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INFLUENCE OF TECTONIC DISLOCATIONS ON OIL SHALE MINING IN THE ESTONIA DEPOSIT

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Three linear tectonic dislocation groups of different orientation (and probably also of different age) cut the Estonian oil shale-kukersite deposits. Two younger groups of structures are typical fault zones with N-NE and NW trends, which are expressed topographically as narrow valleys, partly infilled by till, both on land and offshore. The oldest, third group of structures is represented by narrow, somewhat curvilinear, NE-trending folded and fractured zones, associated with extensive dolomitization, hydrothermal mineralization and karst. Oil shale within these structural zones is oxidized and partly replaced by karst clay. All dislocations disrupt and complicate the structure of deposit, which affects mining conditions from the technical point of view and also causes a loss of oil shale resources.

Introduction

The Estonia oil shale (kukersite) deposit forms an elongated E-W trending lens-shaped body, about 135 km in length, in the Ida-Virumaa County of northern Estonia. The width of the deposit is 45 km in the east, narrowing to 10–15 km in the west (Fig. 1). The richest part of shale belongs to the lower portion of the Kiviõli Member of the Kukruse Stage, which formed in the beginning of the Late Ordovician, about 460 Ma ago [1]. The maximum thickness of the productive layer is about 3 m [2]. The total thickness of the enclosing Ediacaran and Paleozoic sedimentary strata varies from about 150 m in the north to 300 m in the south. The eroded surface of the strongly folded and metamorphosed Paleoproterozoic crystalline basement is present at depths of 150–300 m, dipping southwards, together with the overlying sedimentary cover, with an inclination of about 3 m per km.

The main geotechnical problems in mining are related to tectonic dislocations in bedrock, including the productive layer. The sedimentary cover records the geological history of ancient Baltica and events in neighboring

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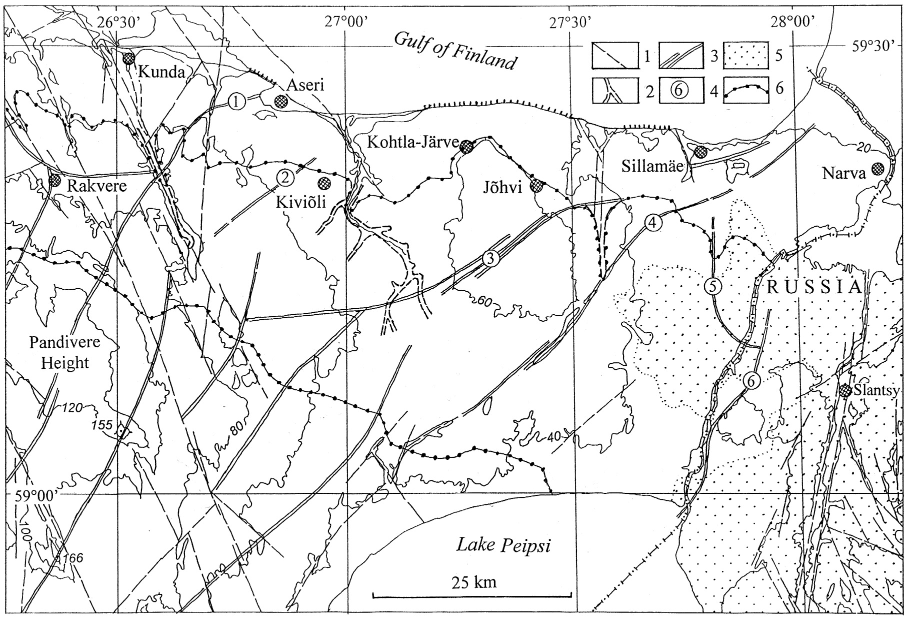

Fig. 1. Linear tectonic dislocations in northeastern Estonia. 1 – Lineaments: straight parts of river valleys or linear escarpments both on land and offshore; 2 – Ancient buried valleys, incised into bedrock through the entire oil shale layer; 3 – Folded and faulted dislocations with wide development of deep level karst, hydrothermal mineralization and dolomitization; 4 – Linear folded and faulted dislocations: Aseri (1), Sonda (2), Ahtme (3), Viivikonna (4), Sirgala (5) and Zagrivskaya (6); 5 – Areas where Ordovician bedrock is covered by Devonian sediments with regional unconformity; 6 – Boundaries of the Estonian commercial oil shale – kukersite deposit.

