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Salt and Sinkhole
——Corrosion as a Principal Factor Governing Topography and Mass Movement in Northeast Thailand——

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Abstract

This paper presents a hypothesis that corrosion of salt beds of the Mahasarakham formation has been the principal factor on the topography development in Northeast Thailand.

Chapter 1 presents observation on salt-making which seems to have its origin in ancient periods some time in B.C.

In Chapter 2 discussions are presented on the possible source of salt, and we agree to the hypothesis by Takaya et al. and Sompob, who sought the source to the clastic members of the Mahasarakham formation.

Chapter 3 presents observations to indicate that, contrary to conventional view to presume thick clastic deposits covering the Mahasarakham formation, this formation is exposed directly on the ground surface. Because of this situation, salt crust is so common at valley floor where "short-distance interflow" seepages out.

Chapter 4 presents a sinkhole hypothesis on the topography of Northeast Thailand. Salt dome development and its collapse due to the salt corrosion are presumed to be the cause of sinkhole topography. Each salt dome development causes an anticlinal dome which can be identified as an assemblage of turtle-back shaped polygons in the aerial photographs. In the course of corrosion, anticlinal dome collapses. This leads to the initiation of sinkhole topography. At advanced stages of corrosion, large-scale sinkholes are developed. This paper presents a first approximation for demarcating anticlinal salt domes and sinkholes based on LANDSAT imageries.

Chapter 5 presents mass movement phenomena caused by sinkholes. Laterite pan and gravel beds retards this mass movement process.

The conclusion of this paper is that Khorat Plateau is a corrosion basin.

Location map of the sites mentioned in the text is given at the end of this paper (Fig. 29).

I Salt and Salt-making

1. *Traditional Way of Salt-making*

Salt in Northeast Thailand has been exploited since ancient time, probably even from B.C. period. It was one of the most important products of this area as well as iron. Salt-making was an important mainstay for the people in the dry season. Traditional way of salt-making is illustrated in Fig. 1. People collect salt crusts which are formed in sandy spots. Salt-making area has four elements of microtopography: ① salt crust site, ② wet and potentially saline belt, ③ naturally inundated depression where

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artificial ditches are frequently made, ④ artificial mound made by disposed sand. Salt crust site occurs on slightly elevated portion, or at the foot of artificial mound. Salt crusts are scraped together with sandy soils, and put to leaching trough ⑤. Trough is made of log wood about 3 m in length and 50 cm in diameter. It can accomodate about 250 kg of sand. A few holes are punched on the bottom, and conducting pipes are inserted to them. Before putting sand, people spread rice husks at the bottom of the trough so as to keep a good percolation in the leaching process. Site ② with clay soil, although it does not produce salt crust, is also important for keeping water of ③ to be salty, and its clay texture prevents the dug pond or ditch from being disrupted. People carry water from ③ and pour it into the trough until the sand is immersed, and keep the sand to be leached.

The leachate coming out from the holes is led to a receiving basin ⑥. The leachate which is quite salty is boiled on tin pan at soil-made furnace ⑦. From 100 *l* of the leachate, 20 kg of salt is produced.

The sand in the trough is disposed nearby. Usually salt-making is continued for long period at fixed spots, and subsequently the waste sand makes up high mound ④. Recently abandoned salt mound is bare. But, older mounds, since salt is leached away, are covered with grass and shrub like *sakae* and *nam ten* on the top, and surrounded by salt-tolerant shrub like *nam daeng* at the foot.

Salt-making site at Ban (abbreviated as B. hereafter) Khok Sung near Amphoe (abbreviated as A. hereafter) Muang Khon Kaen, Changwat (abbreviated as C. hereafter) Khon Kaen illustrated in Fig. 1 has many mounds as shown in Fig. 2. The size of mounds here is rather small; not exceeding 4 m in height and 15 m in diameter. Long ditches are dug from a pond to facilitate the water supply. Even a diversion dam is made, and ditch and mounds are arranged in a systematic plan.

If salt spots continue to exist and salt-making is engaged for long period, the salt mounds become quite large. Around Khon Kaen, large salt mounds are found at Nong Yai, settlement of B. Si That itself and around, Ban Phai, Mancha Kiri, and so on.

The number of salt mounds to the west of Ban Phai is about 70. This area is one of the core areas of salt-making in ancient times, although the dating is unknown.

The salt mound at Nong Yai near A. Muang

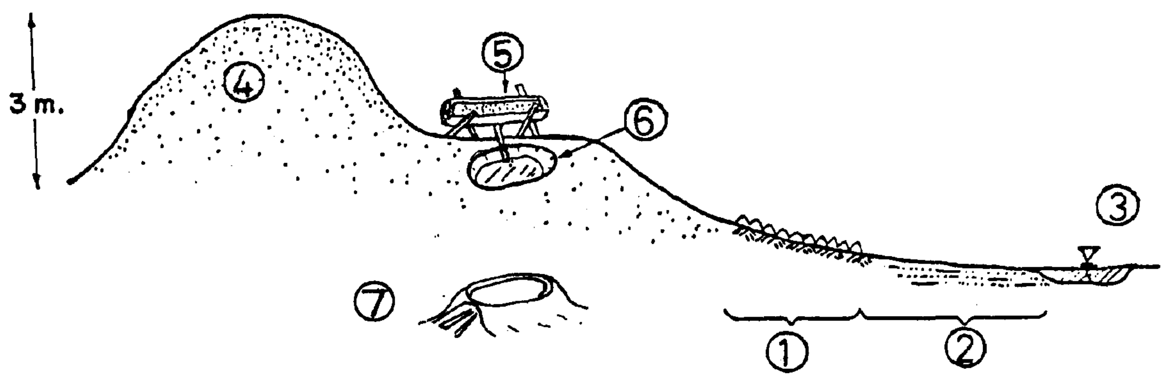


Fig. 1 Traditional Way of Salt-making Still Engaged

Khon Kaen may offer an important clue for dating. It is made of several smaller mounds, and the size of composite mounds is 100 m in length, 40 m in width and 7 m in height. There are other two composite mounds which were cut to level. One of these mounds produces at its basement the pot sherds with red slip which show a close similarity with those found at archaeological site of Non Chai, several hundred meters to the north. These sherds are dated about 500 years B.C. [Pisit and Bayard 1983]. This may provide an estimate on the age of salt mounds at Nong Yai.

The biggest salt mound I noticed so far is located at B. Don Kwang near Choho, A. Non Sung, C. Nakhon Ratchasima to the north of the junction of Highway (HWY) 2 and 2067. It measures 200 m×70 m and 10 m high. Pot sherds which are found at the foot are not so old; Lopburi celadon and low-quality code-marked sherds.

2. *Structure of Salt Mound*

Clear evidences showing that these large mounds were formed due to salt-making are not reported so far. Some people misunderstand that these are sand dunes formed by aeolian process. This view is entirely erroneous, brought about by the ignorance on the natural and human history of Northeast Thailand.

One example showing inner structure of these mounds was observed at B. Nong Suang, A. Non Thai, C. Nakhon Ratchasima, along HWY 2068, about 2 km northeast from the junction of Dan Khun Thot road and Non Thai road. One mound is cut and exposes a profile as illustrated in Fig. 3. Burned sand appears red, and indicates the oven site. Sherds also show burned traces, and are exfoliated on both faces. This exfoliation is caused by the prolonged boiling of salty water, and characteristic to the potteries used for salt boiling. Salty water which permeated into the pottery wall is

