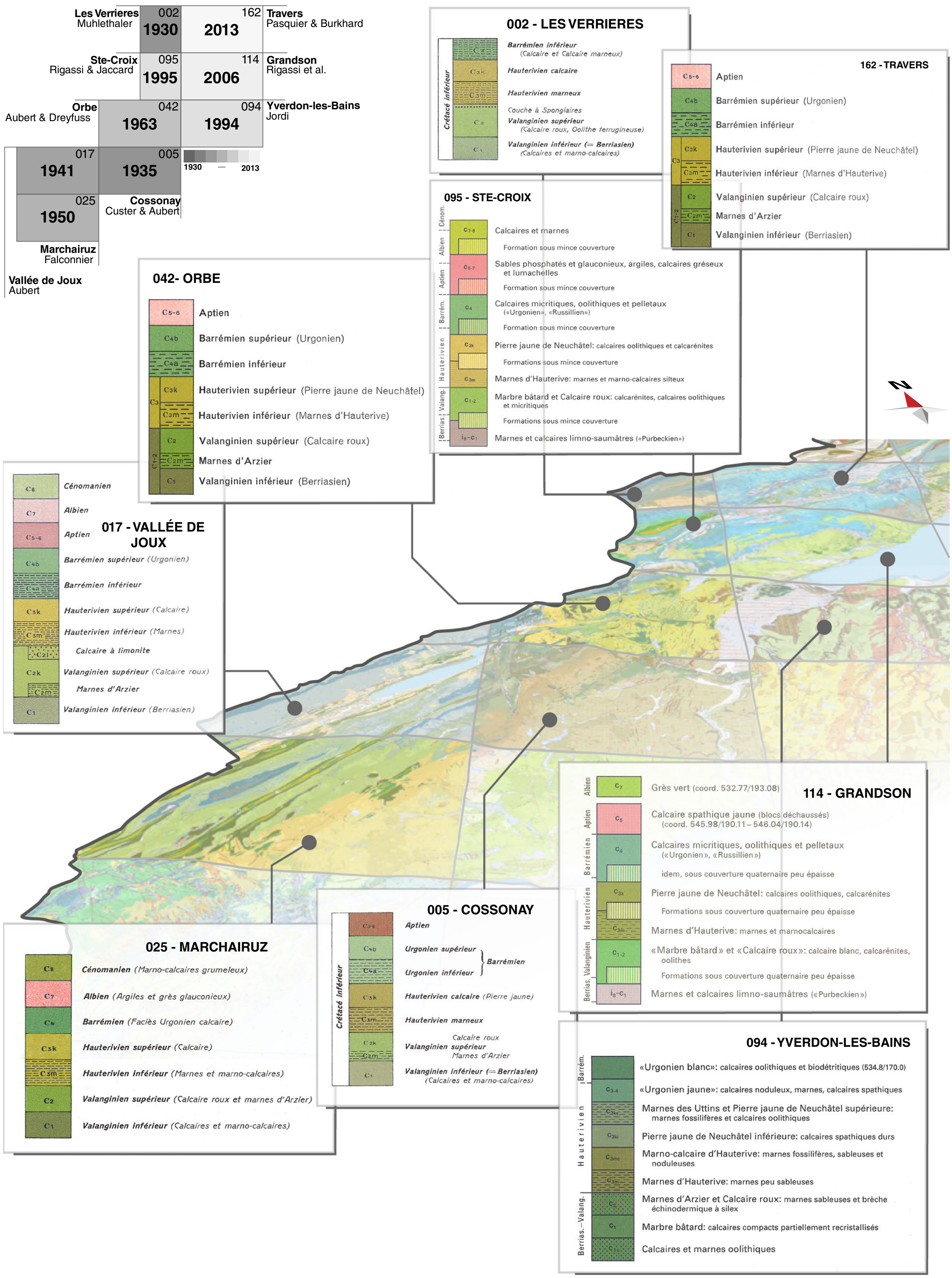
Fig. 1 Example illustrating the heterogeneity of GA25 map legends. ▶ Details of nine GA25 map legends show the varying lithostratigraphic nomenclature of the Cretaceous units in adjacent maps of western Switzerland. References, GA25 map sheet numbers and publication dates (in *bold*) are indicated in the overview in the *upper left corner*. 2.5-Dimensional perspective representation of corresponding GeoCover datasets are from https://map.geo.admin.ch. The height of a GA25 map sheet equals 12 km

sedimentary (including Quaternary deposits, as long as their accumulation is complete), to igneous and metamorphic rocks (Remane et al. 2005; confirmed at plenary session SCS, March 5, 2015). Accordingly, the lithostratigraphic units of Switzerland were considered in a broad sense, including the so-called lithodemic (NACSN 2005) and lithogenetic map units as well.

To harmonise the lithostratigraphic nomenclature in Switzerland, we basically continued and accelerated the work of the SCS (Burkhalter and Heckendorn 2009). In order to guarantee a high quality standard and thus to achieve a wide acceptance of the HARMOS outcome, we closely collaborated with the SCS and acknowledged experts in the field of regional stratigraphy. We organised thematic working groups according to the nine existing sections of the SCS (Burkhalter and Heckendorn 2009) and established one more group to handle basement units, which have not yet been treated by the SCS. Each working group comprised a group leader and two to six members working on a voluntary basis. The HARMOS working groups and their members are listed in Table 1.

The groups were asked to make a standard map legend for each thematic region by defining the most appropriate lithostratigraphic terms for mappable geological units at a scale of 1:25,000, i.e., formations and groups and only rarely members and beds. Correlation tables of the published GA25 map legends served to compare the different nomenclatures and to keep an overview of the great variety of Switzerland's lithological units. Additionally, detailed literature inquiries were carried out to sort out historical terms and to correlate geological units over broader areas. In several individual meetings, coordinated by the Swiss Geological Survey, the standard map legends were developed following the guidelines for lithostratigraphic nomenclature by Remane et al. (2005) with regard to, e.g., the hierarchical classification or the choice of type localities.

