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CAVE MORPHOLOGY AND MOONMILK DEPOSITS OF RYONGMUN CAVERN, DEMOCRATIC PEOPLE'S REPUBLIC OF KOREA: A STUDY FOR THE CONSERVATION OF NATURAL HERITAGE

JAMSKA MORFOLOGIJA IN NAHAJALIŠČA JAMSKEGA MLEKA V JAMI RJONGMUN, DEMOKRATIČNA LJUDSKA REPUBLIKA KOREJA: ŠTUDIJA ZA OHRANJANJE NARAVNE DEDIŠČINE

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Abstract UDC 552.545:551.44(519.3)

Won-Sok Jon, To-Jun Ryang & Hyon Hwangbo: Cave morphology and moonmilk deposits of Ryongmun Cavern, Democratic People's Republic of Korea: A Study for the Conservation of Natural Heritage

The Ryongmun Cavern, registered on the World Heritage Tentative List, is the largest and most beautiful karst cave on the Korean peninsula. The characteristics of the cave morphology and moonmilk deposits in the Ryongmun Cavern were studied. A cross section of the main direction of the cave shows that the Ryongmun Cavern is made up mainly of four strata and this caused 4 stages of decline in underground waterline in the course of cave formation. The cave is mainly characterized by NW–SE-trending, NWW–SEE-trending and NNE–SSW-trending passages. The horizontal passages usually have large and wide spaces, whereas the inclined ones are relatively small and narrow. The cave minerals in the Ryongmun Cavern are mainly calcite and aragonite. In the cave, stalactites, stalagmites, limestone columns, cave pearls, etc. are calcite; and, anthodites are aragonite. In the cave, speleothems display a wonderful underground landscape in harmony with the cave bedrock and groundwater (streams, waterfalls and ponds). The main scenes of the underground karst landscape in the cave are stalactites, stalagmites, limestone columns, stone waterfalls, anthodites, underground waterfalls, and underground ponds.

Izvleček UDK 552.545:551.44(519.3)

Won-Sok Jon, To-Jun Ryang & Hyon Hwangbo: Jamska morfologija in nahajališča jamskega mleka v jami Rjongmun, Demokratična ljudska republika Koreja: študija za ohranjanje naravne dediščine

Jama Rjongmun, vpisana na okvirni seznam svetovne dediščine, je največja in najlepša kraška jama na Korejskem polotoku. V jami Rjongmun so se proučevali značilnosti jamske morfologije in nahajališča jamskega mleka. Prečni prerez po glavni smeri jame kaže, da je jama Rjongmun sestavljena predvsem iz štirih plasti, zaradi česar so se med nastajanjem jame ustvarile štiri stopnje upadanja ravni podzemne vode. Za jamo so značilni predvsem prehodi v smeri severozahod–jugovzhod (SZ-JV), SZZ-JVV in SSV-JJZ. Vodoravni prehodi so običajno veliki in široki, nagnjeni pa so razmeroma majhni in ozki. Jamska minerala v jami Rjongmun sta predvsem kalcit in aragonit. Stalaktiti, stalagmiti, apnenčasti stebri, jamski biseri in podobno so iz kalcita, nekatere druge oblike pa so iz aragonita. Speleotemi v jami prikazujejo čudovito podzemno pokrajino, ki je usklajena z jamsko geološko podlago in podzemno vodo (potoki, slapovi in kotanje). V podzemnem kraškem okolju v jami prevladujejo stalaktiti, stalagmiti, apnenčasti stebri, kamniti slapovi, razne druge oblike, podzemni slapovi in podzemne kotanje. Usedline, ki so nedavno nastale na površini speleotemov in sten v jami, so večinoma iz jamskega mleka, sestavljenega iz hidro-

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The deposits that have been formed recently on the surface of speleothems and walls in the cave are mainly moonmilk composed of hydromagnesite ($Mg_5(CO_3)_4(OH)_2{\bullet}4H_2O$) with an average particle size of 0.55 μm and chemical composition of MgO–29.43% and CaO–6.28%. The moonmilk is present in a white, fine powder form, a hand-rubbed smooth, and a moisture content of 42.0%. Also, the pH is 10.09, which is alkaline. In the Ryongmun Cavern, moonmilk was formed at sites with very low supply of karst water and relatively high wind speeds. The unique underground karst features provide sufficient evidence for geoheritage value of the cave and the characteristics of moonmilk provide a significant implication for management and preservation of the cave environment.
Keywords: Ryongmun Cavern, underground karst, geoheritage, natural heritage, conservation.

magnezita ($Mg_5(CO_3)_4(OH)_2{\bullet}4H_2O$) s povprečno velikostjo delcev 0,55 μm in kemijsko sestavo MgO – 29,43 % in CaO – 6,28 %. Jamsko mleko je bel fin prah, gladko na otip, vsebnost vlage pa je 42,0 %. Njegov pH je 10,09, kar pomeni, da je bazičen. Jamsko mleko v jami Rjongmun je nastalo tam, kjer je zelo malo kraške vode in je razmeroma dobro prevetreno. Edinstvene značilnosti podzemnega krasa so zadosten dokaz za izjemno geološko dediščino jame, značilnosti jamskega mleka pa pomembno vplivajo na upravljanje in ohranjanje jamskega okolja.
Ključne besede: jama Rjongmun, podzemni kras, geološka dediščina, naravna dediščina, ohranjanje

1. INTRODUCTION

There are numerous karst caves in nature, and it has a great impact on human life. From this, karst environmental management problem has been raised long ago, and the rationale for it is not only scientific problem but also economic life problem and social problem (Parise & Pascali, 2003; White & Culver, 2012).

At present, the karst caves are one of the major tourist attractions in the world as well as precious natural heritages (Culver & White, 2005; IUCN, 2008; IUCN, 2018). Karst landforms are usually found in areas of soluble carbonate bedrock and are shaped by chemical dissolution from slightly acidic water (Ford & Williams, 2007; Palmer, 2007). Out of these landforms, cave systems are more significant because they contain valuable resources for scientific research and tourism (Kambesis, 2007). The increased exploration and research of caves in the second half of the 20 century heightened awareness of the importance of caves as a resource (Palmer, 2007). Since the World Heritage Convention was adopted in 1972, in particular, the number of natural caves included in the World Heritage List continues to be growing (IUCN, 2011). In addition, research on the protection of individual karst caves has been conducted in depth, resulting in many significant research papers on their effective management (Grant et al., 2011; Lang et al., 2017; Sebela et al., 2019).

In spite of this, the preservation and management of cave resources in some areas are far from being suffient (Huppert, 1995; LaMoreaux et al., 1997). The destruction of inherent cave resources is an inevitable outcome of lack of proper scientific measures and strategies for their protection (DuChene, 2006).

The Ryongmun Cavern, widely known as the "Underground Palace" in the Democratic People's Republic of Korea, is regarded as one of the significant geoheritages for its scientific and aesthetic value. Located at the foot of Mt. Ryongmun, a branch of the renowned Mt. Myohyang, the Ryongmun Cavern is the largest and most beautiful limestone cave on the Korean peninsula. In this cave, tourism has been active since it was registered as a national scenic spot in 1997.

The cave has been a significant research object among many geographers and geologists and as a result, geographical and geological features such as its size, the age of the host rock etc. studied in detail (Kim, 2001; Ko, 2001; O & Cheo, 2001; Jon et al., 2011). The results of the study were used as the basis for cave development and management, and the cave has now become one of the famous natural tourist attractions equipped with excellent tourism facilities.

Recently, the moonmilk have been partially formed on the surface of cave walls and anthodites in the some place of the cave. Last decade ago, no moonmilk was found in the Ryongmun Cavern. Some people in charge of cave management say that these materials degrade the aesthetic value of cave.