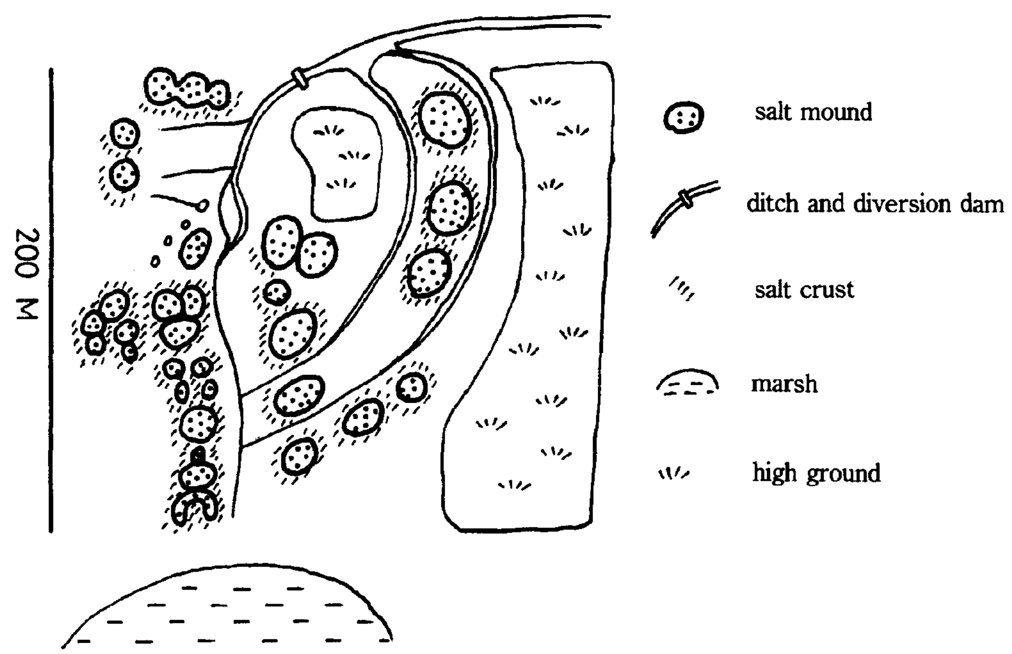


Fig. 2 Arrangement of Salt Mounds and Ditches at B. Khok Sung near Khon Kaen

crystallized there, thus makes the pottery wall to be exfoliated. Low quality is also characteristic to salt boiling pottery; no polishing, no painting, no decoration other than code-mark prints, and no artistic design of the form.

The formation process of this mound comprises three stages; disposal of leached sand and oven ash, boiling and processing of salt, and again disposal of leached sand.

3. *Distribution of Salt Mounds*

Salt mounds are numerous in Northeast Thailand, since high grounds on which villages are located originated as the result of layering of foreign material carried in through salt-making, iron-smelting, pottery-making and so on. As a matter of fact, it is not feasible to count up all the composite mounds. In the following paragraphs, salt mounds refer only to the isolated salt mounds.

A great number of salt mounds are found in B. Nong Suang, B. Pah Yah, and B. Nong Sakae area near A. Non Thai, C. Nakhon Ratchasima, in the upstream of Mae Nam Choeng Krai. Quite large mounds are found near to the junction of HWY 2 and 2067. Khon Sawan area in C. Chaiyaphum has about 15 large salt mounds. Some sporadic salt mounds are found at B. Sida and B. Phon along HWY 2, C. Khon Kaen, and west of Prathai along HWY 207, C. Nakhon Ratchasima. The shallow valley between A. Ban Phai and A. Chonnabot, C. Khon Kaen, has about 70 salt mounds. The chain of lakes from Mancha Kiri to Nam Tong Lake near Khon Kaen is associated with several salt mounds which are located close to the lake shore.

Around B. Nong Samlong, a few km to the north of Udon Thani Town, there are some salt mounds with many pot sherds.

Along the way from B. Kho Noi to A. Nong Hang near Kumphawapi Lake, C. Udon Thani, there is another concentration of large salt mounds with many pot sherds.

Salt mounds are present in Tung Kla Ronhay, too. Nong Pha Khan and Bo Noi to the east of A. Suwannaphum, C. Roi Et, have rather new salt mounds.

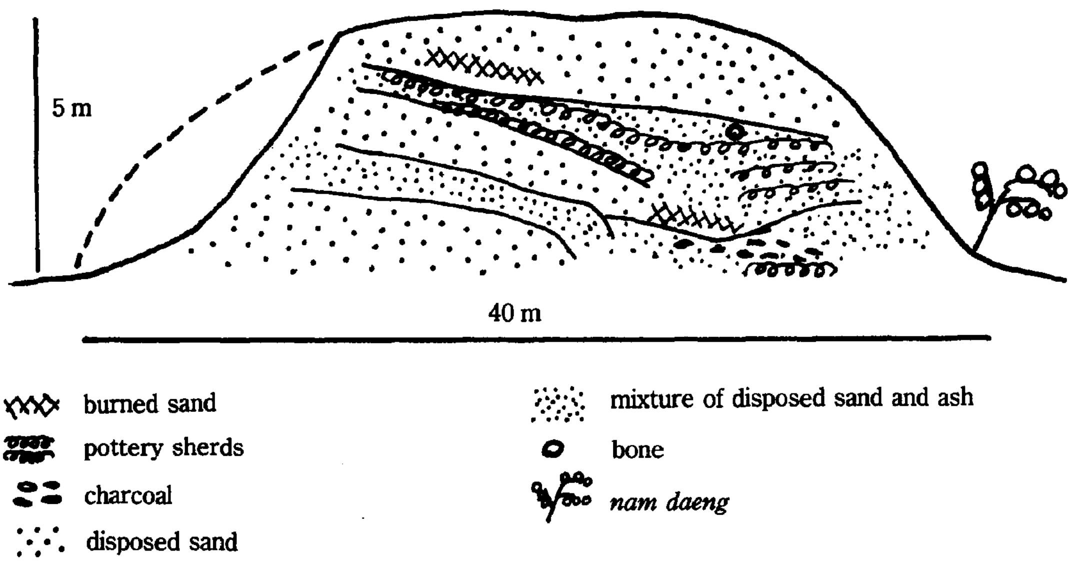


Fig. 3 Exposed Profile of a Salt Mound at B. Nong Suang, A. Non Thai, C. Nakhon Ratchasima

Although sporadic number of salt mounds are noticed everywhere, salt mounds are concentrated in hilly area. Takaya *et al.* [1984] claim that rock salt members are exposed in the hilly area, and because of this exposure, salt crust on the valley slope is remarkable.

II Source of Salt

1. Salt in Clastic Members of Mahasarakham Formation

Contrary to general belief to seek the origin of salt to the rock salt itself, Takaya *et al.* [1984] proposed a hypothesis that salt comes from the clastic members of Mahasarakham formation, and also from Plio-Pleistocene formation. Their hypothesis on salt origin seems to have been well proved by Soil Survey Section of DLD. My observations also conform with their hypothesis. Some examples are given below.

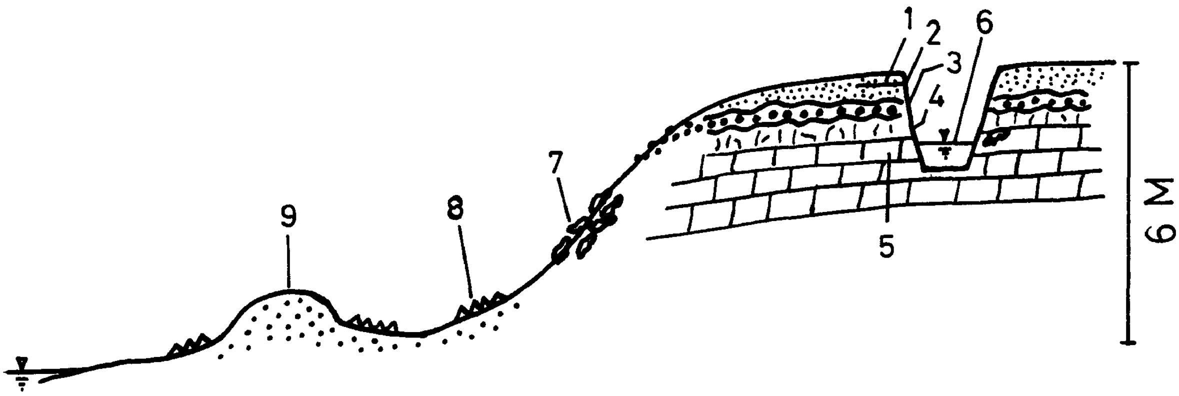
(a) An illustrated example (Fig. 4), located at B. Khok Sung near Bung Kaen Nam Ton, A. Muang Khon Kaen, C. Khon Kaen, shows very salty pond water, and salt crust at sandy patches at the foot of the hill.