As far as possible, lithological composition and further rock specific characteristics of each lithostratigraphic unit were uniformly described according to the attributes and their standard values given in the Swiss geological data model (SGS 2012b). The Swiss Geological Survey conducted data management and a first quality control. After a second quality check by the SCS, the collected data were published in the Lithostratigraphic Lexicon of Switzerland of the Swiss Academy of Sciences (http://www.strati.ch). To improve data management and usability of the lexicon,



Les Verrieres
Muhlethaler
002
1930
162
2013
Travers
Pasquier & Burkhard
Ste-Croix
Rigassi & Jaccard
095
1995
114
2006
Grandson
Rigassi et al.
Orbe
Aubert & Dreyfuss
042
1963
094
1994
Yverdon-les-Bains
Jordi
017
1941
005
1935
1930 — 2013
025
1950
Cossonay
Custer & Aubert
Marchairuz
Falconnier
Vallée de Joux
Aubert
002 - LES VERRIERES
Crétacé inférieur
Barrémien inférieur
(Calcaire et Calcaire marneux)
Hauterivien calcaire
Hauterivien marneux
Couche à Spongiaires
Valanginien supérieur
(Calcaire roux, Oolithe ferrugineuse)
Valanginien inférieur (= Berriasien)
(Calcaires et marno-calcaires)
162 - TRAVERS
Aptien
Barrémien supérieur (Urgonien)
Barrémien inférieur
Hauterivien supérieur (Pierre jaune de Neuchâtel)
Hauterivien inférieur (Marnes d'Hauterive)
Valanginien supérieur (Calcaire roux)
Marnes d'Arzier
Valanginien inférieur (Berriasien)
095 - STE-CROIX
Cénom.
Albien
Aptien
Barrém.
Hauterivien
Valang.
Berrias.
Calcaires et marnes
Formation sous mince couverture
Sables phosphatés et glauconieux, argiles, calcaires gréseux et lumachelles
Formation sous mince couverture
Calcaires micritiques, oolithiques et pelletaux («Urgonien», «Russillien»)
Formation sous mince couverture
Pierre jaune de Neuchâtel: calcaires oolithiques et calcarénites
Formations sous mince couverture
Marnes d'Hauterive: marnes et marno-calcaires silteux
Marbre bâtard et Calcaire roux: calcarénites, calcaires oolithiques et micritiques
Formations sous mince couverture
Marnes et calcaires limno-saumâtres («Purbeckien»)
042- ORBE
Aptien
Barrémien supérieur (Urgonien)
Barrémien inférieur
Hauterivien supérieur (Pierre jaune de Neuchâtel)
Hauterivien inférieur (Marnes d'Hauterive)
Valanginien supérieur (Calcaire roux)
Marnes d'Arzier
Valanginien inférieur (Berriasien)
017 - VALLÉE DE JOUX
Cénomanien
Albien
Aptien
Barrémien supérieur (Urgonien)
Barrémien inférieur
Hauterivien supérieur (Calcaire)
Hauterivien inférieur (Marnes)
Calcaire à limonite
Valanginien supérieur (Calcaire roux)
Marnes d'Arzier
Valanginien inférieur (Berriasien)
N
114 - GRANDSON
Albien
Aptien
Barrémien
Hauterivien
Berrias. Valanginien
Grès vert (coord. 532.77/193.08)
Calcaire spathique jaune (blocs déchaussés) (coord. 545.98/190.11 – 546.04/190.14)
Calcaires micritiques, oolithiques et pelletaux («Urgonien», «Russillien»)
idem, sous couverture quaternaire peu épaisse
Pierre jaune de Neuchâtel: calcaires oolithiques, calcarénites
Formations sous couverture quaternaire peu épaisse
Marnes d'Hauterive: marnes et marnocalcaires
«Marbre bâtard» et «Calcaire roux»: calcaire blanc, calcarénites, oolithes
Formations sous couverture quaternaire peu épaisse
Marnes et calcaires limno-saumâtres («Purbeckien»)
005 - COSSONAY
Crétacé inférieur
Aptien
Urgonien supérieur
Urgonien inférieur
Barrémien
Hauterivien calcaire (Pierre jaune)
Hauterivien marneux
Calcaire roux
Valanginien supérieur
Marnes d'Arzier
Valanginien inférieur (= Berriasien)
(Calcaires et marno-calcaires)
025 - MARCHAIRUZ
Cénomanien (Marno-calcaires grumeleux)
Albien (Argiles et grès glauconieux)
Barrémien (Faciès Urgonien calcaire)
Hauterivien supérieur (Calcaire)
Hauterivien inférieur (Marnes et marno-calcaires)
Valanginien supérieur (Calcaire roux et marnes d'Arzier)
Valanginien inférieur (Calcaires et marno-calcaires)
094 - YVERDON-LES-BAINS
Barrém.
Hauterivien
Berrias.–Valang.
«Urgonien blanc»: calcaires oolithiques et biodétritiques (534.8/170.0)
«Urgonien jaune»: calcaires noduleux, marnes, calcaires spathiques
Marnes des Uttins et Pierre jaune de Neuchâtel supérieure: marnes fossilifères et calcaires oolithiques
Pierre jaune de Neuchâtel inférieure: calcaires spathiques durs
Marno-calcaire d'Hauterive: marnes fossilifères, sableuses et noduleuses
Marnes d'Hauterive: marnes peu sableuses
Marnes d'Arzier et Calcaire roux: marnes sableuses et brèche échinodermique à silex
Marbre bâtard: calcaires compacts partiellement recristallisés
Calcaires et marnes oolithiques

the Swiss Geological Survey took on the maintenance of the lexicon within the context of this project. A new screen design and a data management system were developed for the online lexicon using PHP programming language and TYPO3 Flow to allow professional data management.

3 Results

The results of the HARMOS project are presented and distributed in the online Lithostratigraphic Lexicon of Switzerland (http://www.strati.ch). A compilation of the simplified lithostratigraphic standard map legends is available as a hard copy and for download as supplementary material in Online Resources 1 and 2, which are attached to the online version of this journal and are also available at http://www.strati.ch.

3.1 Lithostratigraphic nomenclature of Switzerland

The results given in this section represent the main outcome of the different HARMOS working groups. They were elaborated by the corresponding group members (see Table 1). In order to follow the guidelines for stratigraphic nomenclature (Remane et al. 2005), informal names such as «Serie/série» or «Schichten/couches» as well as facies terms were generally replaced by formation names. Informal names were kept only in the case of poorly defined lithostratigraphic units.

3.1.1 Jura West

The Jura West working group focussed mainly on the Cretaceous formations, where an improved lithostratigraphic scheme for the Swiss Jura Mountains was defined. Rapid lateral and vertical facies changes as well as multiple hiatuses characterise the complex evolution history of the Swiss Jura realm during the Cretaceous and often made an unequivocal definition of a formation difficult. Where poor outcrop conditions prevented the definition of formations at type localities in Switzerland, sections in the French Jura were chosen. Details regarding the Cretaceous lithostratigraphy of the Swiss Jura Mountains are given in Strasser et al. (2016) and Pictet et al. (2016).

3.1.2 Jura East

Major progress was made in the reorganisation of the lithostratigraphic scheme for the Triassic sedimentary succession of northern Switzerland. The Triassic units were divided as follows: Buntsandstein Group (Dinkelberg Formation), Muschelkalk Group (Kaiseraugst, Zeglingen and Schinznach formations) and Keuper Group (Bänkerjoch and Klettgau formations). Details of the new organisation of the Triassic stratigraphy of northern Switzerland are presented in Jordan (2016), Jordan et al. (2016) and Pietsch et al. (2016).