The aim of this study is to describe the underground karst features of Ryongmun Cavern, one of the famous geological heritages in the DPR Korea, and to clarify in detail the characteristics and formative cause of the moonmilk deposits partially formed in the cave.

Many types of research have been carried out on the formation of the moonmilk deposits in the karst cave. Research data on the moonmilk forming in the karst cave was studied in the literature "Cave Minerals of the World" (Hill & Forti, 1997) and some other papers (Fishbeck & Muller, 1971; Onac & Ghergari, 1993; Cañaveras et al., 1999; Tásler et al., 2001; Martinez et al., 2007).

However, it is difficult to find data on the moonmilk deposits in caves of our country.

In the paper, we studied on the the underground karst features of the Ryongmun Cavern and moonmilk deposits formed in the cave, and revealed its characteristics and formative cause. The unique underground karst features provide sufficient evidence for geoheritage value of the cave and the characteristics and formative cause of the moonmilk deposits will provide a significant implication for management and conservation of cave environment.

This study will contribute significantly to conserving the Natural Heritage value of the Ryongmun Cavern and understanding the moonmilk deposits formed in the karst cave.

2. STUDY AREA

The Ryongmun Cavern is a typical temperate karst cave that was formed by the corrosion of groundwater in the limestone layer of the Mandal Formation of the lower Paleozoic.

Fig. 1: Location map of the study area.

The cave is situated at the foot of Mt. Ryongmun (1,180 m a.s.l.) in Kujang County, North Phyongan Province of the Democratic People's Republic of Korea (Figure 1).

The Ryongmun Cavern is located in the northern part of the Phyongnam Basin, the Sino–Korean Craton.

Distributed in the study area are rocks of various geological ages; Meso-proterozoic sedimentary rocks (quartzite, limestone), Paleozoic sedimentary rocks (Lower Cambrian sandstone, siltstone, Middle Cambrian clayish limestone, Upper Cambrian dolomite, Lower Ordovician massive dolomite, limestone, Middle Ordovician limestone, Carboniferous slate, Permian sandstone, siltstone), Neoarchean metamorphic rocks (gneiss, schist), Neoarchean granitoid etc. (Figure 2).

The dark grey limestone in which the cave is formed limestone layer is the middle Ordovician (O & Choe, 2001; Jon et al., 2011).

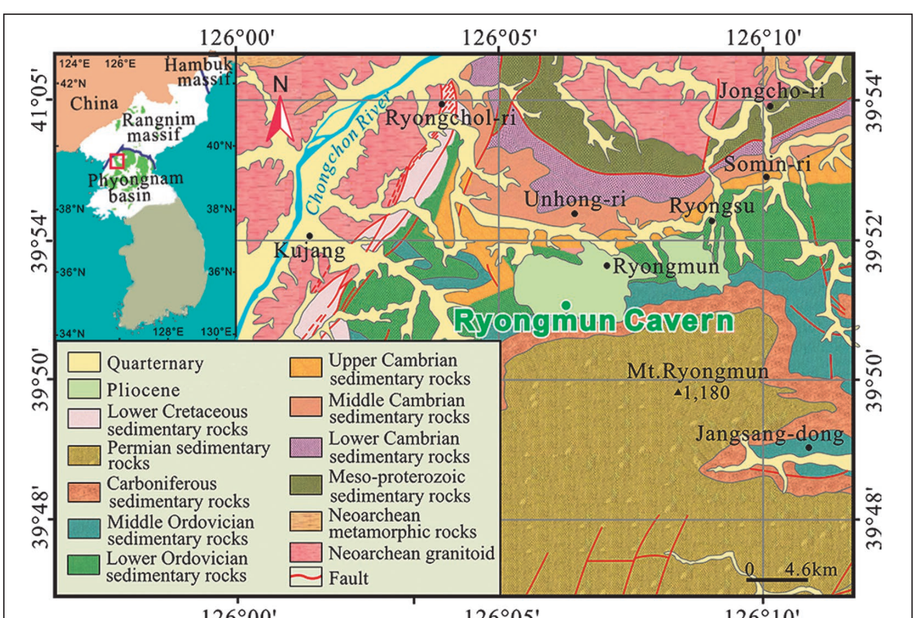

Fig. 2: The geological map of the study area.

This layer, with the cephalopod fossils of *Armenoceras tani, Ormoceras cf. Harioi* and snail fossils, conformably tops the dolomite layer of the lower Ordovician.

This limestone layer is mainly calcite and the size of its particle is about 0.1-1 mm. As for the mineral composition, it is composed of calcite (85-95 wt%), quartz (3-8 wt%), white mica (1-3 wt%) and metal minerals (1-3 wt%). The chemical compositions are CaO (52.36-55.82 wt%), MgO (0.19-0.50 wt%), SiO_2 (0.06-3.98 wt%), Al_2O_3 (0.07-0.16 wt%) and Fe_2O_3 (0.02-0.28 wt%) (Jon et al. 2011).

The upper layer of this limestone is a dolomite of Mandal Formation of the same age with 20-30 m thickness.

The study area is mainly characterized by NW–SE–trending and NE–SW–trending faults, and there are many faults and joints.

Now, the cave has a tourist route of 7.2 km, with 20 major scenic spots of different shapes and features (Figure 2a). Scenic spots are linked to one another with no gap, allowing the whole length of the cave to display different underground karst features.

Every year, many students and tourists visit the cave. The ring-shaped tourist route has guide signs, safety rails and resting places.

3. METHODS

The comprehensive and detailed investigation of the cave in the last two years unveiled the underground karst features of the study area. The location and altitude of the cave entrance were measured with GPS and the altimeter, and based on them, the altitude of each level in the cave was calculated.

In this study, the morphological, chemical and physical properties of the moonmilk were measured, focusing on the mineralogical characteristics of the moonmilk. For this purpose, microscopic observation, X-ray fluorescence (XRF) and X-ray diffraction (XRD), Differential thermal (DT), thermogravimetric (TG) and particle size analyses were applied.

The morphology of the moonmilk was observed by an optical microscope. The the moonmilk was first suspended in distilled water and then observed under a projection microscope. Micrographs were acquired by a digital camera at 1.2 megapixels.

The bulk chemical composition of samples was then determined by wavelength dispersive X-ray fluorescence (WD-XRF: 50 kV, 80 mA) having a detection limit of 0.01 wt% for each elemental species. Samples were first dried at 105 °C to remove the nonstoichiometric components (e.g., CO_2 and H_2O). Loss on ignition was measured weighing the samples before and after heating at 1000 °C for 20 min.

Qualitative phase analyses on samples were advanced by XRD (Rigaku-MINIFLEX: Cu–Kα, 40Kv×100mA, λα-1.54060 Å). Data were collected over the 5 ~ 70° angular range at 0.02° every 30 s. Data were processed by the standard PDXL software embedded in Miniflex.

The thermal decomposition characteristic of the moonmilk was evaluated by differential thermal (DT) thermogravimetric (TG) analyses.

Basic physical properties of the moonmilk such as particle size were also determined for further characterization. The particle size distribution of the moonmilk was measured using a BT-9300H laser particle size analyzer (λ = 635 nm). The measuring range was 0.1–340 μm, and the errors were less than 3%. 1 g of sample and 0.02 g of hexametaphosphate as a dispersing agent were dispersed in an ultrasonic disperser for 5 min, and then the particle size was measured by BT-9300H a laser self-level analyzer. Also, pH of the moonmilk were measured with pH-meter SG2.

4. RESULTS AND DISCUSSION

4.1 CAVE MORPHOLOGY AND DIVERSITY OF SPELEOTHEMS

4.1.1. Cave morphology

The total length of the cave investigated so far is 7.2 km. Figure 3 shows a map of the Ryongmun Cavern investigated so far and a rose diagram representing the distribution trend of cave passages.