(6) is a pond dug up recently. The water is very salty; the electric conductivity (EC) was 35 mS in May, and 48 mS in June, almost same concentration with sea water. Since the pond is located on the crest of a low hill, the source of salt is exactly the rock itself at the site. Rain water which impregnated into the rock saprolite has dissolved salt veinlets in the rock. The rock apparently has calcareous substances, as indicated by the presence of lime nodules on waxing slope, and by calcite crystals (7) embedded in rock saprolite.

Soil profile exposed at pond wall is as follows.

(1) 5 cm brown (7.5YR4/4) HC; few gravels.
(2) 20 cm brown (7.5YR4/5) HC; many pisoliths.
(3) 10–30 cm pisolith layer with undulation.
(4) 50 cm reddish brown (2.5YR5/5) HC; granular; common pisoliths (Ø 5 mm).
(5) 70 cm purplish red (10R5/5) HC; saprolite of Mahasarakham claystone; many fracture surfaces are changed to blue clay; bedding layers are discernible; large lime nodules (Ø 10 cm) are present which have nest of calcite crystals in geode.

(b) Other example in Chaiyaphum is as fol-



(1)–(5) soil layers (see text)
(6) pond (7) lime nodule (8) salt crust
(9) salt mound

Fig. 4 Fish Pond with Salty Water Located on Hill Crest at B. Khok Sung, Khon Kaen lows. The observation was done at B. Nong Na Saeng, A. Muang Chaiyaphum, C. Chaiyaphum, 4.3 km south of HWY 2053 junction, and 100 m west from HWY 201.

(1) 30 cm dark brown (7.5YR3/3) HC.
(2) 40 cm brown (7.5YR4/4) HC; small lime nodules and manganiferous pisoliths.
(3) 30 cm bright reddish brown (2.5YR5/6) HC; saprolite of Mahasarakham claystone; soil tastes salty and also has Na_2CO_3 nodules.

The darker color indicates more calcareous nature than case (a), and original bedrock is supposed to be more calcareous. Co-presence of halite and lime is often noticed elsewhere.

(c) Another example at Choho was observed at B. Khok Sung, C. Nakhon Ratchasima, at a fish pond located 3.3 km from the Choho junction, along HWY 205. The site is in an isolated hill which stands in the flood plain of Mae Nam Mun. The pond water is quite salty and shows EC value higher than 10 mS. Salt crusts are formed on the cut floor around the pond. Soil profile exposed at a pond wall is as follows.

(1) 25 cm dull yellow brown (10YR5/3) HC; many manganiferous pisoliths; very fine lime spots; chloride reaction + + +; soil material reacts with HCl.
(2) 50–100 cm lime nodule layer (Ø 1 cm); dull brown (7.5YR5/3) HC soil material shows chloride reaction + + + +.
(3) 100 cm mosaic of purplish red (10R4/6), pinkish white and olive grey (5Y5/2) HC; saprolite of Mahasarakham claystone; various salt precipitates like lime, NaCl and Na_2CO_3; large lime nodules and halite crystals are abundant in the saprolite matrix.

These examples illustrate that clastic members of Mahasarakham formation involve vein or veinlets or various evaporites, like halite, lime, bers of Mahasarakham formation involve vein of veinlets or various evaporites, like halite, lime, sodium carbonate, gypsum, and so on. These evaporites are released from the weathering saprolite, producing salt crusts at sandy spots, and lime nodules in the soil.

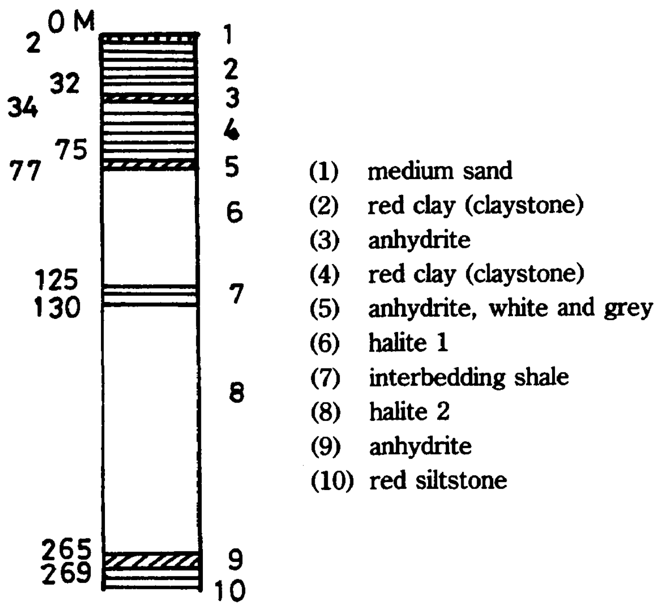


Fig. 5 Drilling Core at Asahi Salt Co., A. Phimai, C. Nakhon Ratchasima

2. Drilling Hole into Rock Salt

Another source of salt for salt-making is rock salt itself. Mahasarakham formation has thick rock salt bed (halite) as well as other evaporites like anhydrite ($CaSO_4$), sylvite (KCl), carnallite ($KCl \cdot MgCl_2 \cdot 6H_2O$), tachyhydrite ($CaCl_2 \cdot 2MgCl_2 \cdot 12H_2O$), and carbonaceous evaporites. Detailed description of deep boring data [Suwanich and Phitak 1982] and rock salt geology may be referred elsewhere (for example, Japakasetr [1985]).

One example of boring data which I was informed of at Asahi Salt Co., A. Phimai, C. Nakhon Ratchasima, is as follows (Fig. 5).

It is halite 1 only that is mined since halite 2 involves carnallite as impurities which make the quality of produced salt poor. The method of salt production is as follows. (1) Vibration generator is inserted into the salt bed to make fractures. (2) Pressured water is poured in, and rock salt is dissolved. (3) The dissolved brine is lifted up by compressor and led to salt pan.

A serious problem arises after prolonged mining works; cavity will develop underground. In order to prevent the subsidence of the ground, two counter-measures are taken; (1) once in three years, drilling boreholes are moved to other ones, (2) crude oil is injected to the cavity of the abandoned borehole.

Besides modernized factories which use modern methods for drilling, local people use traditional way. The method is same with so-called Kazusabori in Japan; outer casing pipe and inner cutting pipe are used; ordinary plumbing pipes are used for this purpose. The inner cutting pipe is attached with a simple cutter at the edge, and water is injected from the top. Two men rotate the inner pipe and drive it in like a screw. Cutting debris is brought out by pressured water flow, passing through the outer casing pipe.

By chance I met the drilling workers at B. Champadon, A. B. Muang, C. Sakon Nakhon. They told that rock salt will be hit at about 60 m depth. I asked how they can tell that drilling reached rock salt bed. Their answer was very interesting; water does not return up once the cutting hits rock salt. The possible interpretation for this fact is only one; there is a cavity in the rock salt bed. Dissolution of rock salt must have advanced under natural conditions.

Salt mining by drilling method will inevitably enlarge the cavity and induce an abrupt subsidence. I asked them about this possibility, and they told that there was actually a catastrophic subsidence at B. Non Kuam, A. B. Muang, C. Sakon Nakhon.

I visited the site. Salt source in this mining is brine. Salt-producing started in 1980. In 1987, catastrophic subsidence took place; an area of land 20 m by 20 m in front of laborers' house fell down as much as 40 m. The hollow was buried up with soil, and water was injected as a measure to prevent more subsidence.

These findings made me to develop a sinkhole hypothesis as will be discussed later.

3. Nam Dung Topography

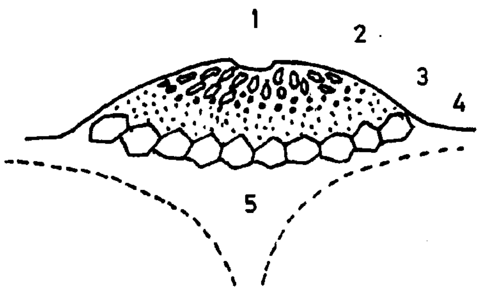
Takaya *et al.* [1984] and Sompob [1986] proposed a short-distance interflow along the ground surface for the transfer of the dissolved salt released from clastic members. Water rich in salt and lime, as well as montmorillonite clay, gushes out at sandy spots, and makes low pimple mounds, which are called ***nam dung*** in Tha Pra, Khon Kaen. Two stages of ***nam dung*** development are described by them; active and moribund one.