orogenic zones, including the Scandinavian Caledonides, Urals and Timanides. Using other names, as Baikalian, for the Timanian East European Orogen is less appropriate and may be misleading [3]. Earlier V. Puura and R. Vaher [4] divided the sedimentary cover of Estonia into three tectonic stages: Baikalian (Vendian and Early Cambrian), Caledonian (Late Cambrian–Early Devonian) and Hercynian (the end of Early Devonian–Late Devonian). However, the structural evolution of Timanides ended with orogenesis and Late-Timanian magmatism in the Late-Ediacara (Vendian) age, about 600–545 Ma ago [3].

The tectonic evolution of Estonia correlates well with the evolution of Scandinavian Caledonides, which are located about 650 km to northwest. Four main compressive/transpressive events are known from the Caledonides [5]. The oldest, Finnmarkian event involved collision of the Baltoscandian margin with an oceanic magmatic arc and subduction, with a peak about 505 Ma. This event caused a long hiatus in sedimentation during the Middle and Late Cambrian in Estonia [6]. The opening of the Iapetus Ocean reached a maximum about 490 Ma ago. After the Trondheim event, about 480–475 Ma, Baltica started to rotate anticlockwise away from Siberia [7]. However, the Taconian 470–465 Ma event is not clearly registered in sedimentary record of Estonia. The continuing migration of Baltica towards the equator led to a more rapid sedimentation in warmer seas, including deposition of the highly fossiliferous Estonian oil shale during the Kukruse Stage of the Late Ordovician. Global sea level fell by 50–100 m, accompanied by regression in the Late Ordovician, correlating with Saharan glaciation. Late Silurian sediments can be found only in SW Estonia. The principal Scandian orogenesis is a product of oblique collision between Baltica and Laurentia in the Late Silurian to Early Devonian, during which the Baltoscandian margin was subducted beneath Laurentia. The Scandian thrusting and deformationected the entire Scandinavian Caledonides and reached its peak at 407 Ma [8]. Scandian deformation also affected areas far from Fennoscandia. The Mõniste–Lokno Precambrian basement uplift in SE Estonia and numerous tectonic deformations in the oil shale basin are the result of Scandian orogeny. The following 20 Ma period in Estonia was characterized by erosion and the formation of a regional unconformity. The Caledonian Solundian extensional phase took place between 405 and 395 Ma and continued after 395 Ma [8]. The Middle Devonian transgression extended across the most of Estonia and possibly also a large portion of the Fennoscandian Shield. Devonian white and red colored sandstone ("Old Red") were deposited unconformably on both Ordovician and Silurian strata. This rapid transgressive event was followed by gradual regression of the sea, and the youngest Estonian Late Devonian bedrock occupies only a very limited area in SE Estonia. Although the prolonged 360 Ma period of post-Devonian erosion might theoretically have eroded the upper part of crust, (a total thickness of about 10 km, for a rate of 0.03 mm per year), it is unlikely that the total amount of sediment removed exceeds several hundred meters. The wide development of deep karst in the oil shale deposit under the Middle Devonian sandstone sequence [9] indicates that the sea level was lower and the area occupied by the current Gulf of Finland was emergent. Likely it remained above sea level until the Pleistocene glacial-related sedimentation [10].

Analysis of tectonic dislocations

The 120–300 m thick sedimentary cover is divided into blocks by linear fracture zones. The zones trending NW 310–335° and NNE 5–25° usually form narrow river valleys or lineaments defined by scarps with length 25–100 km (Fig. 1). Valley floors are up to 100–130 m below the current sea level. Some valleys are filled with Quaternary sediments. The higher density of tectonic joints in the bedrock of valley walls shows that they originated as fracture zones. The NW-trending zones are developed preferentially in the western part of the oil shale deposit in the Ordovician bedrock, while NNE-trending faults occur mostly in the eastern part, where the Ordovician and Silurian sequence is partly covered by Devonian sediments. Previously, Devonian rocks would have been more widespread than at present. In the southeastern Estonia, where the Devonian succession is thickest, buried valleys with northerly and northeasterly trends predominate, with relatively few trending northwest. The rectilinear Purtse River valley flows partly along NW, partly NNE trends. In the deep Purtse River valley and in the buried Vasavere valley the commercial oil shale layer has been completely eroded away [11].