As seen in Figure 3, the cave have mainly NW–SE-trending, NWW–SEE-trending and NNE–SSW-trending passages.

According to the investigation results, the Ryong-

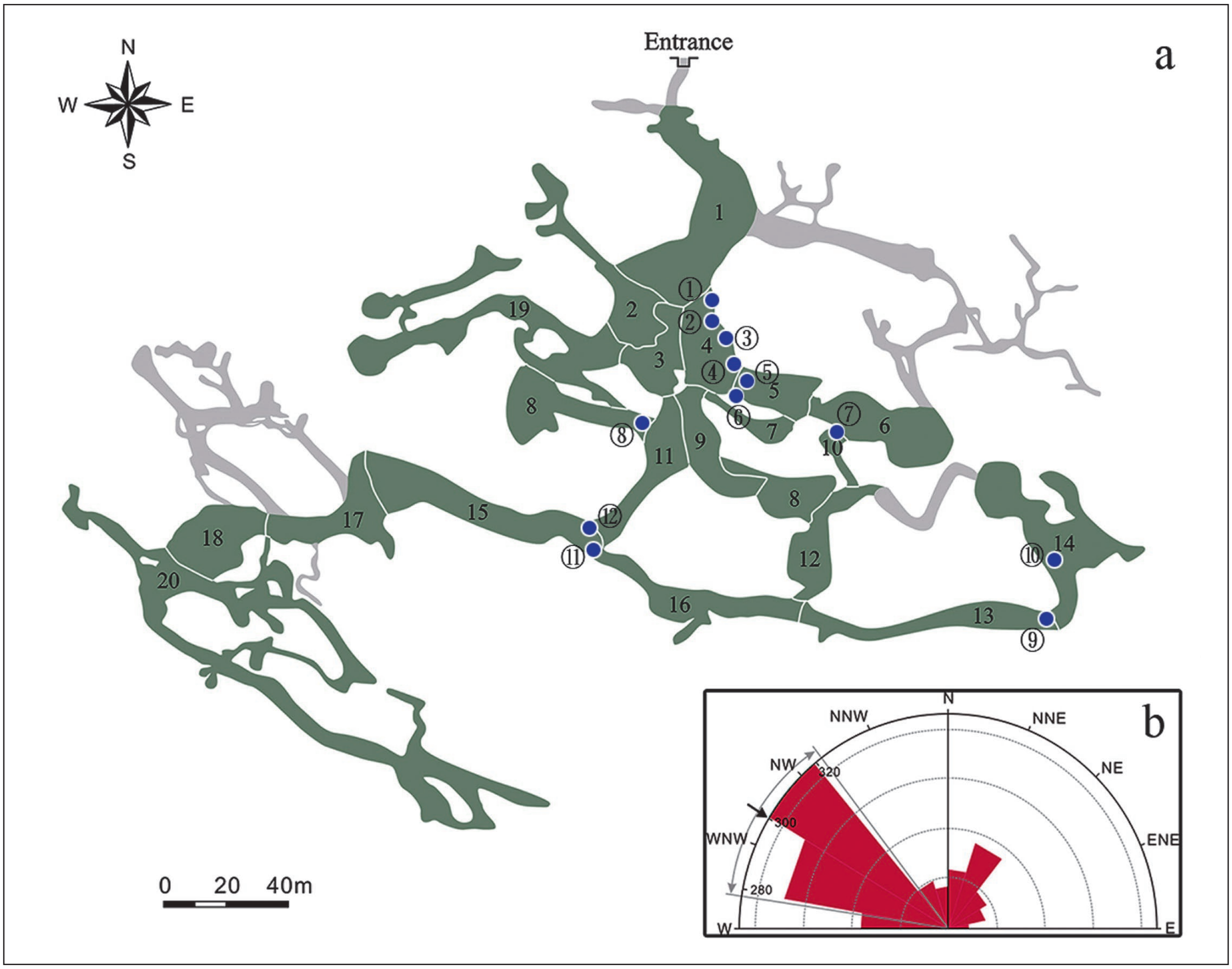

Fig. 3: Map (a) of the Ryongmun Cavern indicating the locations of the major scenic spots (1–20) and the moonmilk deposites (①–⑫); and the rose diagram (b) representing the distribution trend of caves. Key: 1-Pungnyon-dong, 2-Manmul-dong, 3-Ryongmun Square, 4-Sokhwa-dong, 5-Paekhwa-dong, 6-Ryongmun Square No.2, 7-Ryongyon Pit, 8-Ansim Pit, 9-Kumgang Pit, 10-Paektumilyong-dong, 11-Hyongje-dong, 12-Posot-dong, 13-Jimyo Pit, 14-Posok-dong, 15-Chonsangragwon-dong,16-Jangsok-dong, 17-Kwangmyong-dong, 18-Sungli-dong, 19-Unhung Pit, 20-Hamjong Pit.

mun Cavern consists of horizontal passages of several levels and inclined ones connecting them.

Table 1 shows the height data of the floor and the ceilings measured in some horizontal passages of the Ryongmun Cavern.

As in Table 1, there are several levels of horizontal passages in the Ryongmun Cavern, including the horizontal passage connecting Ryongmun Square - Sokhwa-*dong* - Paekhwa-*dong* - Ryongmun Square No.2, the horizontal passage connecting the Paektumilyong-*dong*, and the horizontal passage connecting the Jimyo Pit-Chonsangragwon-*dong*. The passage connecting the Ryongmun Square - Sokhwa-*dong* Paekhwa-*dong* - Ryongmun Square No.2 is between 263.3 m and 290.7 m a. s. l., and the passage connecting the Paektumilyong-*dong* is between 232.2 m and 241.1 m a. s. l., and the passage connecting the Jimyo Pit - Chonsangragwon-*dong* is between 223.34 m and 256.6 m a. s. l. The passage connecting the Jimyo Pit - Chonsangragwon-*dong* is connected in a straight line to Jangsok-*dong*, and its altitude rise to about 283 m. In addition, there are horizontal passages the height range of 283 m - 320 m, 206 m - 219 m, 260 m - 289 m and 207 m - 220 m in the southwest and in the northeast of these major scenic spots. These horizontal passages are NW - SE - trending passages.

The investigation results show that horizontal passages in the Ryongmun Cavern are mainly distributed in the height range of 200-220 m, 220-250 m, 260-290 m and 290-310 m. This shows that the Ryongmun Cavern are vertically distributed between 200 m and 310 m a. s. l. and

Tab. 1: The altitudes of the floor and the ceiling of some horizontal passages.

No	Location	Altitude (m)		No	Location	Altitude (m)	
		Floor	Ceiling			Floor	Ceiling
1	Ryongmun Square	264.00	273.00	30	Paektumilyong-*dong*	234.50	237.90
2	"	267.00	272.30	31	"	236.00	-
3	"	267.68	273.69	32	"	233.40	235.10
4	"	278.10	279.10	33	"	236.70	239.30
5	"	270.70	277.10	34	Jimyo Pit	224.58	235.30
6	Sokhwa-*dong*	267.9	269.5	35	"	224.80	-
7	"	265.16	268.00	36	"	223.42	232.4
8	"	269.20	-	37	"	222.70	272.00
9	Paekhwa-*dong*	265.80	268.60	38	"	223.34	228.90
10	"	264.60	271.60	39	Chonsangragwon-*dong*	228.80	232.80
11	"	263.30	266.50	40	"	236.40	241.70
12	"	263.90	271.40	41	"	236.40	241.70
13	"	263.40	265.40	42	"	232.80	-
14	"	262.70	263.1	43	"	236.40	241.70
15	"	263.40	-	44	"	237.50	240.20
16	"	283.60	288.60	45	"	236.00	256.60
17	"	283.70	288.20	46	"	247.30	-
18	"	283.00	288.00	47	"	247.30	-
19	"	271.15	-	48	"	248.20	251.40
20	"	270.50	-	49	"	248.20	250.20
21	"	270.60	-	50	Jangsok-*dong*	258.90	263.40
22	"	271.4	-	51	"	258.80	266.10
23	Ryongmun Square No.2	274.20	275.70	52	"	263.18	-
24	"	278.70	290.70	53	"	267.18	-
25	"	279.99	-	54	"	265.22	-
26	Paektumilyong-*dong*	236.60	241.40	55	"	267.66	-
27	"	236.62	-	56	"	271.90	273.50
28	"	232.30	237.90	57	"	280.43	-
29	"	232.90	234.90	58	"	283.16	285.20