The following figures illustrate various features observed at active *nam dung* site of B. Suwan Mon Hak Pra, A. Muang Khon Kaen, C. Khon Kaen, 5.4 km east from Tha Pra junction.

Farmers say that water gushes out all of a sudden amidst rice fields. The first breakthrough is very strong and water column sometimes reaches three meters high. Water is not necessarily salty. Because of continuous flow-in of quick clay, sand, lime and pisoliths, a dome-shaped mound is formed. Around the central vent of the dome, various features array in concentric manner (Fig. 6 (a)). The innermost ring is enriched in lime nodules and pisoliths. On middle slope sand accumulates, and on the footslope of mound, clay polygons are formed. Polygonal clay is not necessarily calcareous.

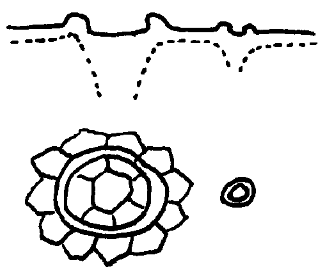
After the first "eruption," water never gushes out, but the bumping ground widens its extent. This implies that the pressure is generated by gravitational water head difference. Once the confinement is released by breaking through a vent, the pressure of the confined aquifer loses its energy. Quick clay rich in montmorillonite flows along underground channels, fills up the interstices of sandy soils, and makes the whole area bumping.

At this stage, many concave vent, besides *nam dung* mounds, are formed (Fig. 6 (b)-(d)). Here and there in *nam dung* fields, mud cracks are formed. Dried quick clay shrinks on the ground surface, then polygonal shapes emerge, separated by mud cracks. Polygon is mostly hexagonal, and about 20 cm in size. Grooves between each neighboring hexagon are 2 cm wide and 2 cm deep. Sands flow in these grooves and encircle whole polygon assemblage. Polygon assemblage in Fig. 6 (c) is flat, while that in (d) shows a slight elevation and has

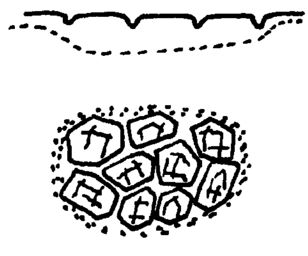


(1) Vent hole.
(2) Lime nodules, iron and manganiferous pisoliths. Lime nodules on the surface are hardened while those inside are yet soft.
(3) Sandy loam.
(4) Clay with polygonal mud cracks.
(5) Quick clay underground saturated with water.

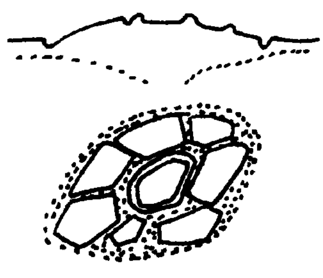
(a) Typical *nam dung*



(b) Un-raised vent hole



(c) Polygonal mud cracks. Many portions show no reaction with HCl.



(d) Mud cracks on slightly elevated mound. Sand flow around polygon units.

Fig. 6 *Nam Dung* Topography, at Tha Pra, Khon Kaen a small vent at the center, as well as small bulge of clay column. Many portions of polygon do not bubble with HCl.

These features are important for correct interpretation of polygon assemblages which are frequently observed on sandstone slab of Phu Phan and other older Khorat groups, as will be discussed later.

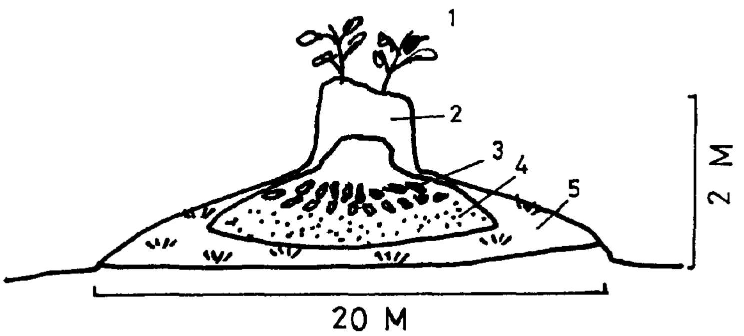
There are many moribund *nam dung* as well. In my view, almost all termite mounds, which are countless in Northeast Thailand, have developed on moribund *nam dung*. The area to the south of A. Muang Si Sa Ket along HWY No. 220 offers a sound evidence for this interpretation. This area has numerous termite mounds in a high density. Fig. 7 illustrates one of the termite mound which was cut into halves and spread for planting *Allium*. Hooves of water-buffalo are printed on (4) which is now quite hard. This indicates that compacted sandy ground was once soft enough to be printed by cattle hooves.

The moribund *nam dung* presumably offered good habitation sites for termite, because termite seeks for elevated ground so as to avoid the danger of flood. Furthermore, termite prefers calcareous soil. Moribund *nam dung* was the best habitat for them in this flat level land having poor sandy soil all around and inevitably suffering from endemic floods. Composite mound of moribund *nam dung* and termite mound, in turn, offered most suitable upland fields for farmers in planting commercial crops. They chose the ground on a same reason with termite.

III Alteration Processes and Products of Clastic Members of Mahasarakham Formation

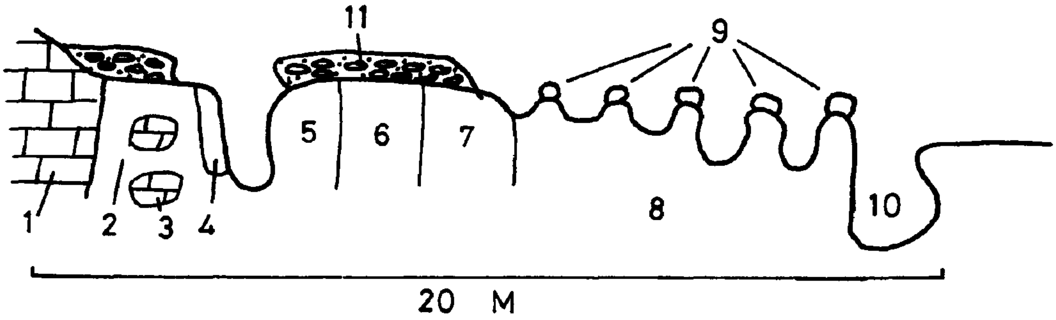
1. Alteration in Lateral Sequence

Although the concept of Plio-Pleistocene formation proposed by Takaya *et al.* [1984] is very much understandable, the thickness of the formation seems very thin as compared to that in other areas. It seems more understandable to suppose that most part of the formation melt away due to the corrosion, and that grey white



(1) *Nam taeng.*
(2) Termite mound made of light yellow, very compact clay which stands one meter high from (3).
(3) Moribund *nam dung* which has many lime nodules spread on the surface.
(4) Sand-covered middle slope.
(5) Grass-covered lower slope.

Fig. 7 Termite Mound on Moribund *Nam Dung* in Si Sa Ket Area



(1) Purplish red (7.5R6/2) fresh sandstone having predominantly feldspar and less quartz and biotite.
(2) Reddish orange (5YR6/6) saprolite still holding sandstone fabric; many fine pores; weak bubbling with HCl.
(3) Light purplish red (2.5YR6/2) sandstone remaining in saprolite; many fine pores.
(4) White sandstone with purplish brown (5YR6/2) surface crust having coarse pores.
(5) Purplish red (7.5YR7/1) HC; many fine pores; greenish grey mottles originating from the fractures in the rock.
(6) Mosaic clay of 5YR6/6, 10YR5/1 and white.
(7) Orange (7.5YR7/6) LiC; common reddish brown (2.5YR5/8) soft pisoliths.
(8) Dull orange (5YR7/4) LiC.
(9) Orange (7.5YR7/6) LiC with lime threads, forming a soil column capped with lime nodules (Ø 3 cm).
(10) Rill carved in flask shape.
(11) Gravel bed composed of predominant quartzite and some black chert and petrified wood.

Fig. 8 Alteration Sequence Developed in Lateral Outcrop of a Purple Sandstone

clay with yellow mottles and lime nodules represent altered layer of clastic Mahasarakham member.

