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Cover photo : Keir Vaughan-Taylor on Lake 2, Koonalda Cave, Nullarbor Plain. (Photo by Kevin Moore)

Back Cover : The Khan and Beagum in Kubla Khan Cave Tasmania (Photo by Garry K. Smith)

Tectonic Control of the Permian Gypsum Karst Belt along the Southern Margin of the Harz-Mountains (Germany)

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Abstract

The Harz Mountains in Germany are an uplifted block of variscan-folded Devonian and Carboniferous rocks with a kilometer-high northward thrust. The overlying, unfolded upper-most Carboniferous, Permian and Buntsandstein (lower Triassic) series are exposed in a wide belt along the South Harz, including a thick series of evaporitic rocks from the upper Permian (Zechstein), dipping with about 10° S to SE. The Zechstein forms an almost continuous karst area nearly 100 km long. The first author, in his dissertation, compiled a geological map for the Zechstein at a scale of 1:10.000, covering an area of 338 km^2, thus revealing the tectonic structure in order to advance our understanding of the karstic features.

Karstification determines the morphology of the area including 184 registered caves, sinkholes, uvalas, sinking creeks and large karstic springs. Specifically, lines of sinkholes appear to follow faults. By detailed mapping of the three lowermost Zechstein cycles, a dense matrix of faults is revealed. 85° to 125° striking faults reoccur every few 100 m, many of them reverse faults with a N-ward thrust. This leads to repetitive exposure of the strata, causing the broadening of the Zechstein outcrop much beyond of what is expected from the local dip of the series. In other areas horst- and graben-structures are apparent, resulting in kilometer-long Lower Buntsandstein ridges that sink into the surrounding Zechstein. Below ground, the groundwater flowing southward along the dip is diverted into the direction of the strike, thus causing strike-parallel depressions, valleys and sinkhole rows. In the final extension phase, faults striking 150° to 180° have caused graben-structures, allowing groundwater and surface rivers to flow southward, breaking through the escarpment of the overlying Lower Buntsandstein. The tectonic structure therefore of the South Harz determines its hydrology and the karst features apparent at the surface.

Keywords:

1. Introduction

Karstification and speleogenesis depend not only on the solubility of rocks and the chemical reactions involved in their dissolution processes, but also on the tectonic structure of the karst-bearing strata. Here we present results of the first author's doctoral thesis that investigates a 338 km^2 large area along the South Harz. The hypothesis is that the tectonic structure is largely determining the hydrogeology and the morphology of this area.

1.1. Geological Situation

Central Europe is characterized by "inversion tectonism", the result of temporal change between (i) extension, (ii) compression, and (iii) extension, locally called "Saxonic Tectonism" (e.g. Kley 2013). After the variscan orogeny in the Upper Carboniferous, that folded much of Central Europe along NE-SW striking axes, the continent extended and sank (i), allowing the deposition kilometers-thick deposits of terrestrial and marine epicontinental series from the uppermost Carboniferous to the Upper Cretaceous. These series came under compression (ii) exerted by the northward thrust of the African Plate underthrusting the Adriatic below the European Plate. This caused the uplift of the Alps and its overthrust tectonics while Central Europe reacted with uplift and dextral tectonics, compensating the thrust. Finally, the expanding Atlantic (iii) dilated the continent E-W that reacted with graben formation.

The compression (ii) led to the uplift of southward dipping blocks of variscan folded series along steeply northward inclined thrust faults striking NW-SE. One of these blocks is the Harz, a mountain range of roughly 90 km NW-SE length

Figure 1. The Harz Mountains, a 80 km long block of raised Devonian and Carboniferous rock. Along the southern border the Zechstein is exposed with varying outcrop width (shaded light blue area). The blue lines represent state-borders. The eastern border of Lower Saxony to the west was the former border between West- and -East-Germany that dissected Harz and South Harz for 40 years, hampering the geological research. The heavy yellow line marks the Eichsfeld High, a paleogeographic rise within the Zechstein Basin

and 30 km width dominated by Devonian and Carboniferous rocks (Fig 1). It was thrust over the Upper Cretaceous series in several pulses along its northern, kilometer-high fault, striking NW-SE (e.g., "wrench-faulting", Wrede 1979, 1988). The direction of this fault system is therefore called "hercynian" (i.e. lat. "Hercynia" for "Harz") and is the dominating direction of faults and joint systems in Central Europe. The dilatation of the continent on the other hand (iii) led to prominent graben systems. The largest of those is the NNE-SSW striking Upper-Rhine-Graben. Its direction is therefore called