3.1.3 Molasse basin

A new classification scheme was developed for the Upper Marine Molasse (OMM) in the central Swiss Plateau, where two new lithostratigraphic units were defined: (1) Safenwil-Muschelsandstein (member of Lucerne Formation, near top of formation) and (2) Staffelbach-Grobsandstein (bed of St. Gallen Formation, local base of formation). A compilation of available biostratigraphic data (mammal teeth) shows that the OMM comprises mammal units MN3a–MN4b and is in good agreement with the results from the southern basin area. Moreover, studies

Table 1 Members of the working groups

Jura	Molasse basin	Helvetic	Prealps	Penninic	Austroalpine South Alpine	Quaternary
A. Strasser[W]	**J.-P. Berger**†	**H. Funk**[S]	**S. Dall'Agnolo**	**Y. Gouffon**[WL]	**H. Furrer**[S]	**C. Schlüchter**
J. Charollais[W]	**D. Kälin**	D. Decrouez[S]	G. Borel	M. Marthaler[W]	D. Bernoulli[S]	C. Ambrosi
M. Conrad[W]	O. Kempf	U. Menkveld-Gfeller[S]	R. Plancherel	M. Sartori[W]	U. Eichenberger[S]	L. Braillard
		A. Pfiffner[S]	M. Thalmann	T. Burri[L]	M. Maggetti[C]	R. Burkhalter
W. Heckendorn†[E]				F. Keller[L]	H.-R. Pfeifer[C]	Y. Gouffon
P. Bitterli[E]		**I. Mercolli**[C]		H. Masson[L]		H.R. Graf
R. Burkhalter[E]		F. Bussy[C]				T. Gubler
G. Comment[E]		E. Gnos[C]		**W. Winkler**[E]		
P. Jordan[E]				A. Isler[E]		
A. Reisdorf[E]				M. Wiederkehr[E]		

Group leaders are marked in bold

† Berger, Heckendorn: Deceased

Superscript letters indicate thematic subdivisions of the working groups: *W* western part, *E* eastern part, *L* Lepontine area, *S* sedimentary rocks, *C* crystalline rocks on teeth of Selachian faunas indicate changes in the palaeoenvironment of the depositional realm. Details of the new lithostratigraphic scheme of the OMM are given in Jost et al. (2016).

3.1.4 Helvetic, sedimentary rocks

For the sedimentary rocks of the Helvetic realm the main focus was placed on a simplified and partially newly defined lithostratigraphic nomenclature of the Helvetic Palaeogene (in continuation to Herb 1988), which comprises nummulitic deposits as well as north-, south- and ultrahelvetic flysch deposits. Based on palaeogeographic reconstructions, the evolution history of the Helvetic sedimentary sequences during the Palaeogene is shown by: (1) reconstruction of pre-Palaeogene substratum, (2) temporal and spatial distribution of Euthal, Bürgen, Klimsenhorn and Wildstrubel formations and (3) temporal and spatial distribution of Niederhorn and Sanetsch formations. The findings are completed by two chronostratigraphic profiles across the Helvetic realm of western and central/eastern Switzerland spanning from the Palaeocene/Eocene until the early Oligocene. The revision of the Helvetic Palaeogene is presented in Menkveld-Gfeller et al. (2016).

3.1.5 Helvetic, basement units

A stratigraphic scheme for the wide variety of basement units in Switzerland was developed. These units include metasedimentary and weakly deformed plutonic rocks as well as polymetamorphic and migmatitic rocks (Table 2). The classification scheme is based on the relative age of the basement units (stratigraphic succession, as well as intrusion and deformation history) and is further subdivided by taking petrographic criteria and spatial separation into account. This general concept was further applied to the basement units of the Helvetic domain, including the establishment of a new formal lithostratigraphic nomenclature (Berger et al. 2016).

Table 2 Classification scheme for basement units

	Approximate age range	Main rock types	Deformation
Late to Post-Variscan	Late Pennsylvanian to Asselian (307–295 Ma)	Plutonic, sedimentary and volcaniclastic rocks	No or very little pre-Alpine deformation
Middle Variscan	Middle Pennsylvanian (315–307 Ma)	Plutonic rocks	Both Late-Variscan and Alpine deformations
Early Variscan	Visean (347–331 Ma)	Plutonic rocks	
Pre- to Early Variscan	Early Carboniferous and older	Sedimentary and volcaniclastic rocks	
Pre-Variscan	Proterozoic to Devonian	Orthogneiss, paragneiss, amphibolites, migmatites, …	Polycyclic deformation, a migmatisation event is often recorded in Middle Ordovician times

Age ranges are indicative and based on the International Stratigraphic Chart, Version 2016/04 (http://www.stratigraphy.org)

3.1.6 Prealps

A refined lithostratigraphic scheme for the upper Prealpine nappes (Sarine, Dranses, Simme and Gets nappes), Breccia nappe and Préalpes Médianes (Klippen nappe) was established. In the latter, the «Calcaires Massifs» are newly subdivided into two separate formations (Dorfflüe and Moléson) as a result of the wide lithological variability reflecting both basin and platform facies.

Chaotic mixed rock bodies occurring between Prealpine nappes were defined as melanges. They are composed of rock fragments of variable age and size, embedded in a clayey or sandy matrix. Since each block may represent a single formation or a composite of several formations, melanges were considered as groups in terms of lithostratigraphy. As type localities, those regions with the widest lithological variability of fragments have been chosen (Plancherel et al. 2012).

3.1.7 Penninic West

The lithostratigraphic sequence within the Swiss part of the Sion-Courmayeur zone as described by Trümpy (1951, 1954) has been largely confirmed. In the tectonic subunit of the Roignais-Versoyen, the following succession can be observed from oldest to youngest: Versoyen Complex, Peula, Aroley, Marmontains and St-Christophe formations. Absolute chronologies are missing.

The lithostratigraphic scheme for the Triassic of the «Zone Houillère» is comparable to the sequences observed in the Siviez-Mischabel nappe and the Préalpes Médianes for the units of Early Triassic (Sartori et al. 2006) and Middle–Late Triassic age (Mégard-Galli and Baud 1977), respectively. For the deposits of Late Palaeozoic age, lithostratigraphic units need to be defined in France because of their better development and the lower degree of deformation on French territory.

The lithostratigraphy of the Siviez-Mischabel and Mont Fort nappes is already well defined by Sartori et al. (2006) for rock units older than Middle Triassic. The younger rock sequence in those nappes is comparable to the lithostratigraphic sequence of the Préalpes Médianes.

Finally, three rock series can be identified in the Tsaté nappe from oldest to youngest: (1) ophiolite series, (2) radiolarite and/or conglomeratic marble series and (3) flysch sequence comprising Flysch de la Fêta d'Août, Série de la Garde de Bordon, Série Grise and Série Rousse.