The profile at Choho described before, for example, is interpreted as a residual alteration product on the Mahasarakham clastic rock. More complete sequences are frequently observed, which show a successive change from fresh purple red claystone/siltstone to yellowish brown soil with lime segregation. Some examples are given below.

(a) One representative outcrop was observed on the way from A. Khemmarat to A. Chanuman, at 7.5 km west from A. Khemmarat, C. Ubon Ratchathani (Fig. 8).

Various alteration products described above actually originate from one bed, e.g., purple sandstone. Alteration process revealed in this sequence is interpreted as follows. Feldspathic sandstone containing lime and possibly other evaporites released lime and evaporites first, then underwent the transformation of feldspar to clay, and subsequent segregation of clay and iron compounds. Fig. 9 schematically expresses the process.

Fine pores found in the saprolite are considered as cavities due to the release of evaporites. The rill which appears as carved-in trough having flask-shape was presumably formed after the evaporite dyke melt away.

(b) Numerous fractures are frequently noticed in clastic members. A new outcrop was observed on the way connecting A. Kranuan, C. Udon Thani and A. Waritchaphum, C. Sakon

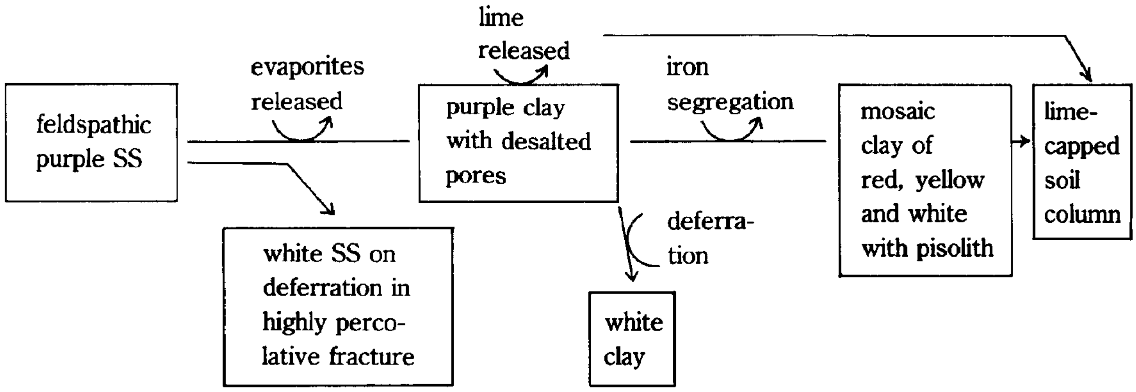


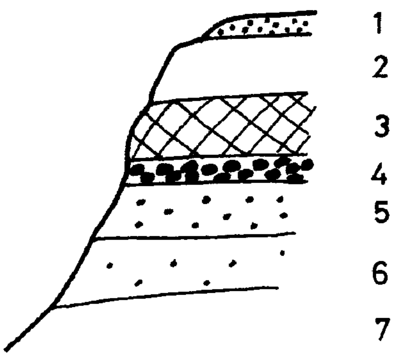
Fig. 9 Alteration of Purple Sandstone into Various Formations

Nakhon at 11.2 km south of B. Thung Chuak which is located in a sinkhole. The bedrock is purple (7.5R4/3) claystone with pronounced lamination. Greenish grey clay along numerous fractures runs both laterally and longitudinally. Lime precipitates in replica of fractures are formed as fine threads. Feldspathic pink sandstone also outcrops nearby. Many tortuous voids are formed probably due to the dissolution of lime and other evaporites.

2. *Alteration in Vertical Sequence*

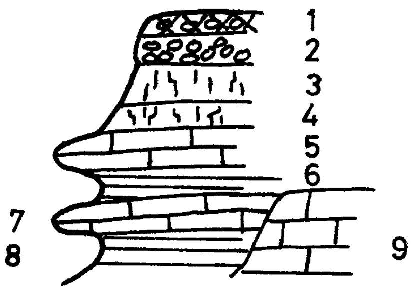
(a) Vertical sequences in soil profile indicate the same principle as illustrated in Fig. 9 operating in differentiation of alteration products. I want to stress that the later mantle covering the saprolite is quite thin. One representative profile was observed on gently undulating hill at 19 km west from A. Phuttaisong, C. Buriram on HWY 202 to A. Prathai, C. Nakhon Ratchasima (Fig. 10).

I interprete that layers (5) to (7) are altered saprolite of Mahasarakham claystone. Pisolith layer and botryoidal iron nodule layer also resulted from accumulation of pisolith through surface disturbance. Therefore, layer (1) and (2) alone are recent deposits, which were brought by local transport.



(1) 15 cm pinkish grey LFS.
(2) 70 cm pinkish brown (7.5YR7/3) SCL.
(3) 40 cm abundant botryoidal iron nodules.
(4) 20 cm abundant iron pisoliths with white clay filling the interstices.
(5) 50 cm greyish white (2.5Y8/1) HC; with many iron pisoliths (Ø 2 mm); with increasing red mottles downward.
(6) 60 cm purplish red (10R5/6) and light grey HC; with disturbed lamination; with a few hard iron pisoliths (Ø 4 mm).
(7) 50 cm+purplish red (10R4/6) HC; with manganiferous coatings; disturbed lamination.

Fig. 10 Vertical Sequence of Alteration Products of Mahasarakham Claystone



(1) 10 cm upper part of gravel bed, indurated by iron oxides.
(2) 20 cm small pebble layer, cherty.
(3) 40 cm light yellow (10YR7/4) LiC; with many yellowish brown coarse mottles.
(4) 30 cm greyish white (7.5Y8/1) HC; with many yellowish brown coarse mottles.
(5) 30 cm greyish white (7.5Y8/1) and orange (7.5YR6/6) feldspathic sandstone (fine sand with many mica); color mosaic is resulted because of iron segregation.
(6) 30 cm greyish white HC; same as (4).
(7) 30 cm mosaic-colored sandstone; same as (5).
(8) 40 cm bluish white (10Y8/1) sandstone (feldspathic) with lamination.
(9) 60 cm + purple feldspathic sandstone with many mica; with lamination. This bed associates with (7) and (8).

Fig. 11 Vertical Exposure of Differently Altered Saprolite

(b) Alternation of sand and clay, which may appear as Plio-Pleistocene deposits, composes one member of Mahasarakham formation. The observation was made at 4.8 km east of HWY 2 and 2039 junction, A. Nam Phong, C. Khon Kaen (Fig. 11).

Association of purple sandstone and grey sandstone is resulted due to the differentiation from the same bed. The mineral composition and lamination fabric imply the same origin. Since the 9th layer is Mahasarakham formation, it follows that layers (5) to (8) also belong to Mahasarakham formation, and that the layers (3) and (4) are residual soil. Later addition is gravel bed only.

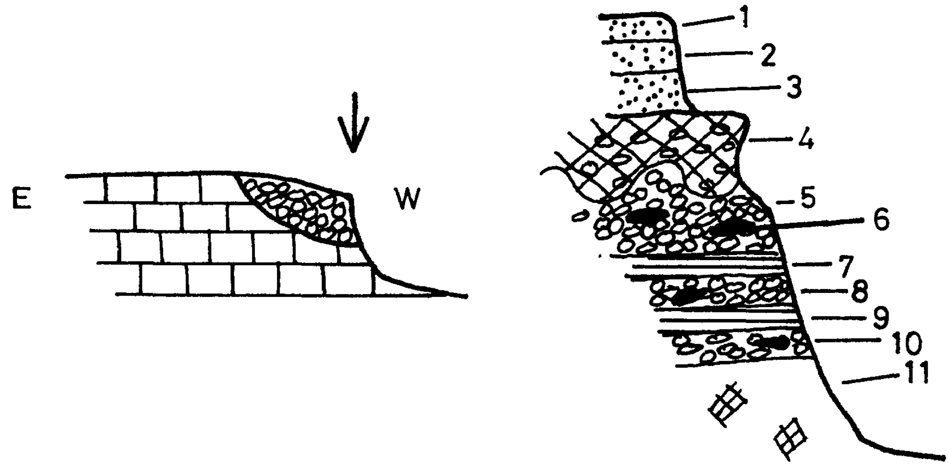
3. *Limited Extent of Gravel Bed*

Frequently, gravel bed attains a remarkable thickness and exposes itself at the periphery of elevated terrain. This caused some scholars to assume a remarkable development of Pleistocene terraces. The gravel bed, however, does not cover the whole elevated terrain. In many cases the gravel bed is limited to the periphery of the elevated terrain which is denuded plain of Mahasarakham bedrock.