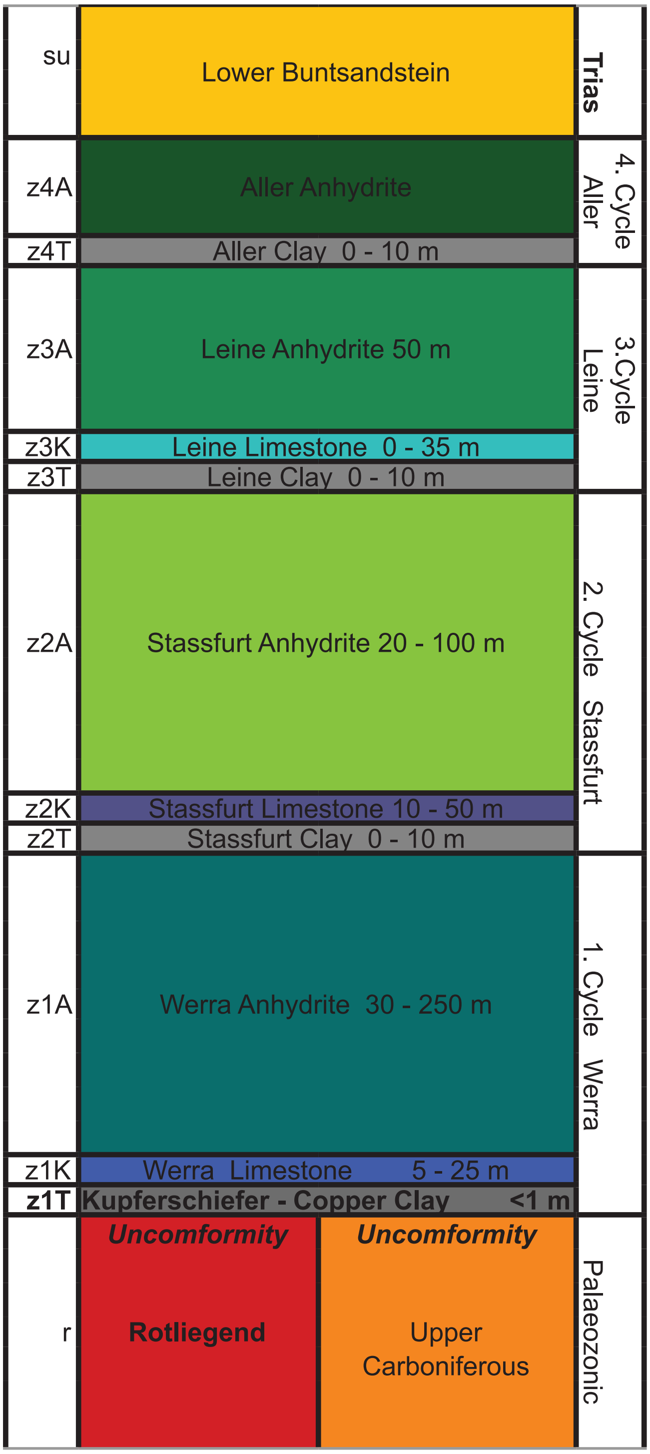

Figure 2. Stratigraphic column of the South-Harz Zechstein.

"rhenish", representing the second most important direction of faults and joints in Central Europe.

In contrast to the prominent thrust-faults on its northern side, the Harz block dips below the unfolded uppermost Carboniferous and Permian series on its southern rim. This area, geographically called South Harz, is by area, the largest outcrop of the upper Permian, marine Zechstein in Germany. The Zechstein, one of the oldest formation names in geological history, is today considered a lithostratigraphc group correlating to the chronostratigraphic stages of Wuchiapingium and Changhsingium comprising the series of the Lopingium (257.3 to 251 Ma). The Zechstein contains up to seven cycles of evaporitic rocks including kilometer-thick salt layers

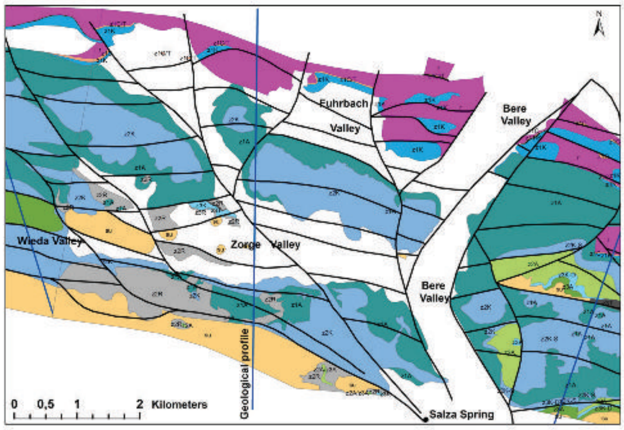

Figure 3. Geological and tectonic map of the Zechstein area on both sides of the Bere-Graben north of Nordhausen. The area is structured into blocks defined by ca. E-W striking faults and by later NW-SE faults converging at the site of the Salza Spring, one of the large karstic springs of the area. The general dip of all blocks is to the S. Color coding see Fig. 2. White areas are covered by Quaternary deposits.