3.1.8 Penninic-Lepontine

In this complex region, particularly at the boundary between the Helvetic and Penninic domains, any stratigraphic update is intimately linked to the revision of the tectonic scheme, which is at present in preparation. Recent field investigations allowed to locally clarify the lithostratigraphic nomenclature, which opens the way for new palaeogeographic interpretations.

For the polymetamorphic basement, mostly informal petrographic names were retained within the general concept for basement units (Table 2). Although absolute age determinations are rare, the concept for basement units has proven to be useful for the production of the GA25 map series.

3.1.9 Penninic East

Detailed lithostratigraphic correlations between the different nappes are difficult because of differing historically developed subdivision concepts, minimal chronostratigraphic constraints, as well as variable metamorphic overprint. Therefore, the harmonisation consisted of compiling existing lithostratigraphic nomenclature from Switzerland (e.g., Ibele et al. 2016) and neighbouring countries (Allemann 2002; Friebe 2007) with some tentative parallelisation. Here again, for the polymetamorphic basement, mostly informal petrographic names were retained within the general concept for basement units (see Table 2). Comparisons between western and eastern units, classically grouped as «Bündnerschiefer», are still in progress (e.g. Tsaté and Avers nappes), while recent investigations, such as sediment source tracing by detrital zircon (e.g. Bütler et al. 2011; Beltrán-Triviño et al. 2013), helped to clarify the palaeogeographic, palaeotectonic and stratigraphic context for the deposition of flysch units. Laser ablation inductively coupled plasma mass spectrometry dating of detrital zircons of Bündnerschiefer units (Klus, Sassauna and Oberälpli formations) and the flysch unit (Ruchberg Formation) show very distinct age patterns (Beltrán-Triviño et al. 2013). In the former, the dominance of Post-Variscan and Variscan ages (250–350 Ma) is obvious, and early Palaeozoic zircons are in the minority. Both populations are present in the Ruchberg Formation as well. In the latter, however, those age spectra are framed by (1) abundant Neoproterozoic and older zircons and (2) a younger population spanning the Late Triassic—Early Jurassic. The occurrence of Triassic zircons is characteristic for the provenance of the detrital material from the southern Tethys margin (eastern and southern Alps units, Beltrán-Triviño et al. 2013, 2016). This prominent change during the Early Eocene implies a shift in the source of the detrital material towards basement and sedimentary rocks of emerging nappes south of the North Penninic Basin.

3.1.10 Austroalpine

A revised lithostratigraphic nomenclature of sedimentary rocks of the Austroalpine nappes (in continuation to Furrer 1985) and a new lithostratigraphic scheme for Proterozoic and Palaeozoic basement units were defined. The lithostratigraphic scheme of the well-developed Permian to Cretaceous sedimentary sequences of the Upper Austroalpine nappes was applied to the much thinner sequences of the Lower Austroalpine nappes as far as possible. Clearly, different lithological units, occurring only in the Lower Austroalpine nappes, were defined as new formations and members. Moreover, recent biostratigraphic and radiometric age determinations allowed a chronostratigraphic correlation of some lithostratigraphic units.

3.1.11 South Alpine

An improved lithostratigraphic nomenclature of South Alpine Carboniferous to Pliocene sedimentary rocks was established on the basis of the GA25 map sheet Mendrisio (Bernoulli et al. 2016), where the most complete South Alpine sedimentary sequence occurs. Many lithostratigraphic terms and definitions derive from the Italian Stratigraphic Commission (Commissione Italiana di Stratigrafia 2000–2007).

A new lithostratigraphic scheme for Proterozoic to Palaeozoic basement units was also developed, taking into account recent absolute age determinations.

3.1.12 Quaternary

Quaternary stratigraphy follows international standards (Cohen and Gibbard 2011) but takes local differences in the Quaternary sedimentary record of Switzerland (extra-LGM, intra-LGM, Southern Alps) into consideration. As Holocene deposits are not subject of a stratigraphic denomination (Remane et al. 2005), the Swiss Quaternary stratigraphy is organised into four groups from oldest to youngest: Höhere Deckenschotter, Tiefere Deckenschotter, Hochterrasse and Niederterrasse. In this context, the Middle Pleistocene morphotectonic event, i.e. the Middle Pleistocene revolution (e.g. Schlüchter 1987; Head and Gibbard 2005), is considered as an important change in Quaternary landscape evolution.

A more detailed concept for the stratigraphic classification and nomenclature of the Swiss Quaternary deposits is presented by Graf and Burkhalter (2016).

3.2 Lithostratigraphic Lexicon of Switzerland

The lithostratigraphic lexicon of Switzerland currently contains about 3000 lithostratigraphic names. Approximately one-third of them represent names, which have been retained during the HARMOS project and are approved by the SCS. These valid units are grouped according to their generic tectonic or stratigraphic affiliation in the online lexicon. As far as possible, they are listed in a stratigraphic order from bottom to top, representing a sequence from the oldest to the youngest lithostratigraphic unit, respectively. The remaining two-thirds are historical names and registered as full or partial synonyms (e.g. Paulin Member is a full synonym for Vabenau Member, whereas Hilfern Formation is a partial synonym for «Hilferen-Schichten», as the Hilfern Formation corresponds only to the lower part of the original «Hilferen-Schichten»). Some historical names are also indicated as non-synonymous expressions to avoid confusion as, e.g., in the case of the Gérignoz Limestone of the Prealps and the Gérignoz Beds of the Molasse, which represent two completely unrelated stratigraphic units. All unit names (including variable spellings found in the literature) are searchable and cross-linked (direct access to the valid nomenclature).

Each lithostratigraphic unit is described in a uniform structure and can be displayed either as a brief summary or as a more detailed view. In addition to static descriptive elements (status, definition and main characteristics of the unit, thickness, or age range, among other information), integrated hyperlinks allow, e.g., to check the position of the type locality on the Swiss federal map viewer (https://map.geo.admin.ch) or to retrieve important bibliographic references. Navigation between stratigraphically related units (subunits, units at floor/roof, lateral equivalents, etc.) is also possible by means of internal links. Where available, accompanying photos give an idea of the appearance of the lithostratigraphic unit in the field. Furthermore, defined values for the RGB and CMYK colour models are given for the representation on geological maps and profiles. Additional data and documents for download can be shared on this platform as well.