(a) The following observation, for example, was made at B. Sadao, A. Muang Yasothon, C. Yasothon, 6.6 km east of HWY 23 and 202 junction (Fig. 12). The lowermost layer represents a hardened plinthite which was formed under alternating saturated and unsaturated conditions with temporal groundwater flow along the fractures of sandstone. Consequently sandstone was transformed into clay mass, in which segregation of iron compounds proceeded. Oxidation of iron compounds took place in narrow cracks, resulting in the hardening of the plinthite mass.

(b) Similar alteration products, with no gravel bed in this case, are found frequently in the flat level plain of northeastern rim of Tung Kla Ronhay. An outcrop was observed at a pond cut in level rice fields of B. Bung Khrua, A. Kham Khuan Kaeo, C. Yasothon, 6 km southwest of B. Kaen Yai on HWY 23 to Ubon. The profile is as follows.

(1) 15 cm pinkish grey (10YR7/4) LFS; a few



(1) 15 cm grey (10YR5/1) LFS.
(2) 40 cm pale grey (10YR7/1) LFS.
(3) 50 cm yellowish brown LFS.
(4) 30–100 cm sand and gravel bed indurated by iron-containing seepage.
(5) 100 cm sand and gravel bed, consisting of sub-rounded to sub-angular small pebble; quartzite and elongated chert; sand is 10YR8/2.
(6) iron-indurated gravel lense.
(7) 20 cm pinkish (7.5YR8/1) LiC; with hardened mottles of purplish red (7.5R4/4) and yellowish brown (10YR6/8).
(8) 20 cm sand and gravel bed, same as (5).
(9) 25 cm pinkish grey LiC, same as (7).
(10) 20 cm sand and gravel; with coarse fragment of petrified wood.
(11) 60 cm+pinkish white (10YR8/1) LiC filling the pores in hardened vesicular laterite blocks which have dark purplish red (7.5YR3/3) sandstone core and yellow (10YR7/7) coatings. This layer is saprolite of Mahasarakham bedrock.

Fig. 12 Thick Gravel Bed Covering the Saprolite

iron pisoliths (Ø 5 mm) with concentric crust and goethite-rich soil material around purple sandstone fabric.

(2) 25 cm pinkish brown (10YR5/2) HC; with many faint yellow mottles; common rounded iron pisoliths (Ø up to 1.5 cm) having similar fabric as above.

(3) 50 cm pinkish grey (7.5YR7/3) HC; many yellow orange (10YR7/8) mottles and purplish red (7.5R3/4) stone fragment; common lime nodule (Ø 5 mm).

(4) 20 cm mosaic of pinkish grey (10YR8/2), yellowish brown (10YR7/6) HC; common ironstone which has mammilated surface and purple siltstone core derived from bedrock; common lime nodules (Ø up to 2 cm).

(5) 25 cm mosaic of white (N8/0) and yellowish orange (10YR7/8) HC; many fine pores; many ironstone same as above.

(6) 30 cm mosaic of white clay, yellowish orange (10YR7/7) HC; with ironstone derived from siltstone having purple (7.5R4/6 and 3/3) color; this layer represents hardened plinthite with tortuous cavities.

In layers (5) and (6), segregation of iron compounds and clay resulted in the formation of vesicular laterite. Layers (3) and (4) have undergone pedological transformation, yet it is clear that they are derived from alteration products. Layers (1) and (2) are recent deposits.

Observations described above indicate that Mahasarakham bedrocks lie at shallow depth from the ground surface. Later deposits are quite thin. This suggests that Plio-Pleistocene formation, even if it had been formed, was melt away. This view is derived from a sinkhole hypothesis which is presented in the next chapter. Topography of Northeast Thailand has been governed by corrosion process after the deposition and subsequent uplift of Mahasarakham formation took place.

IV Sinkhole Topography

1. *Large Sinkhole*

As described above, halite and other kinds of evaporites are embedded as small veins in clastic members of Mahasarakham formation. Furthermore, thick rock salt beds underlie the clastic members. In my view, other formations like Khok Kruat, Phra Wihan, and Phu Phan also contain salt veins.

Evaporite-containing rocks show entirely different behavior in weathering process as compared to siliceous rocks. First, evaporites are melt away with water much much faster once they come into weathering sphere. Those evaporites like carnallite and tachyhydrite show a high deliquescence. Contact with the air already causes the dissolution. Second, they leave no weathering detritus, and leave cavity behind. These cavities cause catastrophic subsidence of the capping layers, and make sinkholes. Actually there are many sinkholes in Khorat Plateau.

The examples of most well defined sinkholes can be seen in oval-shaped basin of Phu Wiang (cf. Fig. 16 (a)), C. Khon Kaen, and Khao Wong (cf. Fig. 16 (d)), C. Kalasin. Basin floor of Phu Wiang is surrounded by circular rock wall. The diameter of the basin is 17 km. The basin level is engraved as much as 125 m even from the lowest crest level. There is only one outlet, through which small stream flows out. Is it possible that this deep engraving in oval-shape was completed by this small stream? Conventional concept of weathering and erosion seems to be unapplicable. Khao Wong basin is also oval-shaped and much bigger. The long axis is 33 km and short axis is 15 km. Basin floor is carved in as much as 60 m from the lowest crest around.

Reasonable explanation of Phu Wiang landform is only one; to suppose a sinkhole formation due to the corrosion of rock salt bed. According to a geological map, Phu Wiang is composed of Phra Wihan formation in the upper half, and Sau Kruat formation in the lower half. Both are claimed to have no salt bed. But, as a fact, salt-making used to be done until recently. Actually, salt crusts are found in many rice fields, and many shallow wells give salty water. Measurement of well-water at B. Muang Mai, A. Phu Wiang, C. Khon Kaen, showed EC of 7 mS on June 24, 1987.

I interprete that Phu Wiang landform was initiated by salt dome development. The situation may be compared to squeezing out tooth paste by pressing both ends of the container. Tooth paste will flow in the container and make a bulge somewhere. In this respect, flowage structure of rock salt which is noticed and described in DMR Report [Suwanich and Phitak 1982] is to be noted. Flowage structure is substantiated by "flattened halite grains" or by

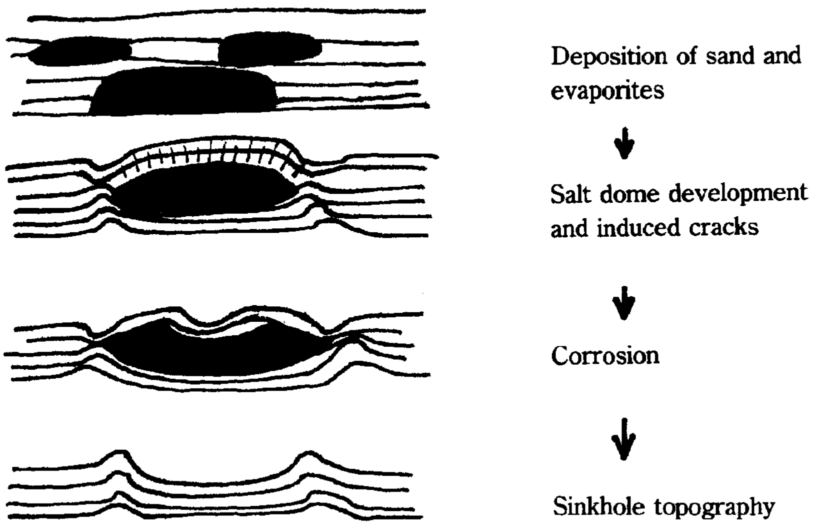


Fig. 13 Schematic Diagram of Phu Wiang Landform

"formation of sheet which break easily along the flowage direction." Highly plastic nature of rock salt beds is well known. Rock salt is an incompetent rock mass. When overlying deposits become thick enough and exert pressure on incompetent rock salt, it flows and makes salt dome. This causes upwarping of the capping layers, which are eroded rapidly because of high percolation rate through numerous fractures.