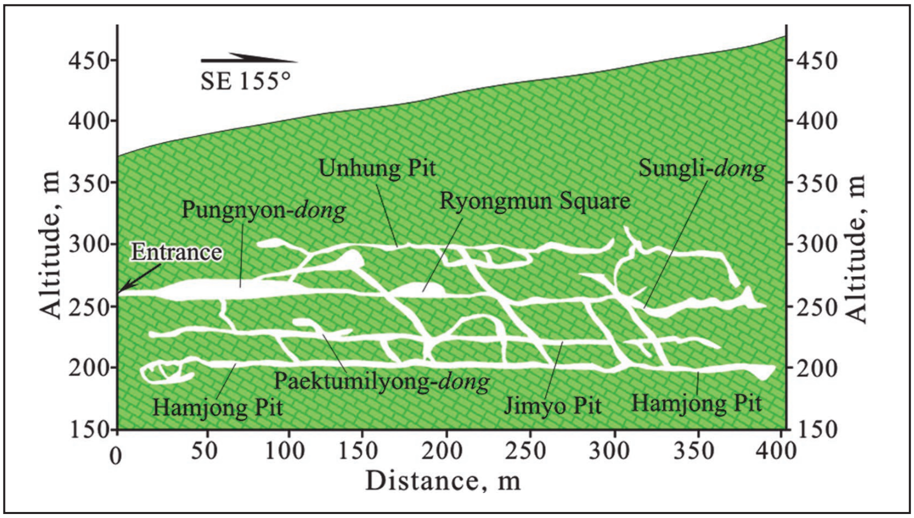

Fig. 4: The cross section of the Ryongmun Cavern.

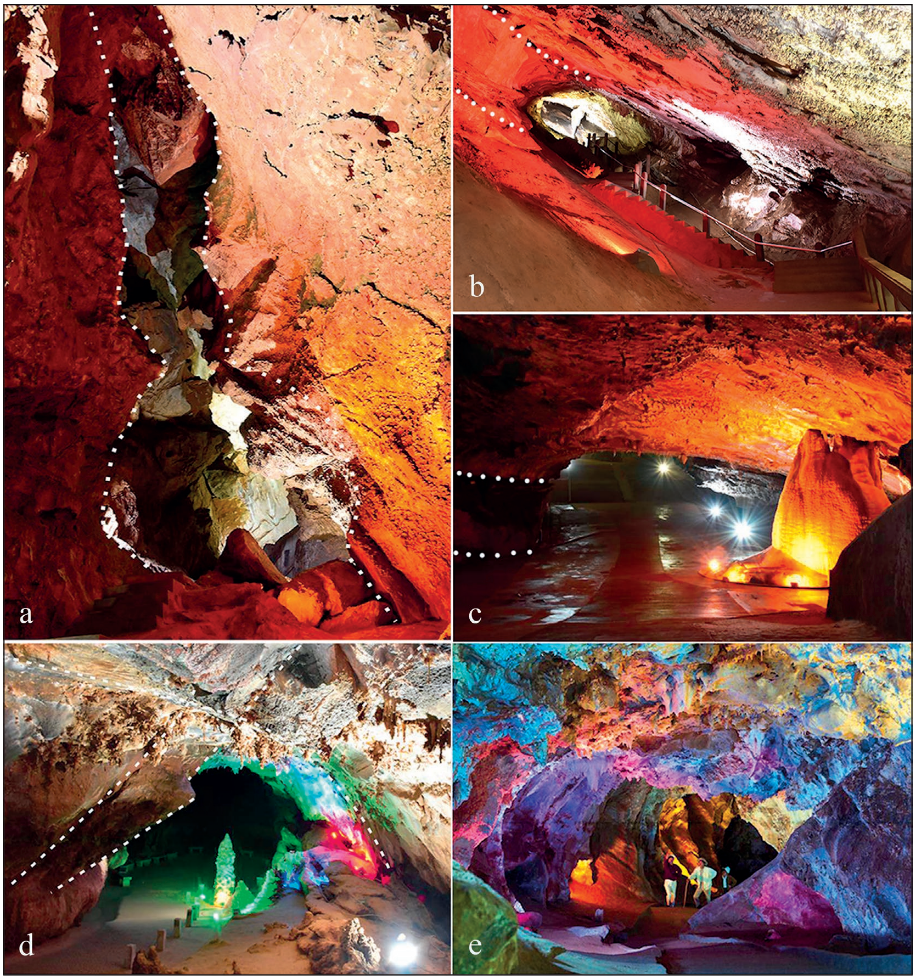

Fig. 5: Examples of passage cross-sections from the Ryongmun Cavern. White dotted lines indicate location of the fault (a) and bedding (b, c, d). Key: a-Posot-dong, b-Hyongje-dong, c-Pungnyon-dong, d-Paektumilyong-dong, e-Ansim Pit.

has mainly 4 passage levels (Figure 4). That is, the height difference between the 1st level to the 4th is 110 m.

The inclined passages connecting the horizontal ones are mainly NE-SW direction with the inclination angel of approximately 38° to 45°.

The direction and the cross-section shape of the passages in the cave are mainly related to the bedding of the limestone and fault (Figure 5).

The horizontal passages have usually large and wide spaces, whereas the inclined ones are relatively small and narrow.

4.1.2. Diversity of speleothems

Speleothem consists of cave minerals. There are hundreds of kinds of cave minerals worldwide. One researcher published the first magazine on cave minerals, which describes 68 cave minerals (Moore, 1970). The first book of the world's cave minerals titled "Cave Minerals of World" was subsequently published (Hill & Forti, 1986). It was followed by the second book published in 1997, where 255 cave minerals were reported, 125 of which were deposited in a particular cave environment (Hill and Forti 1997). Further data on cave minerals were published afterwards (Moore & Sullivan, 1997; Ford & Williams, 2007; Onac & Forti, 2011).

The cave minerals that grew up in the karst caves are mostly calcite. The calcite crystals make agglomerate of different types in the underground ponds where karst water is collected, and the ceilings, walls and floors of the caves with a big volume of karst water flow. They are speleothems such as stalactite and stalagmite, limestone columns of various sizes (Kempe, 2013).

The cave minerals in the Ryongmun Cavern are mainly calcite and aragonite. In a Ryongmun Cavern, stalactite, stalagmite, limestone columns, cave pearls etc. are calcite, and anthodites are aragonite (Figure 6).

The variety of the shape of the calcite crystals in the Ryongmun Cavern is quite varied, and they are made up of smaller elements. The speleothems in the Ryongmun Cavern consisting of calcite are basically stalactite and stalagmite, limestone columns, flowstone, cave pearls, etc (Figure 7a, b, c, d, e, f, h).