4 Discussion

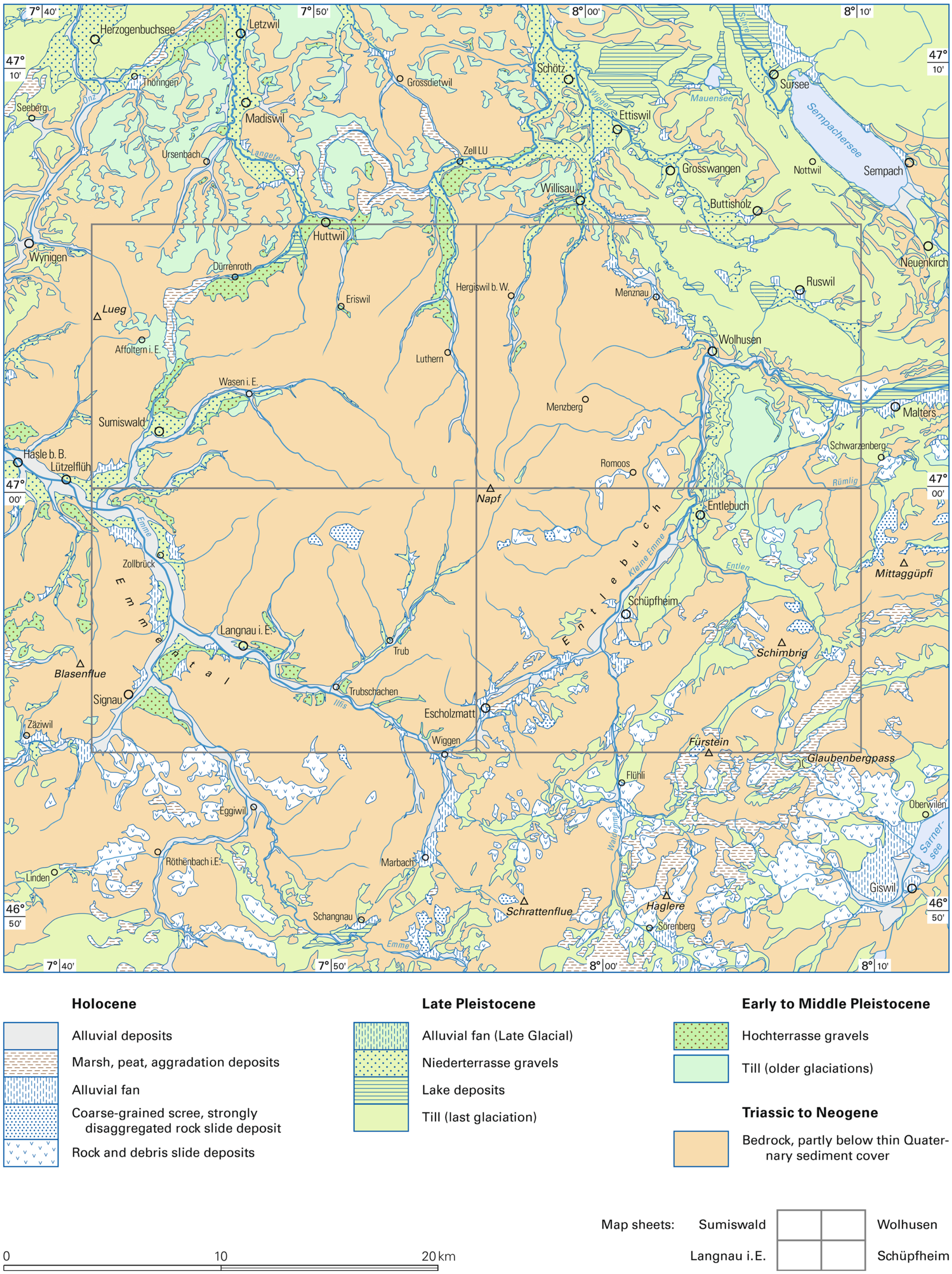
The lack of a uniform description of Switzerland's lithostratigraphic units led us to bring together the stratigraphic experts and to harmonise the geological map legends. Today, geological units that are mappable at a scale of 1:25,000, i.e., mainly formations, are consequently named according to the national stratigraphic guidelines by Remane et al. (2005) and organised in standard map legends. By incorporating and describing the individual lithostratigraphic units of these standard map legends at http://www.strati.ch, we increased the number of terms in the Lithostratigraphic Lexicon of Switzerland from about 350 to more than 3000. This nearly tenfold increase indicates the impact of the HARMOS project, and it shows that a significant amount of existing data was compiled and that new lithostratigraphic information has been added.

The advantages and applications of the HARMOS results are numerous. The most obvious benefit is the possibility to create uniform geological maps and datasets. This was the main goal of the HARMOS project and allows the Swiss Geological Survey to prepare a detailed uniform geological GIS dataset of Switzerland (GeoCover). More than 90 years after the resignation of A. Heim from the Swiss Geological Commission, Heim's reservations concerning the GA25 (Heim 1924) could thus be eliminated. However, 149 GA25 map sheets and knowledge from numerous stratigraphic experts were necessary to overcome Heim's doubt and to establish a uniform map legend and foundation for a seamless geological dataset.

The new lithostratigraphic framework allows creating any kind of map or dataset containing lithostratigraphic information. This possibility can be illustrated with the following three examples, where the new lithostratigraphic concept was applied to show the potential of harmonised datasets at various scales and for different purposes.

4.1 Quaternary overview map

The discussion about past, present and future climate change requires tangible data. Quaternary maps provide such datasets, which allow, e.g., to represent the sedimentary record of former glaciations as sensitive (palaeo-) climate proxies. Harmonised Quaternary maps enable the comparison of the current spatial distribution of glaciers with former ice extents during different periods of the Pleistocene to reveal important palaeoclimatic information. The new Swiss Quaternary stratigraphy yields the potential to clarify the view on the complex Quaternary sedimentary record by means of a simple concept applicable at the scale of the GA25 but also at smaller scales to produce overview maps. Figure 2 shows an example of such an overview map in the Napf region. Apart from small exceptions in the summit area of the Napf (local glaciation), the map shows that the limit of Late Pleistocene till deposits forms a circle around the Napf, following the main valleys of the Emme, Kleine Emme, Önz and Wigger. Older till is found beyond this limit mainly in the northwestern map area, reaching Wasen i.E. and Willisau. Gravel deposits of the