that underlie much of Germany. They formed in a sinking intracontinental basin with restricted access from the world ocean at a tropical latitude. Along the South Harz the lower four Zechstein-cycles are exposed (Werra-, Stassfurt-, Leine, Aller-Cycles), typically starting with a clay-layer, followed by limestone and/or dolomite and superseded by anhydrite, surficially altered to gypsum. These series can be up to 300 m thick (Fig 2). The originally intercalated Na- and K-salts are dissolved at depth and are not exposed due to the humid climate of Europe. To the south, the Zechstein is overlain by thick Lower Triassic continental series, the "Buntsandstein", forming an impervious cap over the Zechstein.

2. Methods

In Germany, systematic geological mapping at a scale of 1:25 000 started in the late 19th century. Some of the quadrants have never been remapped and still show the old Zechstein bipartition into older and younger series instead of the tripartition (neglecting the Aller-series that is mostly buried below solifluction blankets of the clayey Lower Buntsandstein). Furthermore, the Zechstein was considered as being disturbed by karstification, preventing its thorough tectonic analysis. The latest edition of a South Harz map is sheet Osterode (Jordan 1976) which is still lacking adequate tectonic treatment.

The division of Germany prohibited a comprehensive and unified approach to the South Harz, its stratigraphy and tectonics. The second author therefore started in the 1980s to conduct advanced mapping courses within the curriculum of the geosciences at the University of Hamburg and later at the University of Technology, Darmstadt. Additionally, about 40 diploma theses (equivalent to MSc) were supervised that mapped Zechstein areas. After the reunification in 1989, courses and thesis works were extended to the area east of the former border. This material, plus the published geological maps plus additional field work, lists of wells and of sinkholes are summarized in the current PhD thesis. All data were georeferenced and entered into ARCGIS, enabling us to deduce areas and lengths and undertake statistical analyses. Layers containing the different geological and morphological maps,

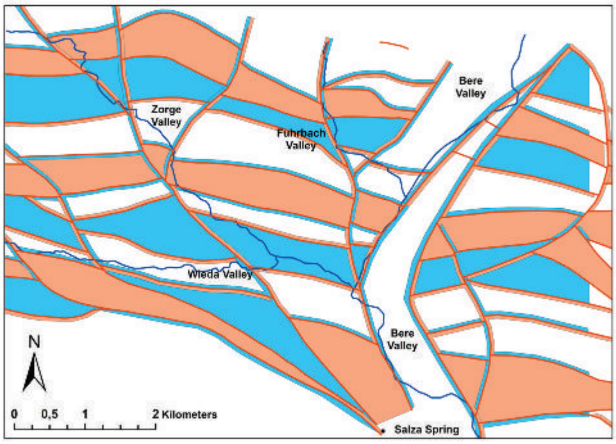

Figure 4. Tectonic model of the area in Figure 3 showing Hercynian reverse faulting and resulting horst (red) and graben (blue) blocks as well as dilatational "rhenish" faults offsetting the older compressional faulting, the downthrow blocks are blue und the upthrow blocks are red marked.

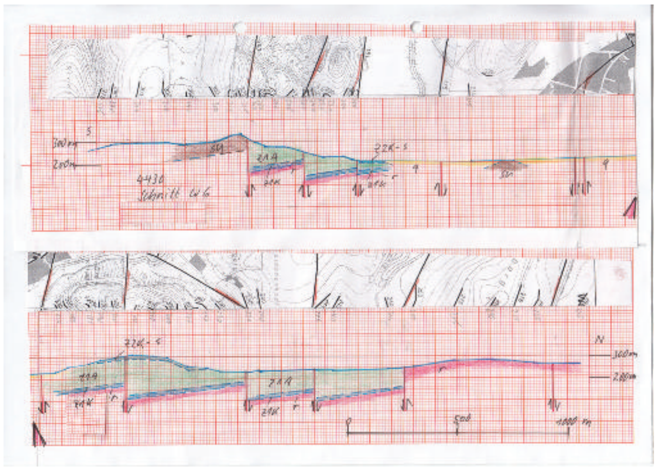

Figure 5. N-S Geological profile showing the tectonic structure of a section from the area in Fig. 3. Lower section fits to the right (N) of upper section.

geological units and other features allow to compare results and to find the best overall interpretation of tectonics.