Another important tectonic dislocation trend between NE 25–60° was first encountered in 1943 while drilling near the Ahtme mine. Despite the fact that oil shale has been oxidized in fault zones and has no commercial value, some fault zones have been studied in detail. Following the discovery of some further similar dislocations, a decision was made to construct a tunnel specifically through the Ahtme dislocation zone. This tunnel along the oil shale bed was made in 1975–1978 where the fracture zone is narrowest, with a width of 500 m, and accessed three distinctly separate zones. The outermost zone was slightly folded and faulted, layers dipping between 1–4º instead of the usual uniform dip of 15 minutes. The next zone consisted of jointed and altered bedrock with oxidization of oil shale, dolomitization of limestone intercalations and weak sulfide mineralization (pyrite, marcasite, sphalerite, galena) with vein dolomite and calcite. The central zone, about 80 m in width, consisted of crushed and cavernous dolostone and karst, partly replaced by bluish karst clay. In places the dolostone was variably coloured due to ferrous compounds. In this area, layering was tilted, commonly dipping at 12–18º. Mining stopped after passing the central zone. The bedrock throughout the entire dislocation zone is folded, often faulted and with karst development; the maximum vertical displacement measure is 13 m [12].

There are about 20 such dislocations that have been mapped and studied in northeastern Estonia (Fig. 1). This northeast (mainly NE 30–60º) trend of dislocations is not usually expressed by valleys, although they may be parallel to chains of eskers (Viivikonna zone). All such zones were discovered during mining or geological study and the best known Aseri, Ahtme, Sonda and Viivikonna dislocations have vertical amplitude varying from 5 to 25 m and lengths from 10 up to 150 km [12, 13]. The biggest dislocations are regularly spaced, about 12–16 km apart. Each slightly curved dislocation is associated with open anticlinal and synclinal folds with wavelengths of 2–3 km, complicated by minor folds. Dislocations often consist of swarms of parallel zones typically with 5–6 or more parallel faults with intervening folded and fractured bedrock blocks. Bedding on the major fold limbs dips at very small angles, not more than 1–4°, but minor folds may have dips between 18–45° (Fig. 2A, B). Smaller open folds with wavelengths of 5–20 m and amplitude 2–3 m (Fig. 2C) as well as karst occurrences are developed sporadically between the main zones of dislocation. Electrical resistivity prospecting, performed throughout the whole mining area,

(a)

(b)

Fig. 2. Some typical medium scale tectonic structures in the Põhja-Kiviõli quarry. (a) – Anticlinal and synclinal folds in the quarry eastern wall, outside the Sonda dislocation. The length of hammer is 50cm. (b) – Anticlinal fold in the central part of Sonda dislocation.

(c)

(d)