7° 40'
7° 50'
8° 00'
8° 10'
47° 10'
47° 00'
46° 50'
Herzogenbuchsee
Letzwil
Thörigen
Seeberg
Madiswil
Grossdietwil
Schötz
Ettiswil
Sursee
Mauensee
Sempachersee
Sempach
Nottwil
Grosswangen
Buttisholz
Zell LU
Willisau
Ursenbach
Langete
Wigger
Huttwil
Wynigen
Dürrenroth
Eriswil
Hergiswil b. W.
Menznau
Ruswil
Neuenkirch
Lueg
Affoltern i. E.
Luthern
Wolhusen
Wasen i. E.
Menzberg
Malters
Sumiswald
Schwarzenberg
Hasle b. B.
Lützelflüh
Romoos
Rümlig
Napf
Entlebuch
Emme
Zollbrück
Kleine Emme
Entlen
Mittaggüpfi
Emmental
Entlebuch
Schüpfheim
Langnau i. E.
Trub
Schimbrig
Blasenflue
Signau
Trubschachen
Ilfis
Escholzmatt
Zäziwil
Wiggen
Fürstein
Glaubenbergpass
Flühli
Eggiwil
Oberwilen
Sarnersee
Röthenbach i.E.
Marbach
Linden
Haglere
Giswil
Schangnau
Schrattenflue
Sörenberg
Emme
Waldemme
Holocene
Alluvial deposits
Marsh, peat, aggradation deposits
Alluvial fan
Coarse-grained scree, strongly disaggregated rock slide deposit
Rock and debris slide deposits
Late Pleistocene
Alluvial fan (Late Glacial)
Niederterrasse gravels
Lake deposits
Till (last glaciation)
Early to Middle Pleistocene
Hochterrasse gravels
Till (older glaciations)
Triassic to Neogene
Bedrock, partly below thin Quaternary sediment cover
Map sheets:
Sumiswald
Wolhusen
Langnau i.E.
Schüpfheim
0
10
20 km

◀**Fig. 2** Overview map of Quaternary deposits in the Napf region based on harmonised GIS data according to the new simplified concept of Quaternary stratigraphy. Map scale is 1:250,000

Niederterrasse and Hochterrasse further document these ice-marginal and proximal positions, respectively, and represent important georesources (e.g., aggregates) today.

4.2 Geological map of the Aar Massif, Tavetsch and Gotthard nappes

In a joint project between the Institute of Geological Sciences, University of Bern, and the Swiss Geological Survey, the classification concept of basement units was successfully applied and refined to produce a harmonised geological map of the Aar Massif, Tavetsch and Gotthard nappes at a scale of 1:100,000 (Berger et al. 2016). For this special map, 27 individual GeoCover datasets served as a basis. Figure 3 shows an extract of the resulting harmonisation at the junction of the four GeoCover datasets Innertkirchen, Meiental, Urseren and Guttannen.

The harmonisation not only implied the need for uniform terminology but also required a new tectono-stratigraphic interpretation. The following examples illustrate some of the corrections and modifications that were proposed, from simple nomenclatorial adaptations to more complex conceptual considerations:

- A unique name was retained for the Innertkirchen-Lauterbunnen Gneiss Complex (eliminating the many different spellings such as «Innertkirchner Granit» or «Innertkirchen-Kristallin»);
- The name Trift Formation had not been used in the compiled GeoCover dataset of the map sheet Innertkirchen, although this small segment—where the type locality actually lies—forms the junction between two datasets where this unit was recognised and properly named;
- A small granitic lens located in the map sheet Innertkirchen between the Guttannen Gneiss Complex and the Trift Formation was tentatively attributed to the Mittagflue Granite, as its former attribution to the border facies of the Central Aar Granite is probably wrong;
- The biotite gneisses in the north of the Central Aar Granite (map sheets Urseren and Meiental) were aggregated with the «Ofenhorn-Stampfhorn Einheit» in the southwest (map sheet Guttannen) to form the Ofenhorn-Stampfhorn Gneiss Complex.

Thus the production of the harmonised special map helped to identify erroneous parts within original datasets and to overcome obsolete concepts. Although some questions still need to be resolved, the harmonisation approach considerably increased the value of the existing individual datasets.

4.3 Geological 3D models

During the last decade 3D geological visualisation of the subsurface and the deeper underground has become increasingly important to address questions in pure and applied earth sciences. Harmonised 2D geological datasets serve as fundamental input data for 3D modelling and are, thus, a prerequisite for any meaningful 3D subsurface representation of the geological setting at a national or a regional scale. In another project, the Swiss Geological Survey has created 3D geological models of the Swiss Molasse basin (GeoMol). Therefore, GeoCover datasets were harmonised according to the standard map legends, and lithostratigraphic units were grouped to form the GeoMol units, as defined within the project framework. Figure 4 illustrates an example of a 3D visualisation of the GeoMol dataset and underlines the interplay between 2D and 3D datasets.

5 Summary

The heterogeneous lithostratigraphic nomenclature in the published GA25 map sheets considerably limited their potential for GIS analyses involving several map sheets. With the HARMOS project we overcame those limitations by harmonising the lithostratigraphic nomenclature in Switzerland and by supplying standard map legends. Fundamental new elements of these standardised map legends include improved lithostratigraphic schemes, namely for sedimentary sequences of the Jura Mountains region (Triassic, Jordan 2016; Jordan et al. 2016; Pietsch et al. 2016; and Cretaceous, Strasser et al. 2016; Pictet et al. 2016), the Upper Marine Molasse (Jost et al. 2016), the Helvetic Palaeogene (Menkveld-Gfeller et al. 2016), the Prealpine and partially the Penninic nappes, as well as the Austroalpine nappes and the South Alpine domain. By combining the revised and updated sedimentary succession of the map legends with the new classification scheme for basement units (Table 2) and Quaternary stratigraphy (Graf and Burkhalter 2016), a homogeneous compilation of Switzerland's lithostratigraphic units from the Proterozoic to the Quaternary is possible for the first time (Online Resources 1 and 2).

The harmonisation of the lithostratigraphic nomenclature sets a new reference in the lithostratigraphy in Switzerland. It permits the production of uniform geological maps and datasets at different scales and allows harmonising the GA25 map series. This result considerably increases the potential for GIS analyses relevant to the earth sciences. Furthermore, we secured knowledge from more than 40 experts in the field of regional stratigraphy and made it available to a broad community at http://www.strati.ch.