The speleothems in the Ryongmun Cavern consisting of aragonite are anthodites (Figure 7g). There are

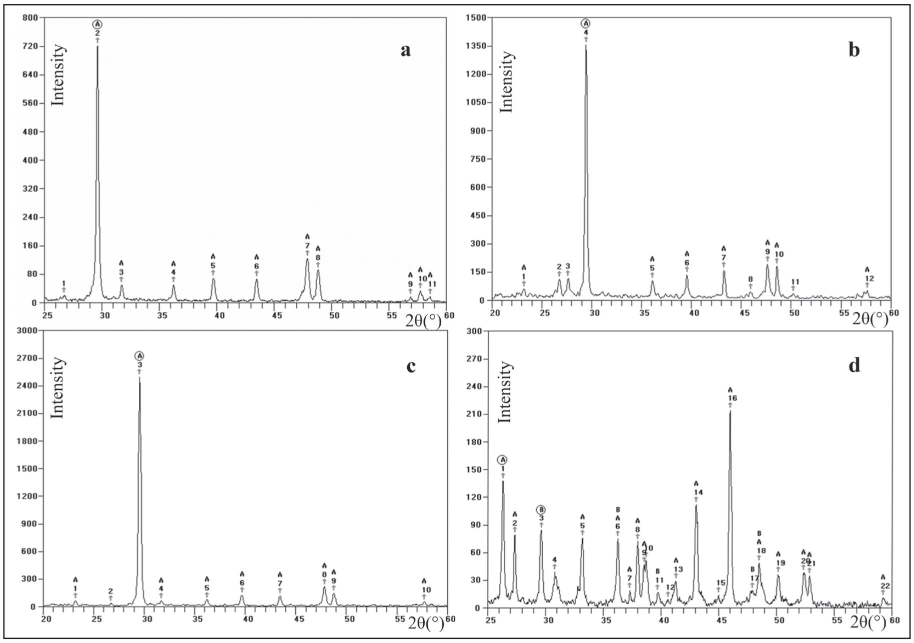

Fig. 6: X–ray results of speleothems in Ryongmun Cavern (a–stalactite, b–stalagmite, c–cave pearl, d–anthodites).

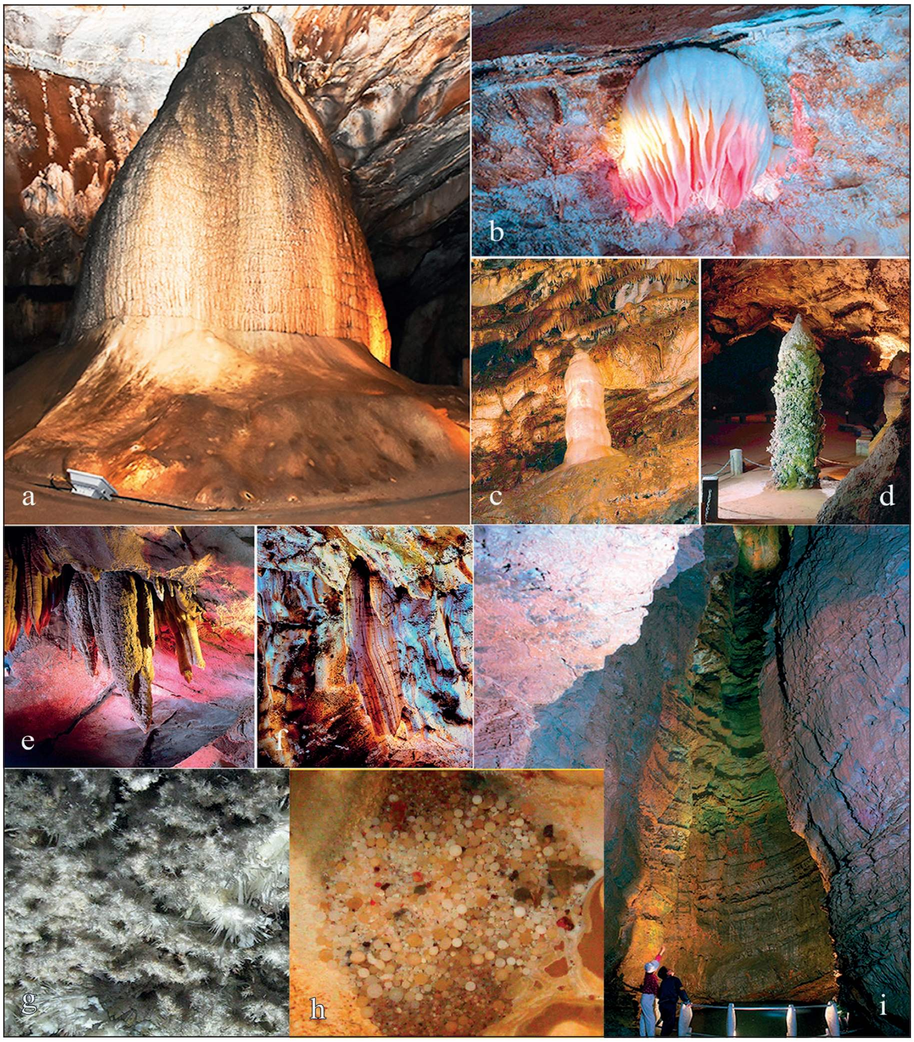

Fig. 7: Typical speleothems (a-h) and subterranean waterfall (i) in Ryongmun Cavern. Key: a-"Pungnyon Tower" in Pungnyon-dong, b-"Hideous Club" in Kwangmyong-dong, c-A stalagmite in Chonsangragwon-dong, d-Juniper tree-like stalagmitein Paektumilyong-dong, e-A stalactite in Manmul-dong, f-A dolphin-like stalactite in Pungnyon-dong, g-Anthodites in Sokhwa-dong, h-Cave pearls in Manmul-dong, i-"Samsonam Falls" in Chonsangragwon-dong.

many uniquely shaped speleothems in the Ryongmun Cavern. Typical of them are the "Pungnyon Tower" (Figure 7a) in Pungnyon-*dong* (5.5 m high, 15 m round), the "Giant Chandelier" (Figure 7b) in Kwangmyong-*dong* (3 m round), the Juniper tree (Figure 7d)-like stalagmite (3 m high, 2.16 m round) in Paektumilyong-*dong*. There are many small-sized and shallow subterrenean ponds in the cave, which habitat thousands of cave pearls (Figure 7h), 2 – 5 mm in diameter.

In the cave, there are many erosion traces in diverse forms, which unfold a mysterious underground landscape combined with speleothems.

4.2 LOCATION AND FEATURES OF MOONMILK DEPOSITS

4.2.1 Location of moonmilk deposits

The deposits currently formed in the Ryongmun Cavern is moonmilk, which is randomly distributed on the surface of anthodites and walls in the cave.

The moonmilk deposits in the cave is distributed on the salient part (Figure 8a, b, c) and anthodites' tips (Figure 8f), and is linearly distributed along the joints (Figure 8d, e). At the cave walls and the anthodites' tips where moonmilk formed, the flow of karst water was not observable and relatively dry. The thickness of moonmilk deposits formed on the cave walls is below 3~4 mm.