Once salt dome comes within the weathering sphere, it will be rapidly dissolved by percolating water, and melt away leaving cavity. When the cavity becomes large, and can not support the load of capping layers, it causes catastrophic fall-down of the capping layers. A sinkhole is thus made. This view is schematically illustrated in Fig. 13.

As a matter of course, no rock salt is exposed now in Phu Wiang landform. However, there are various features which indicate the former presence of plastic flowage of rock salt. One example is found at Tham Kwang of Wat Songsira near to B. Hing Rong, A. Phu Wiang, C. Khon Kaen. Here is a large exposure of sandstone slab with remarkable cross-laminae. The rock mass has many caves and large trough (Fig. 14).

The trough is carved-in into sandstone. The rock surface of the trough is quite smooth and polished. This kind of trough is commonly

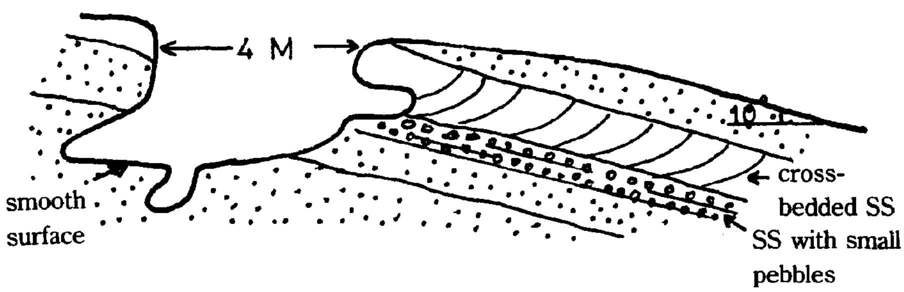
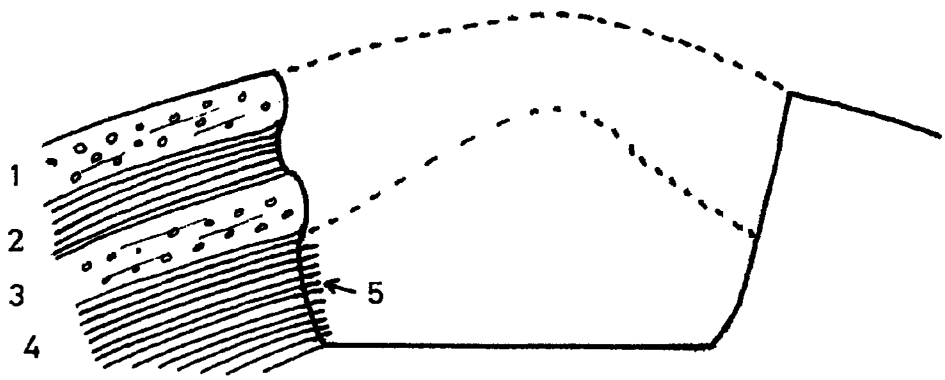


Fig. 14 Replica of Salt Dyke Showing the Former Flowage of Rock Salt, at Tham Kwang, B. Hing Rong, A. Phu Wiang, C. Khon Kaen



(1) white sandstone with small round pebbles.
(2) dark brown claystone with many manganiferous pisoliths.
(3) same as (1).
(4) bluish grey claystone, calcareous.
(5) platy lime precipitates.

Fig. 15 Schematic Diagram of Khao Wong Sinkhole

found at other temple sites, too. These troughs were formed by rock salt dykes intruding into surrounding sandstone when rock salt underwent plastic flowage. Supposedly salt dykes or plugs stretched out from the central salt dome. After the salt dyke was melt away, its replica figure was left as the trough. Although no trace of salt remains on the trough surface, there is some trace at the cave roof. The cave roof shows distinctly different fabric compared to the inner matrix; numerous tortuous hollows (Ø 1 mm to 1 cm) lie in the thin, lighter-colored crust. This crust shows positive reaction with $AgNO_3$. This crust is the contact face between salt dyke and intruded sandstone.

In case of Khao Wong, there is an interesting road cut at the intersection of HWY 2291 and the surrounding "crater," as illustrated in Fig. 15. The upper three layers represent rather resistant member. The thick claystone at the bottom is soft, very much calcareous, and represents non-resistant member. Lime precipitates eject out in plates from the exposure face. The bedding of the clay shows upwarping, which was caused by the growth of salt dome underground. These capping layers collapsed due to the cavity development.

The normal size of salt domes is known to be less than 10 km in diameter elsewhere in the world. Salt domes in Khorat Plateau seem to have a similar size, as will be inferred by airphoto analysis shown later.

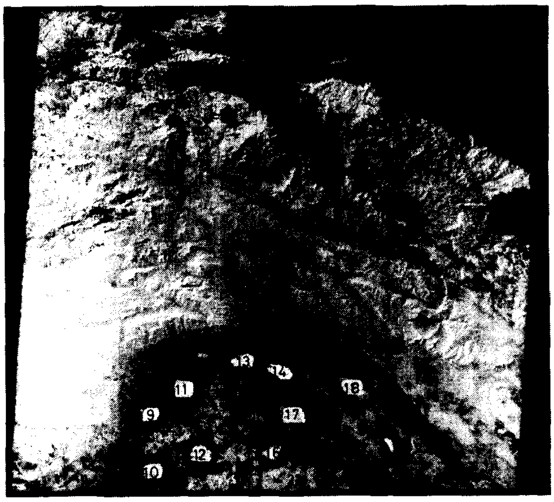
2. Distribution of Large Sinkholes

2.1 Approach through LANDSAT Imageries

Observation of LANDSAT imageries reveals many large sinkholes in Khorat Plateau. The following plates (Fig. 16) show a first approximation for demarcating the sinkholes recognizable in LANDSAT imageries. The demarcation is primarily based on striated geological structure which encircles the depression of oval shape. The sinkholes are rather clear around Phu Phan range, Chaiyaphum and Khon Kaen areas. On the other hand, they are unclear in Mun-Chi basin; the encircling cliff is diffuse and

(a) Scene 138–48. 31 Dec. 1975
1. Phu Kra Dung SH 2. Phu Wiang SH 3. Phu Kao SH 4. Ban Phu SH

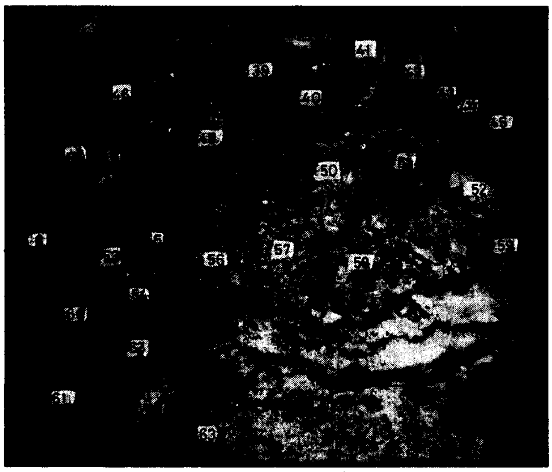
(b) Scene 138–49. 1 Mar. 1973
5. Ban Thaen SH 6. Khon Sawan SH 7. Chaiyaphum SH 8. Chaiyaphum–Nakhon Ratchasima AD



(c) Scene 137–47. 17 Jan. 1975
9. B. Phak Kha SH 10. B. Na Tan Mai SH 11. B. Khlong Khem SH 12. B. Tum SH 13. B. Don Po SH 14. A. Bung Kan SH 15. B. Phon Sawan SH 16. B. Don Siat SH 17. B. Nong Chan SH 18. Phu Mai La SH 19. Nong Khai AD

(d) Scene 137–48. 17 Jan. 1976
4. B. Phu AD 20. Udon AD 21. B. Dung AD 22. B. Muang AD 23. Si Songkhram SH 24. Na Wa SH 25. Wanon Niwat AD 26. B. Sum Phat SH 27. Kumpawapi SH 28. Lam Pao SH 29. An Kep Nam Phong SH 30. Waritchaphum SH 31. B. Tung Chuak SH 32. Kut Bak SH 33. Sakon Nakhon SH 34. Si That SH 35. Phu Pong SH 36. B. Phon SH 37. Somdet SH 38. Khao Wong SH