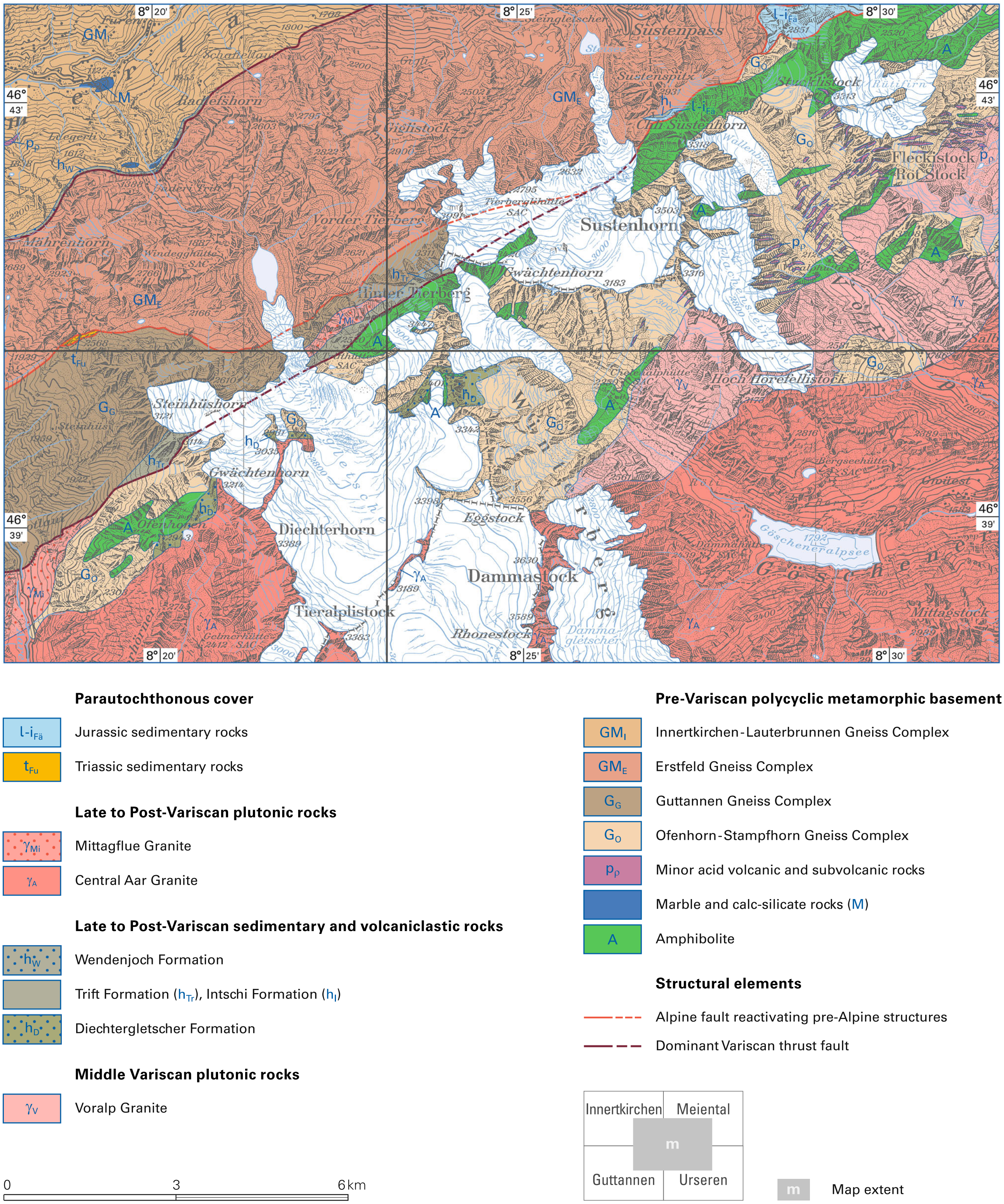


Fig. 3 Extract of the Geological Map of the Aar Massif, Tavetsch and Gotthard nappes 1:100,000 (Berger et al. 2016) covering parts of four adjacent GeoCover datasets in the region of the Aar Massif between Gadmertal in the northwest and Göschenertal in the southeast. The map is based on the new classification scheme for basement units

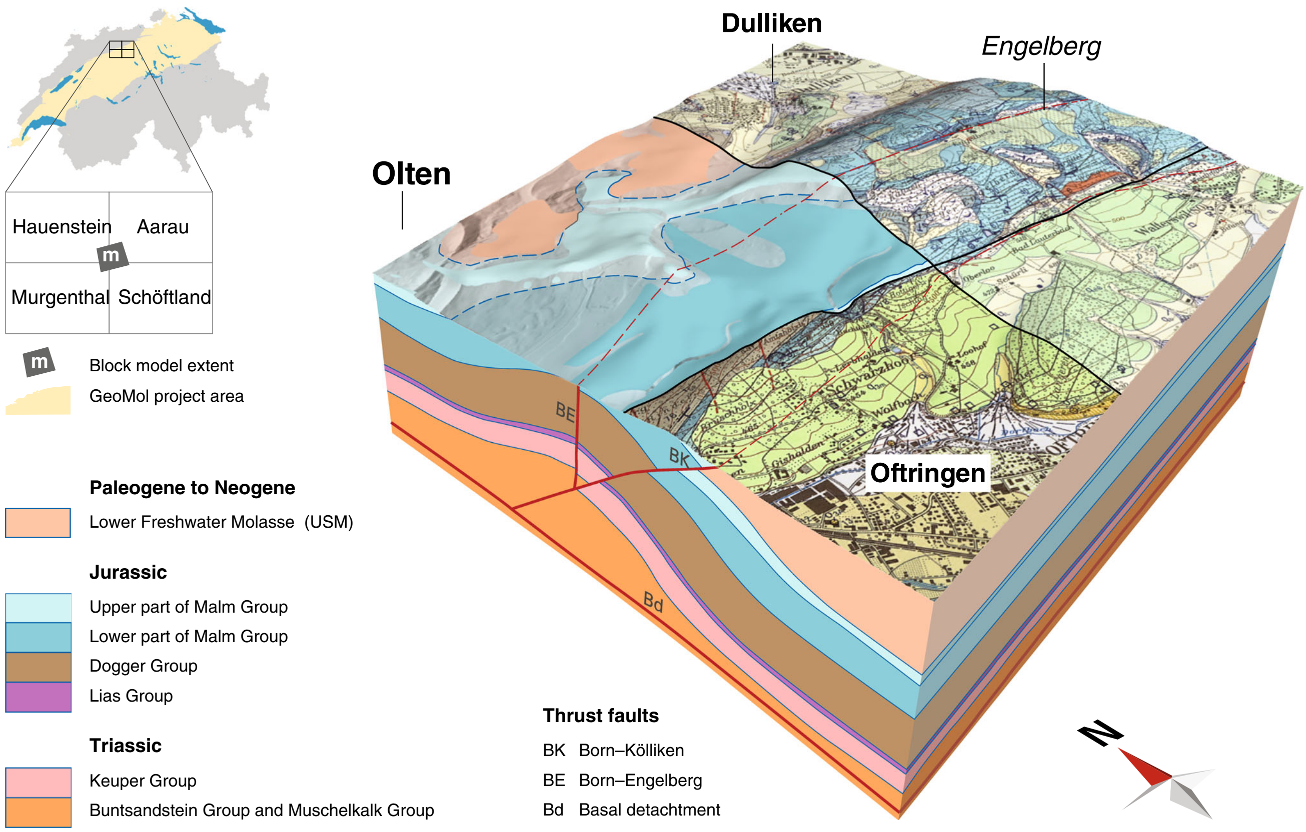


Fig. 4 A 3D block model of the Born–Engelberg structure in the border area of four map sheets derived from the GeoMol dataset. The heterogeneous 2-dimensional datasets, draping the digital elevation model, were harmonised according to the HARMOS results, simplified and reduced to bedrock maps. An example of such a bedrock map is depicted in the Hauenstein map sheet area. *Light colours* represent bedrock surfaces beneath Quaternary deposits, which were delimited by subcrop lines (*blue dashed lines*). The simplified harmonised bedrock maps were combined with existing geological profiles in order to establish the 3D model