The moonmilk deposits in the Ryongmun Cavern were formed at 12 sites including Sokhwa-*dong*, Paekhwa-*dong*, Ryongyon Pit, Jimyo Pit, Posok-*dong* and Chonsangragwon-*dong*.According to the distribution characteristics (Table 2) of the moonmilk deposits and wind speed data (Table 3) within the cave show that the formation of moonmilk was mainly related to factors affecting evaporation. In the Ryongmun Cavern, the moonmilk deposits are mainly distributed near the entrance, near the road. It is also distributed in the cave passages with a cave width less than 8 m. Considering the maximum cave width of 20 m in the Ryongmun Cavern, it can be said that the moonmilk deposits distributes in

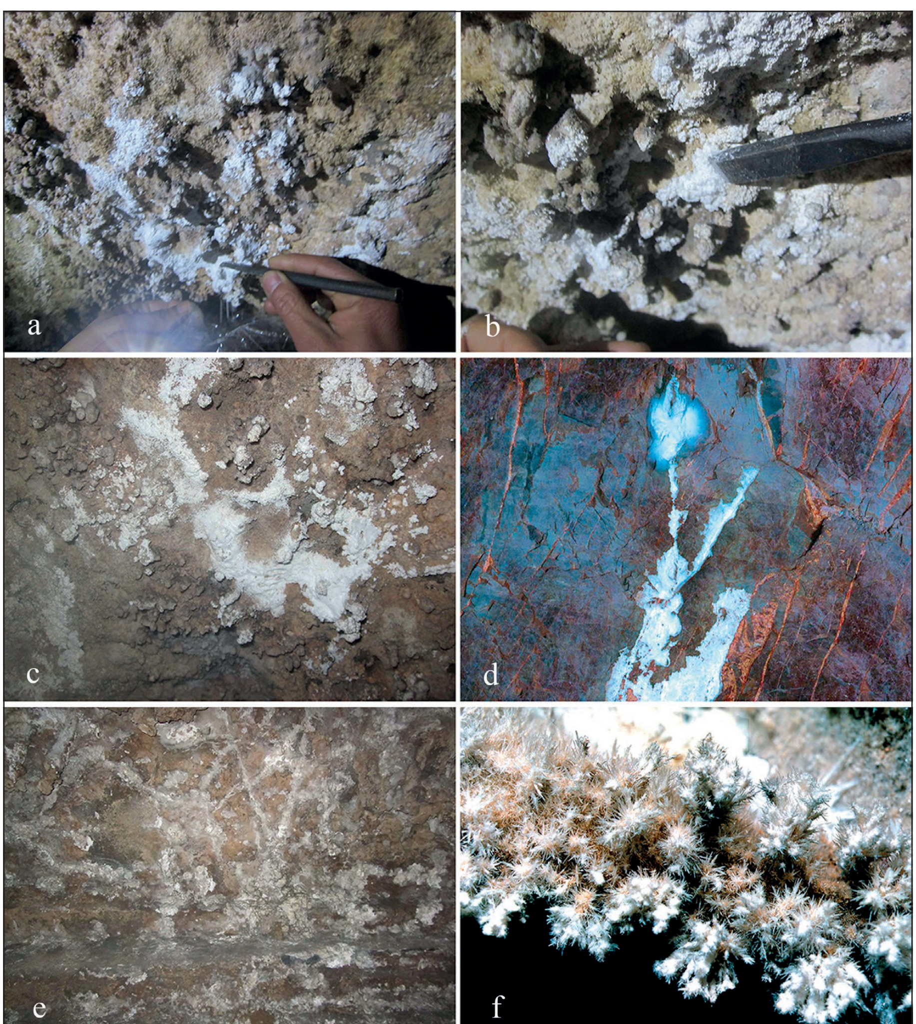

Fig. 8: Some moonmilk formed in the Ryongmun Cavern (a, b, c-moonmilk on the salient part; d, e-moonmilk distributed linearly; and, f-moonmilk on the anthodites' tips).

a relatively narrow cave passages. The wind speed in the natural state inside the Ryongmun Cavern is very fine. However, the wind speed at the time of the tour is more than 1 m/s. According to Table 3, the moonmilk deposits was formed in the Sokhwa-*dong*, Ryongyon Pit, Jimyo Pit, Posok-*dong* and Chonsangragwon-*dong* with the highest wind speed during the tour. This suggests that the wind speed in the Ryongmun Cavern is one of the main conditions for the formation of the moonmilk.

Tab. 2: Distribution location (Figure 3a) and distribution characteristics of the moonmilk deposits in Ryongmun Cavern.

No	Location	Altitude /m	Distance from the entrance /m	Formative site	Area /m^2	Distance from the road /m	Cave width at the formative site /m
①	Sokhwa-*dong*	265.8	338	Anthodites' tips	10	1	6
②	Sokhwa-*dong*	265.8	400	Anthodites' tips	1	1	3
③	Sokhwa-*dong*	269.2	380	Cave wall	1	0.5	4
④	Sokhwa-*dong*	265.8	415	Cave wall	1	3	8
⑤	Paekhwa-*dong*	264.6	420	Cave wall	0.2	3	6
⑥	Paekhwa-*dong*	263	430	Cave wall	3	1	4
⑦	Ryongyon Pit	250	445	Anthodites' tips	14	1	3
⑧	Paektumilyong-*dong*	223.4	700	Cave wall	3	1	5
⑨	Jimyo Pit	223.3	637	Cave wall	3	1.5	3
⑩	Posok-*dong*	231.9	740	Cave wall	2	3	8
⑪	Chonsangragwon-*dong*	231.7	630	Cave wall	1	2	10
⑫	Chonsangragwon-*dong*	236.4	680	Cave wall	1	0.5	4

Tab. 3: Wind speed data in the Ryongmun Cavern (Annual average)

No	Location	Wind speed in natural state (m/s)	Wind speed during tourism (m/s)
1	Pungnyon-*dong*	0.124	0.024
2	Manmul-*dong*	0.050	0.350
3	Ryongmun Square	0.132	0.068
4	Sokhwa-*dong*	0.151	1.502
5	Paekhwa-*dong*	0.065	0.435
6	Ryongmun Square No.2	0.115	0.015
7	Ryongyon Pit	0.219	1.639
8	Ansim Pit	0.048	0.848
9	Kumgang Pit	0.096	0.304
10	Paektumilyong-*dong*	0.157	0.243
11	Hyongje-*dong*	0.068	0.232
12	Posot-*dong*	0.180	0.320
13	Jimyo Pit	0.148	1.496
14	Posok-*dong*	0.058	1.316
15	Chonsangragwon-*dong*	0.159	1.359
16	Jangsok-*dong*	0.166	0.134
17	Kwangmyong-*dong*	0.110	0.190
18	Sungli-*dong*	0.040	0.360
19	Unhung Pit	0.075	0.145
20	Hamjong Pit	0.116	0.132

4.2.2 Features of moonmilk deposits

1) Morphology and chemical composition

Figure 9 shows the micrograph of the moonmilk under a projection microscope after suspending in distilled water. As shown in Figure 9, the crystal form of the the moonmilk is not like a crystalline form of aragonite and calcite. Crystal growth in the [001] direction is much faster than other directions, giving the moonmilk a parallel habit. But the grain particles of aragonite are formed into an acicular habit, and the grain particles of calcite are formed into a net shape by being formed into a chain shape.

The results of the chemical analysis showed that MgO, with MgO-29.43% and CaO-6.28%, was about 4.69 times higher than CaO. The moonmilk is high in MgO and low in CaO compared to aragonite, calcite, and dolomite, compared with 56.03% of the theoretical content of CaO in aragonite and calcite, 30.41% and 21.86% of the theoretical content of CaO and MgO in dolomite. The MgO/CaO ratio of moonmilk from Ryongmun Cavern is 4.69.

2) X-ray difraction (XRD) analyses

The X-ray result shows that the moonmilk is composed of hydromagnesite–$Mg_5(CO_3)_4(OH)_2{\cdot}4H_2O$ (Figure10). The X-ray result of moonmilk is different from X-ray result of aragonite and calcite.

Hydromagnesite should not contain any calcium.