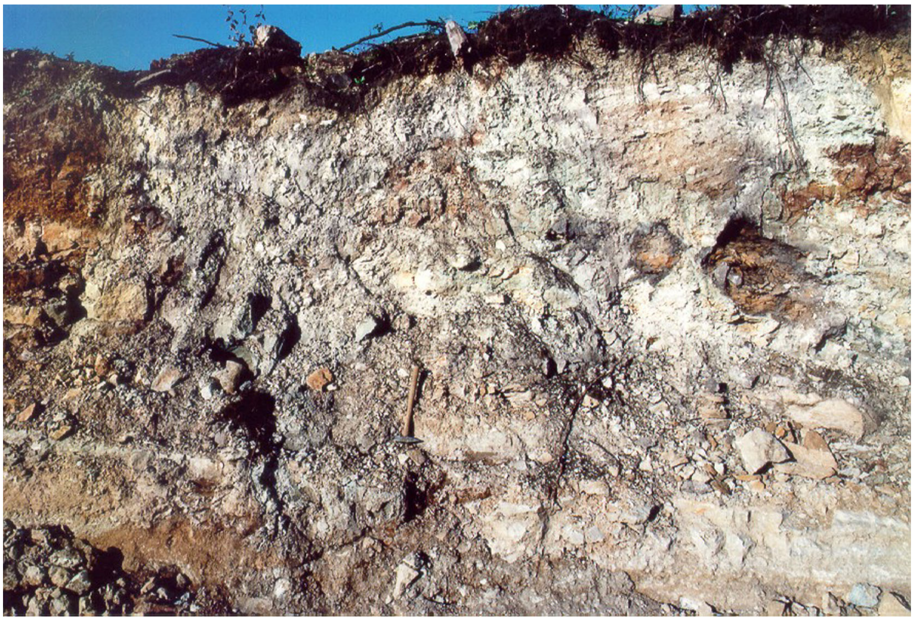

Fig. 2. (c) – Dipping of bedding at about 20° in the wall of the quarry-water trench, at northwestern margin of the Sonda dislocation zone. (d) – Karst clay zone in the northwestern margin of the Sonda dislocation. Brown patches with black marginal zones belong to oxidized oil shale.

(e)

(f)

Fig. 2. (e) – Funnel-shape karst zone filled by bluish clay in the central part of the Sonda dislocation. (f) – The southeastern marginal zone of the Sonda dislocation in the eastern part of the Põhja-Kiviõli quarry, showing fault and thrust.

revealed numerous (more than 700) narrow and conspicuous zones of lower resistivity, which correspond to minor fractures and jointed zones in bedrock. These anomalies are aligned parallel to the main dislocations and may be up to a kilometer in length [14].

In 2005, quarrying at Põhja-Kiviõli oil shale deposit revealed the Sonda dislocation zone, associated with strongly disturbed bedrock, folds, faults and karst occurrences. Where studied so far, the dislocation zone trends NE 53° (Fig. 3). Earlier evidence for the existence of dislocation in this zone had been obtained from electrical resistivity surveys and drilling data. Further resistivity measurements were made by the authors in 2005–2006. Resistivity depth-sounding was carried outside of known karstified fracture zones to study resistivity patterns in a normal geological vertical section. The Schlumberger array was used in which the halfspace (CC/2) distance between the outer electrodes was 3, 5, 9, 15, 25, 40, 65, 100 and 150 m. For (CC/2) 3, 5 and 9–150 m apparent resistivity values were 140, 190 and 250–270 ohm-metres, respectively.

The aim of resistivity profiling was to study a karsified tectonic zone in the commercial oil-shale layer and surrounding carbonaceous bedrock. Profiling was carried out with a station spacing of 10 m using a double-dipole configuration [15]. The electrode separation of both dipoles was 10 m and distance between centres of dipoles l = 20 m. According to I. M. Blokh [16] l = 20 m corresponds to CC/2 = 15 m of the Schlumberger configuration. On the resistivity profile along the vertical wall of the quarry, a solid line marks observed apparent-resistivity curve (Fig. 4). The dotted line represents the same curve shifted 20 m from the current dipole. Apparent resistivity is least (110–140 ohm-metres) above the most fractured and karsted portions of the dislocation (between intervals 3–54 and 185–244 m in Fig. 3). The existence of such a low-resistivity anomaly on twelve profiles enabled us to trace the karsted dislocation zone over about 900 m of strike length.

The bedrock in the Sonda zone is blanketed by a thin (0.5 m) boulder clay horizon, despite the intensity of fracturing and folding [17], indicating a preglacial origin for deformation. Well preserved mesoscopic folds near the present surface indicate that there must have been at least some overlying cover sequence, whereas at present, the depth to the commercial oil shale layer is less than 10 m. The dislocation zone shows sharp boundaries in the wall of open pit and is evident as a folded and faulted zone with wide development of karst clay (Fig. 3), as well as in the apparent resistivity profile (Fig. 4). A very slight homoclinal dipping of beds to the south, with a gradient of about 2.8 m per km, continues to the NE and SW from zone of deformation. The dislocation zone is 200 m wide and folding is evident throughout, the largest folds having wavelengths of 35–50 m and amplitude of 7–8 m. Most anticlinal fold hinges, and sometimes fold limbs as well, are complicated by jointing and faulting, including thrusts. Bedrock in the karst zones is replaced by bluish clay with partly reworked limestone fragments and