In the field, the three series are best differentiated by the z2K, a brittle limestone formation with a characteristic smell called "Stinkschiefer" and the z3T, a typical gray clay ("Grauer Salzton"). By mapping these, a unified geological map showing all three series of the entire South Harz was derived for the first time. Wide-spread Harz river terraces, Elsterian moraines as well as glacial solifluction blankets cover about 43% of the Zechstein outcrops.

Our tectonic analysis assumes that the Zechstein basis is dipping with about 10 to 15° S-ward. This is measurable at the lower border of the series where the – undisturbed by karstification and salt-leaching – z1K ("Zechsteinkalk") overlies clastics of either the lower Permian or uppermost Carboniferous or peneplained folded Variscan series (all of these constituting the basement of the Zechstein). Because of this relatively large inclination, the surface outcrop of the undisturbed series is generally only a narrow belt. However, the outcrop width reaches several kilometers in places. This can be explained by repeated reverse faulting. In contrast to this model most earlier authors assumed that the basement dip is diminishing or even reversing southward, avoiding thereby the necessity to assume faulting. One more geological feature complicates the analysis. and this is the "Eichsfeld Schwelle" (ES, Fig 1), a paleogeographic high within the Zechstein basin.

On top of the ES, the z1A and z2A are missing. Along the sides of the ES their thickness first increases to a few hundred meters and then reduces towards the W and E, i.e. towards the centers of the marine basin (Herrmann 1956).

3. Results

Figure 4 shows a central area of the South Harz, north of the city of Nordhausen. It features repeating E-W striking ridges of Werra Anhydrite (z1A) overlain by the Stinkschiefer (z2K) and a graben with lower Buntsandstein. In the S the Lower Buntsandstein is downfaulted against the Zechstein. The E-W ridges are transected by a N-S striking graben, the Bere valley. It could be a small pull-apart basin with the associated dextral strike-slip faults being located north of Ilfeld in the lower Permian volcanics and south of Nordhausen in the Buntsandstein. The presence of pull-apart structures is consistent with transpressional ridges that are also present within the Zechstein in a few sites near Osterode (even though these may be more associated with the Gittelde Graben terminating the Zechstein outcrop in the West). Further NW-SE striking fault lines, along which valleys developed, are offsetting the

Table 1. Areal distribution of important formations and units within the South Harz Zechstein outcrop.

Toposheet Quadrants	*Area [km²]*	*Quaternary [km²]*	*Soli-fluction area [km²]*	*z1A [km²]*	*z2A [km²]*	*z3A [km²]*	*z1K [km²]*	*z2K [km²]*	*z3K [km²]*
4227	39	24	2	3	3	3	-	21	0
4327	43	31	0	3	0	1	1	2	0
4328	39	11	1	-	-	0	7	14	3
4428	11	1	0	-	-	-	1	5	0
4429	67	27	2	7	0	2	2	24	1
4430	47	24	2	10	1	0	1	9	0
4431	50	16	2	5	3	1	3	6	1
4532	18	6	1	3	2	1	2	1	-
4433	24	6	3	1	2	2	2	2	0
Summen	338	146	12	31	11	12	20	83	5

hercynian ridges as well. The vertical thrust of all these faults is varying between a few to a few hundred meters. In Figure 4 the pattern of relative horsts (red) and grabens (blue), as well as series of N-up-thrusted blocks (white) are highlighted, showing the overall structure of the area more clearly.

Figure 5 shows one of the 150 geological profiles that have been constructed every 500 m throughout the entire stretch of the Zechstein outcrop. Constructing these profiles add additional constrains on the tectonic interpretation. The profile illustrates that where the basement is thrusted upward by the revers faulting impervious (or less pervious) shoulders are created representing underground barriers against the southward flowing karst waters. The Zechsteinkalk (z1K) is, because of its bedding planes and jointing, a good aquifer even without considering its potential karstification. Water can thus sink underneath the Werra Anhydrite (z1A), dissolving it from below, a typical hypogene karstification (e.g., Kempe, 1996). Therefore, the valleys develop faster along the reverse faults than along normal faults. In turning around the argument one can assume that the larger dissolutional valleys are developed above reverse fault lines. Figure 4 also shows that several of the NW-SE striking faults converge at a point. At this junction, a large karstic spring exists, the Salza-Quelle. Its discharge amounts to ca. 440 l/sec on average (Völker and Völker 2016). The tectonic pattern shows that the faults can in fact guide water underground from a large tributary area to this point of emergence.

4. Conclusions

In summary, we have to solve an equation with three unknowns when trying to understand the tectonic structure of the Zechstein plateau along the South Harz: Thicknesses of the series, faulting, and inclination, knowing only one factor: Surface geology. However, the reconstruction not only shows internal consistency, it also is embedded into the larger tectonic history of Central Europe and it can explain prominent features of the karst hydrology and morphology.

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