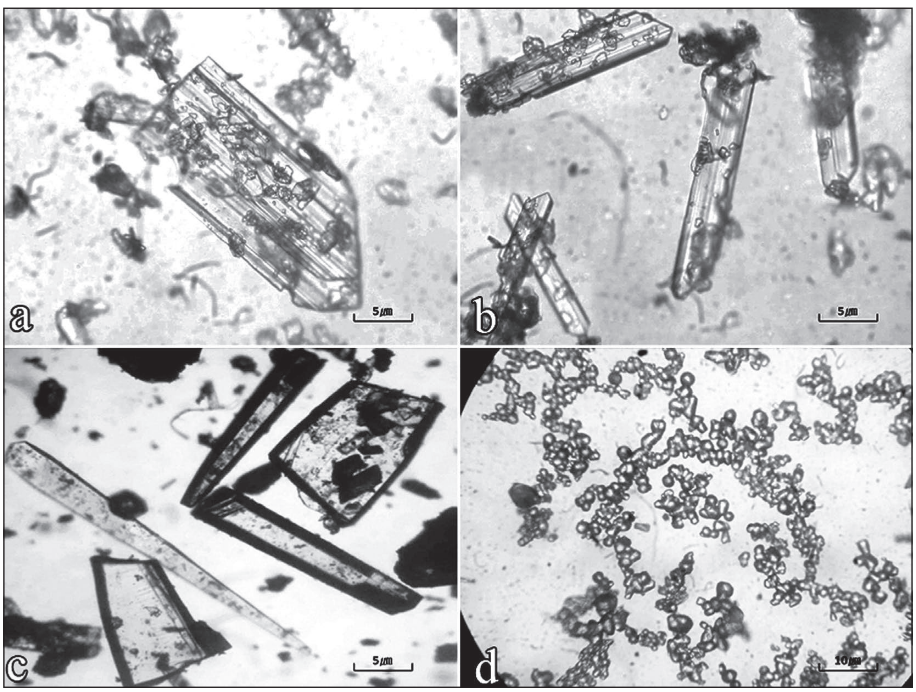

Fig. 9: Micrographs of the investigated moonmilk (a, b), aragonite (c) and calcite (d) in Ryongmun Cavern.

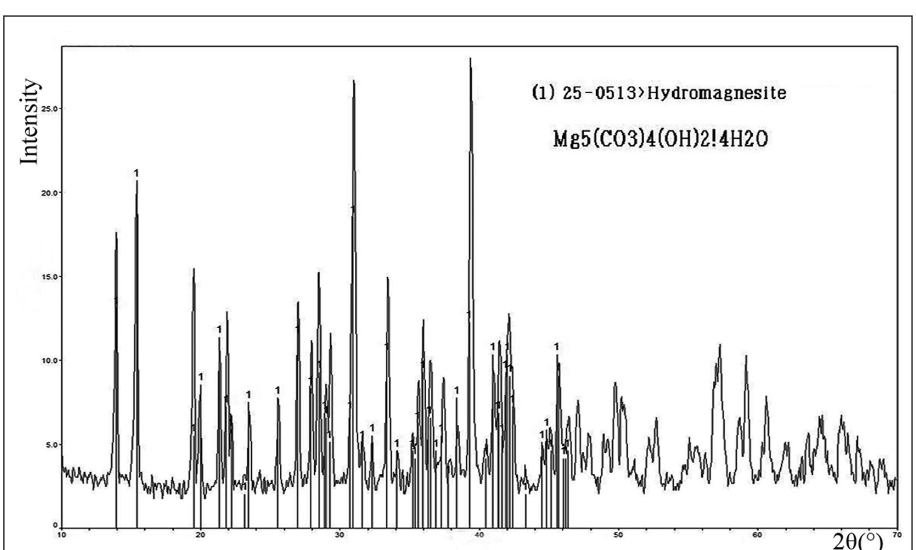

Fig. 10: X-ray results of the investigated moonmilk in Ryongmun Cavern.

The content of CaO of moonmilk from Ryongmun Cavern shows that the moonmilk probably contains other minerals such as aragonite.

3) Differential thermal (DT) and thermogravimetric (TG) analyses

The moonmilk was further evaluated by differential thermal (DT) and thermogravimetric (TG) analyses. Figure 11 shows the endothermic peak at 374.4°C and 538.15°C and the exothermic peak at 519.41°C. This compares well with the thermogravimetric results in Figure 12. The weight loss between 322.99°C and 454.38°C with the first endothermic peak is 18.79%, and the weight loss from 454.38°C to 528.07°C with 519.41°C exothermic peak and 538.15°C endothermic peak is 18.33%. The exothermic peak at 519.41 °C is presumed to be due to water-soluble organics doped with a moonmilk (View of authors). Water-soluble organic matter can be incorporated into a moonmilk. It indicates that water forming a moonmilk is surface water and therefore organic matter can be released from plants distributed on the surface.

4) Physical property

The physical properties of minerals are closely related to its crystal structure and chemical composition. In the Ryongmun Cavern, moonmilk is present in the form

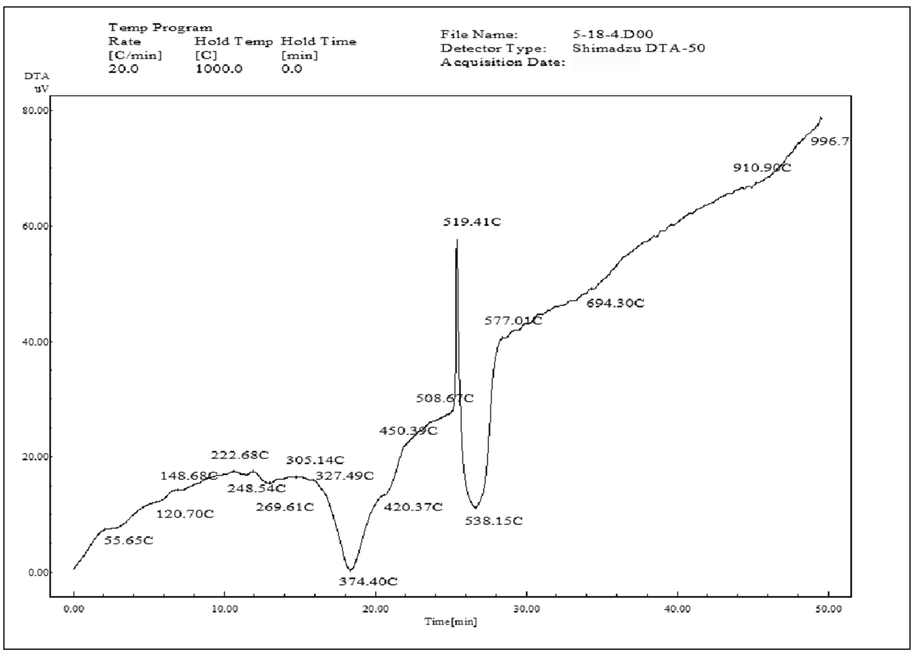

Fig. 11: DTA curve of the investigated moonmilk in Ryongmun Cavern.

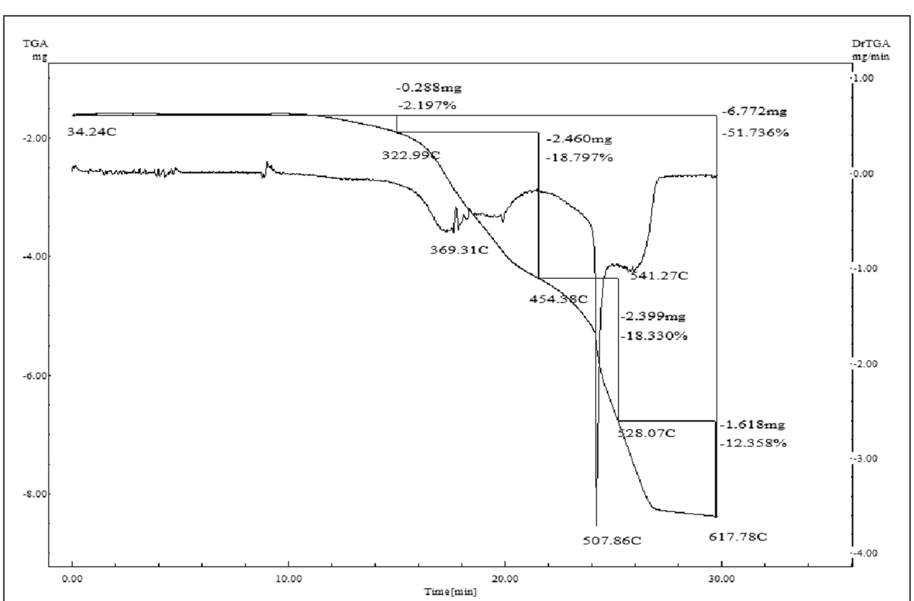

Fig. 12: TGA curve of the investigated moonmilk in Ryongmun Cavern.

of white fine powder, which is high in whiteness, very small in size, smooth in hand rubbing. The measurement result of the moonmilk particle size by the laser analyzer BT-9300H is 0.55 μm. The water content was 42.0% and the pH of the moonmilk was about 10.09, alkaline and sulfuric acid radical were not detected.