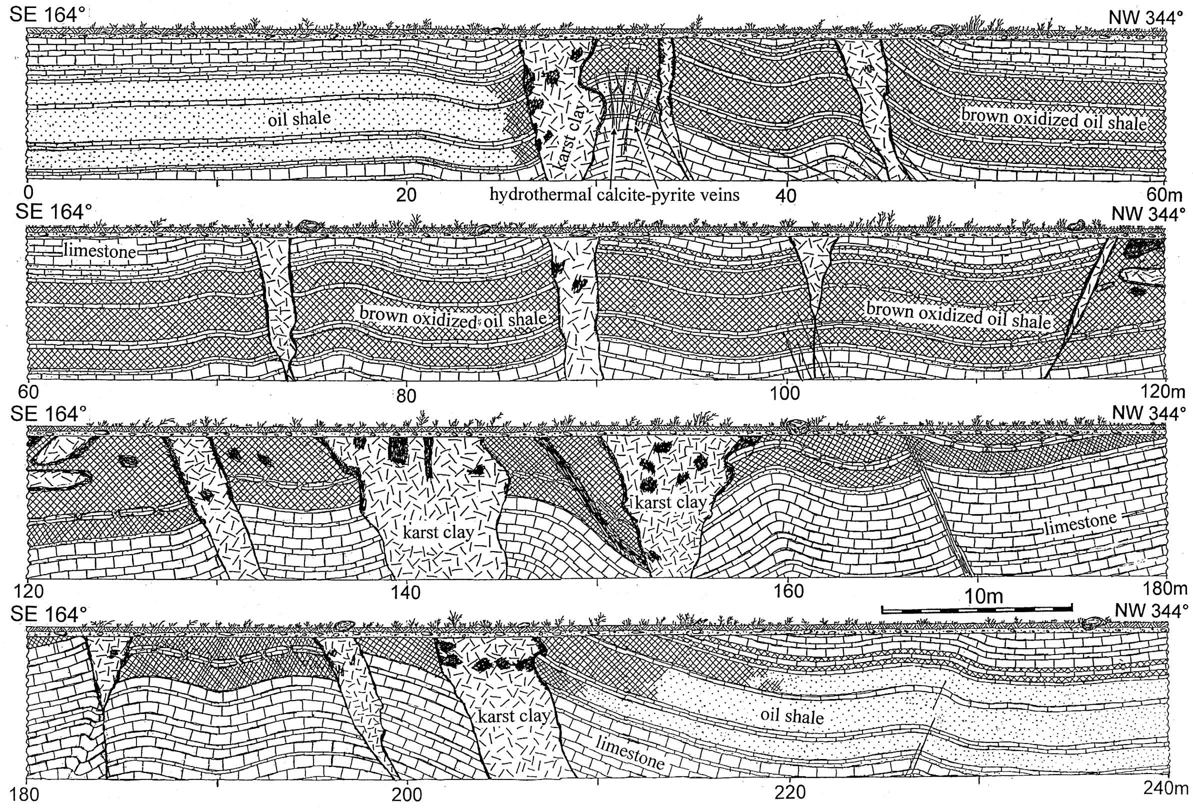

Fig. 3. Near to perpendicular cross-section through the Sonda dislocation (its direction is NE 53º) in the Põhja-Kiviõli quarry in spring 2007. Vertical and horizontal scales the same. Drawn by Y. J. Systra.

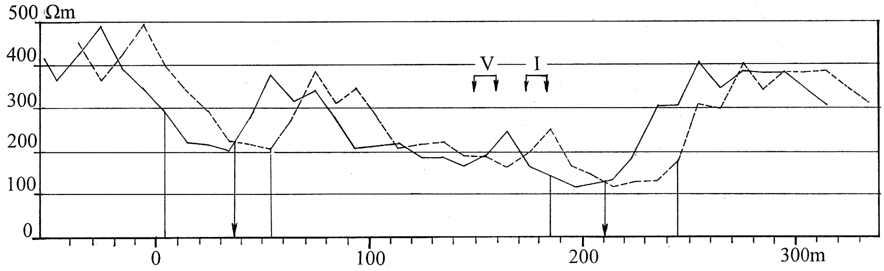

Fig. 4. Resistivity profile along the Sonda dislocation cross-section, shown in Fig. 3.