6 Conclusions

The project approach involving many acknowledged experts from different institutions such as universities, private companies and governmental organisations in the field of regional stratigraphy and under the patronage of the SCS was straightforward. Beneficial and necessary compromises were reached under the leadership of the Swiss Geological Survey, and the goals were achieved within only three years. Owing to the close collaboration with the experts, we were able to fulfil the quality requirements and ensure the acceptance of the geological community. The publication of the HARMOS results by means of an online lexicon (http://www.strati.ch) further helps to distribute the lithostratigraphic information and to establish the new reference. Therefore, the results from HARMOS are not only indispensable for uniform nationwide geological datasets but also represent a fundamental knowledge base for the geology of Switzerland. Additionally, they contribute to the European effort to harmonise geological data (Asch et al. 2010; Asch and Gdaniec 2014) with a unique level of detail.

Moreover, defining lithostratigraphic units is not only helpful for mapping purposes but also stimulates research, e.g., to better understand the evolution of the Jura platform during the Cretaceous (Strasser et al. 2016) or to unravel the palaeoenvironmental changes during the deposition of the Upper Marine Molasse (Jost et al. 2016). More research is also needed to better constrain or revise the ages of many formations by relative or absolute age determination.

7 Outlook

Swisstopo will integrate the newly developed lithostratigraphic reference model in the production of upcoming GA25 map sheets and currently applies it to the existing vector datasets of GeoCover by renaming and reattributing the formations according to HARMOS. This first step in modifying the data will enhance the usability of these vector datasets, as it allows nationwide queries concerning formations or attributes. Moreover, the online lexicon will be further developed, completed (new insights in regional stratigraphy will be taken into account and subsequently

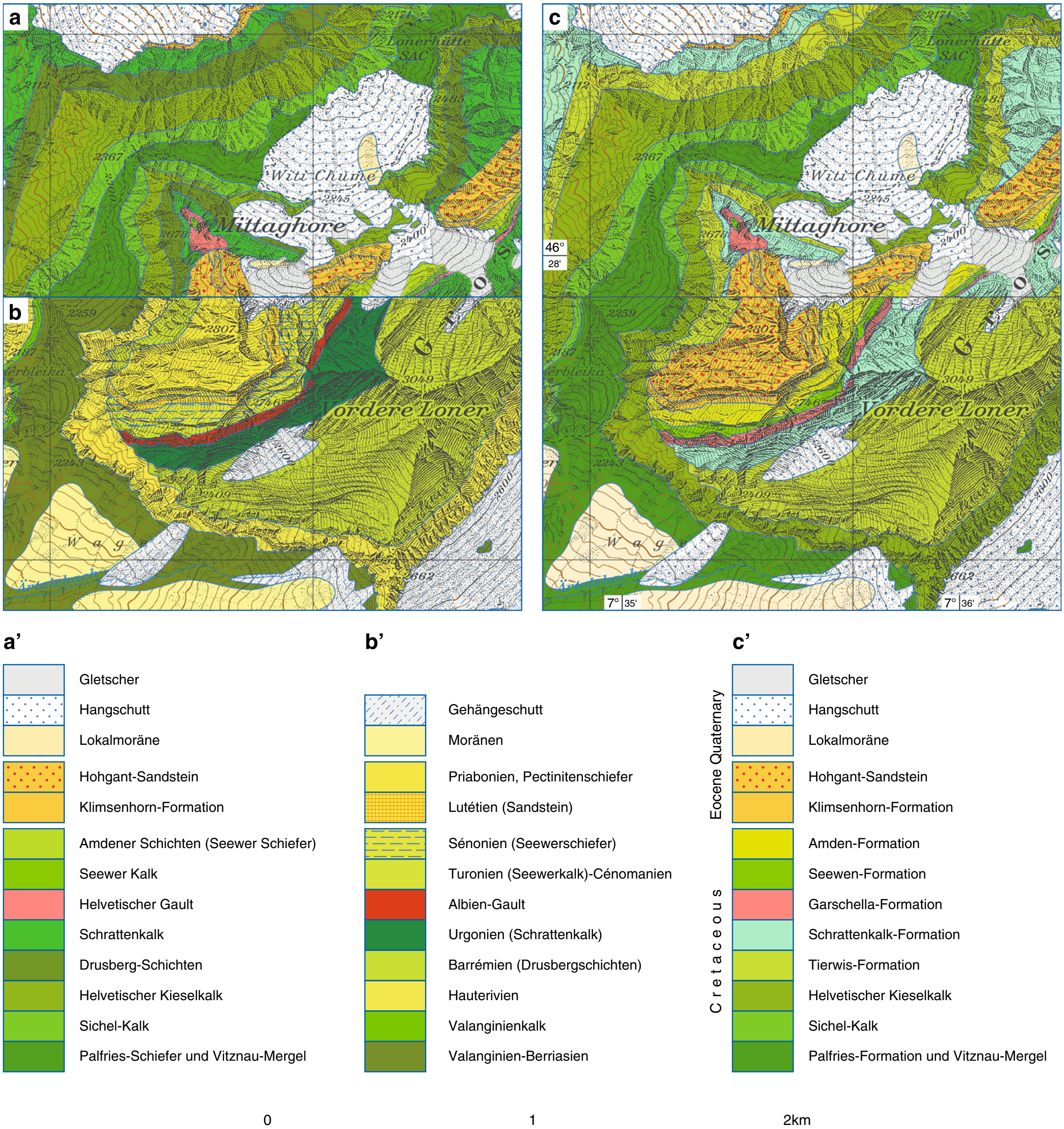


Fig. 5 Extract of the GA25 map sheets **a** Adelboden (Furrer et al. 1993) and **b** Gemmi (Furrer et al. 1956) before and **c** after data harmonisation. The corresponding original legends *a'* and *b'*, as well as the harmonised legend *c'* are given below. Geometric problems along initial boundaries of adjacent maps are clearly visible in the *middle right portion* of figure (**c**). Map scale is 1:25,000

incorporated) and linked to the vector datasets, so that full interaction between the mapped units and the lithostratigraphic lexicon can be guaranteed.

However, in order to prepare a seamless homogenous geological GIS dataset of Switzerland, geometrical revisions along initial map sheet boundaries will be necessary (Fig. 5), and the level of detail has to be homogenised between neighbouring map sheets.

Not only maps and datasets will benefit from the work carried out within the HARMOS project. The results also allow a uniform description of rock formations in boreholes and 3D models that will enhance data exchange and facilitate data generation for the benefit of research as well as applied geology.

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