4.3 FORMATIVE CAUSE OF MOONMILK DEPOSITS

The formation of the moonmilk deposits (hydromagnesite) in the Ryongmun Cavern requires the supply of Mg-rich water. To do so, there must be a source of Mg, i.e. rock, which can supply Mg in the Ryongmun Cavern, but only the Lower Paleozoic dolomite layer above the cave host rock.

The upper part of the Lower Paleozoic limestone, which formed the Ryongmun Cavern, is overlain by the Lower Paleozoic dolomite layer, which is believed to contain Mg components as surface water passes through this dolomite layer. That is, it can be seen that the surface water containing carbon dioxide penetrated through the dolomite layer, containing the Mg component, and then penetrated into the cave of the limestone layer below the dolomite layer to form a moonmilk, hydromagnesite.

Dolomite consists of a complex mineral of $CaCO_3$ and $MgCO_3$, and the solubility of $MgCO_3$ is considerably greater than that of $CaCO_3$.

To verify the condition of Mg enrichment by dolomite, simulations were carried out by the chemical process simulation program <ASPEN >. The simulational result of the solubility of $MgCO_3$ and $CaCO_3$ at 10 °C is shown in Figure 13.

As shown in Figure 13, after 1 h of reaction, the MgO/CaO ratio is 8.25, and it decreases relatively rapidly until the reaction time is about 7 h and thereafter slowly, reaching 0.75 at 12 h. For further reaction times, the specific values hardly change. This is because the theoretical value of MgO/CaO ratio in dolomite is 0.72. If the MgO/CaO ratio in the solution reaches 0.72 would be a fully dissolved state of dolomite. Based on the chemical analysis of the moonmilk formed in the cave, the simulation time to reach the MgO/CaO ratio of 4.69 is about 2 h and 40 min. This shows that, considering the thickness of dolomite layer to be about 20-30 m, the water descends at a rate of about 0.125-0.185 m/min, and that during this time it reacts with dolomite and is enriched in Mg.

CO_2 is released from the karst water bearing Ca and Mg that flows through the cave along the joints, and $CaCO_3$ precipitates first. At 10 °C, the solubility of calcium carbonate is 7×10^{-2} g/L and the solubility of magnesium carbonate is 1.12 g/L, which is 16 times different in the solubility of the two materials. Therefore, calcium carbonate precipitates prior to magnesium carbonate. Also, the content of magnesium carbonate in the karst water, precipitated the calcium carbonate, is increased. Thus, the chemical equilibrium of karst water gradually transforms from CaMg-HCO_3 to Mg-HCO_3, and as water continues to evaporate, the carbonate of magnesium is concentrated and hydromagnesite precipitates (Figure 14).

In the Ryongmun Cavern, the moonmilk deposits is distributed at sites where the supply of water is very low and the wind speed is relatively high (Table 3). Where the moonmilk deposits is present, there is no gravity water flowing down from the cave walls and anthodites. In addition, wind causes evaporation of water, creating conditions under which hydromagnesite can be formed.

In general, the formation of the moonmilk deposits in the Ryongmun Cavern is believed to be due to the fact that the moisture in the cave has decreased and the cave has been drying for several reasons in the last decade.

Therefore, it is important to maintain the humidity in the cave normally.

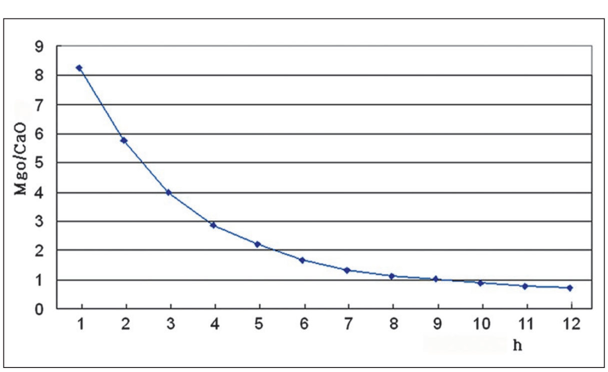

Fig. 13: Simulational result of the solubility of $MgCO_3$ and $CaCO_3$ at 10 °C.

$$CaMg(HCO_3)_4 \rightarrow CaCO_3 \downarrow + Mg(HCO_3)_2 + CO_2 + H_2O$$

$$Mg(HCO_3)_2 \rightarrow Mg_5(CO_3)_4(OH)_2(H_2O)_4) \downarrow + H_2O$$

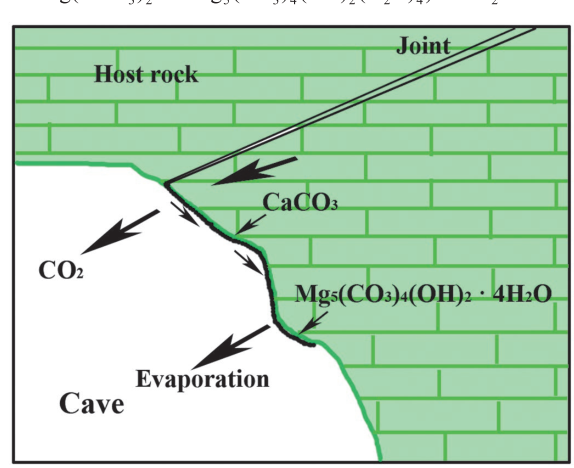

Fig. 14: Formative process of the hydromagnesite in the Ryongmun Cavern.

5. CONCLUSION

The Ryongmun Cavern is a typical temperate karst cave formed in the limestone layer of the lower Paleozoic era. The limestone layer is mainly composed of dark grey limestone.

The Ryongmun Cavern is vertically between 200 m and 310 m above sea level and has 4 main levels. The caves are mainly NW - SE - trending, NWW - SEE - trending and NNE - SSW - trending caves. The horizontal passages are mainly NW - SE - trending and NWW - SEE - trending passages, and the inclined ones are NNE - SSW - trending passages. The horizontal passages usually large and spacious, but inclined ones are characterized by relatively being small and narrow. The inclination angle of inclined passages is about 38° to 45°.

The direction and the cross-section form of the cave are mainly related to the bedding of the limestone layer and fault.

There are a large number of diverse and beautiful speleothems consisting of aragonite and calcite in the Ryongmun Cavern.

The recently formed moonmilk deposits in Ryongmun Cavern is mainly composed of hydromagnesite, with chemical composition of MgO-29.43% and CaO-6.28%.

The moonmilk is present in a white color, fine powder form, with a particle size of 0.55 μm, a hand-rubbed smooth, and a moisture content of 42.0%. Also, the pH is 10.09, which is alkaline.

In the Ryongmun Cavern, the moonmilk deposits was formed at sites with very low supply of karst water and relatively high wind speeds.

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