brown patches of oxidized oil shale, which often have black margins. In the studied section (Fig. 3) there are more than ten karst zones that vary in width from some tens of cm to 10–12 m (Fig. 2D); many of them are narrower in the lower part and funnel-shaped in cross-section (Fig. 2E). Karst zones can commonly be traced into the limestone strata beneath the oil shale layers. Throughout the entire fracture zone limestone is dolomitized and oil shale oxidized. On the SE margin of the Sonda dislocation, within the hinge zone of a mesoscopic anticlinal fold, intensive hydrothermal mineralization is developed, with numerous narrow (1–4 cm) veins of calcite, pyrite and small amount of galena. The transparent prismatic crystals of calcite found here usually form at temperature between 100 and 200 °C [18]. The vertical profile of the studied Sonda dislocation changes rapidly along strike, so that in the next profile, 60 m to NE, the width of karst zones was quite different [17], while at the NE termination, the structure of the fracture zone is complicated by thrusting and faulting (Fig. 4F).

Faults commonly dip towards the NW at angles of 80–55°, which is appropriate for foreland reverse fault activation associated with the Scandian phase of the Caledonian orogeny, which was centered some 600 km to the NW. During the Late Silurian and Early Devonian time Baltica continent was located near the equator, so that weathering rates were rapid, consistent with widespread surface and deep karst in the Ordovician limestone-oil shale sequence, following fault zones and single joints [9]. Individual open joints trending NE 48–75° and with nearly vertical dips (85–90° to NW or NE) are filled by clastic dykes (sandstone), which are also found present in the oil shale horizon, where it is covered by Devonian sandstones**.** Clastic dykes have been identified in 120 different places in the oil shale mines of Estonia and the Leningrad Region. Their thickness is usually 5–15 cm and changes rapidly along strike; they commonly taper downwards. In many places the upper parts of dykes have been displaced several centimeters along bedding planes towards the SE [19]. These displacements had previously been attributed to glaciotectonic processes [2], although the occurrence of such of displacements between layers during flexural-slip folding is a common phenomenon and a likely alternative explanation.

Deep karst is developed only in the disturbed rocks through the whole limestone sequence and up to 30 m beneath the oil shale layer. Deep karst shows zonation, such that the inner 10–15 m of oil shale is changed to karst clay. This central zone is surrounded on both sides by a fractured zone (up to 15–20 m) and more intensively jointed rocks in the outer 20–30 m zone. Bedrock in the fractured zones is also dolomitized and often contains calcite and pyrite veins, sometimes with marcasite, galena, sphalerite, barite and some other minerals. Kerogen in shale is oxidized, dehydrated and humified, has loosed the most of calorific value and oil resources [2, 20].

Conclusions

Tectonic dislocations and especially karst zones in bedrock represent the main problems for mining. Within the dislocation zones, karst clay may occupy about 10–15% by volume and in blocks between zones oil shale losses are 1–4%. Oil shale is oxidized and of no commercial value in dislocation zones. In all zones of karst and dolomitization, the content and quality of shale kerogen is diminished [21]. Cross-sections of dislocations vary considerably along strike, as does the thickness of the commercial shale horizon. Fractured zones are also water-rich and blocks between faults unstable. All of these factors both reduce the quality of oil shale resources and make mining difficult or impractical.

Away from the main linear tectonic zones, karst is rarely developed at the Ahtme and Estonia mines, observed over less than 1% of the mine area; in the Tammiku, Viru and Sompa mines, karst is present over 2–4% of the respective areas, while in the Kiviõli, Kohtla and Käva 2 and 4 deposits, karstification is practically absent. In the ancient deep buried valleys the commercial oil shale layers have been completely eroded away. Similarly, at the top of some small dome-like structures the oil shale horizon has been eroded. In some places, prospecting and mining has shown that the commercially mineable layer is absent, even where there is no evidence for tectonic dislocations.

Accurate tectonic data in these essentially subhorizontal sedimentary hard rock sequences enable planning of optimum configuration and orientation for future mining developments and also influence the choice of mining and extraction techniques. The greatest risks for mining in the Estonian oil shale mine are within the karst zones, where hard rock has been replaced by soft masses of clay with limestone relicts. To ensure safe mining of oil shale in deeper mines, a new detailed study of the tectonic dislocations in the Estonian oil shale deposit is needed.

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