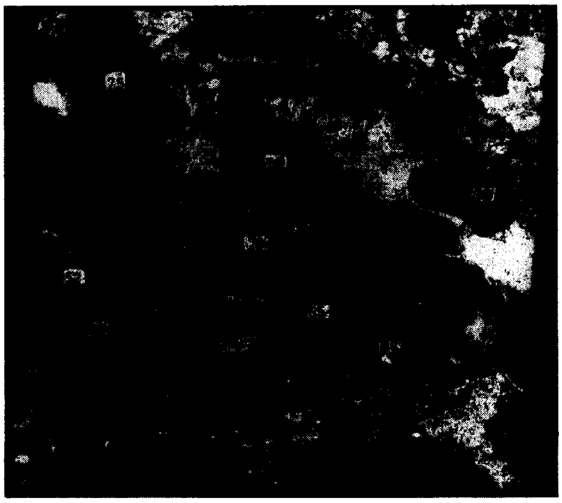
Fig. 16 Sinkhole Topography in Northeast Thailand
solid line: sinkhole (SH)
dotted line: anticlinal dome (AD) due to salt dome development



(e) Scene 137–49. 7 Oct. 1979
6. Khon Sawan SH 39. Chiang Yun SH 40. Kuntharawichai SH 41. Kalasin SH 42. Pho Chat SH 43. B. Na Phaeng SH 44. Phong Thong SH 45. Selaphum SH 46. Khon Kaen SH 47. Mancha Kiri SH 48. B. Phai SH 49. Kosum Phisai AD 50. Mahasarakham AD 51. Roi Et AD 52. Southeast Roi Et SH 53. Bung Thung Phung Phut SH 54. B. Raroeng SH 55. Phon AD 56. Nong Song Hong AD 57. Borabu AD 58. Wapi Pathum AD 59. Suwannaphum SH 60. Chatturat SH 61. Kham Sakae Saeng SH 62. Prathai SH 63. Chum Phuang AD

(f) Scene 137-50. 24 Nov. 1979
63. Chum Phuang AD 64. Choho AD 65. Nakhon Ratchasima East AD 66. Chakarat AD 67. B. Nong Yang AD 68. B. Khu Muang AD 69. Satuk South AD

(g) Scene 136–48. 16 Jan. 1976
24. Na Wa SH 33. Sakon Nakhon SH 38. Khao Wong SH 70. Kusuman SH 71. Na Kae SH 72. B. Kok Tum SH 73. A. Don Luang SH 74. A. Khamcha SH



(h) Scene 136–49. 16 Jan. 1976
52. Southeast Roi Et SH 59. Suwannaphum SH 75. Kuchinarai SH 76. A. Loeng Nok Tha SH 77. Khemmarat South SH 78. A. Sai Mun SH 79. A. Kut Chim SH 80. Amanat Charoen SH 81. Yasothon North SH 82. Yasothon East SH 83. Lam Se Bok SH 84. A. Tra Kan Phut Pon SH 85. A. Muang Sam Sip SH 86. Ubon North SH 87. Bung Lap SH 88. Mae Nam Chi SH

Fig. 16–Continued

(i) Scene 135–49. 22 Nov. 1975
77. Khemmarat South SH 89. B. Nam SH

Fig. 16–Continued

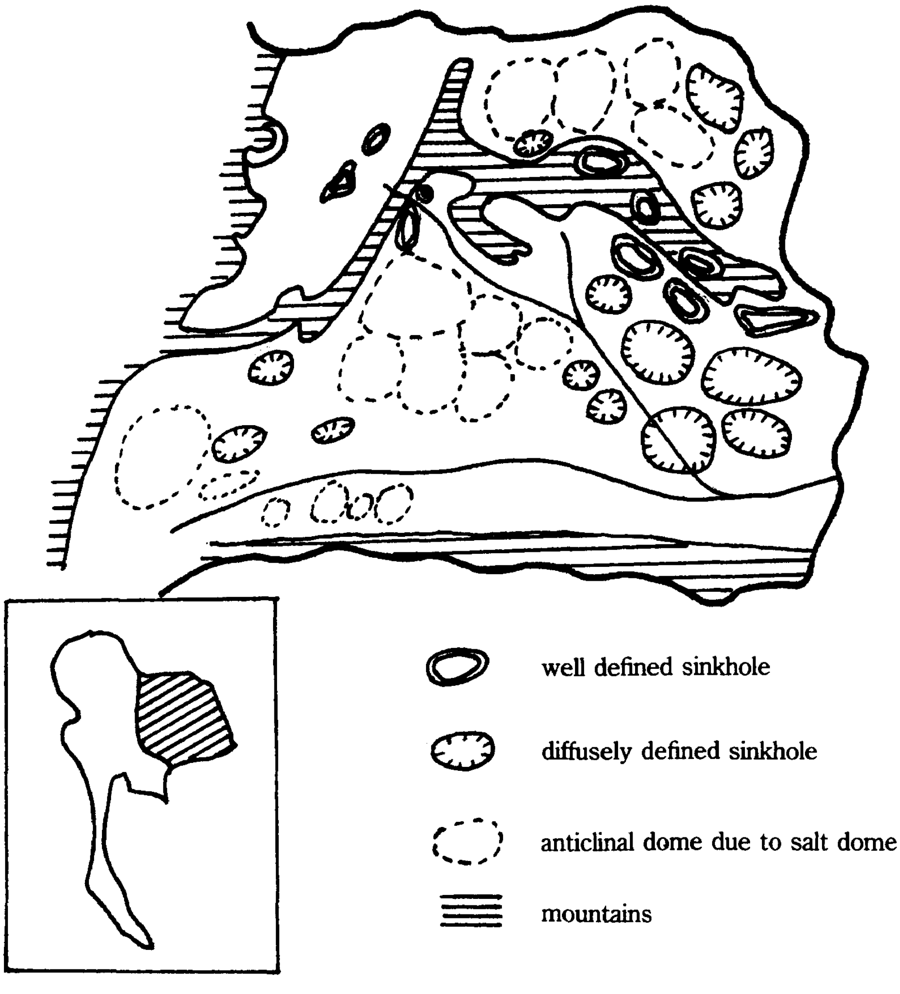


Fig. 17 Schematic Distribution Map of Sinkhole Topography in Khorat Plateau

discontinuous in many cases. Remnant hillocks, however, slightly outcrop on the ground in circular shape, as can be seen in Suwannaphum-Yasothon-Ubon-Rasi Salai area, and still make it possible to demarcate sinkholes. Tung Kla Ronghay is also supposed to be an assemblage of sinkholes, although demarcation is difficult due to surfacial turbation.

2.2 Salt Dome Hypothesis

Fig. 16 indicates not only sinkholes, but also anticlinal domes in dotted lines, which are supposed to have been caused by the salt dome development underground. These are observed in (1) Sakon Nakhon basin, (2) Khon Kaen–Phon–Nong Song Hong–Kosum Phisai area, (3) Chatturat–Sikhiu–Choho–Bua Yai area, and (4) basin south of Mun River. Assemblages of anticlinal domes are identified by clusters of hills in turtleback-shaped configuration and dendritic troughs.

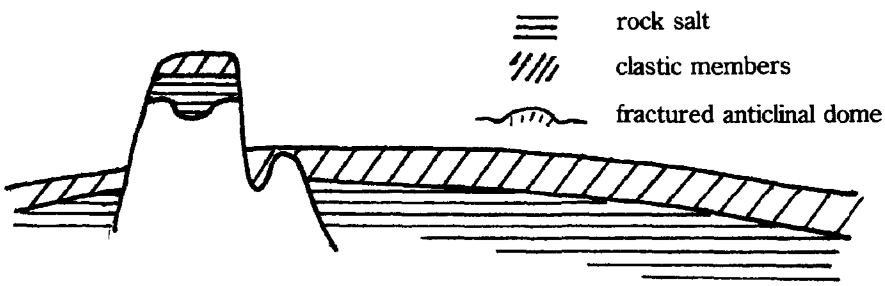
Anticlinal domes and large sinkholes are closely related each other, and represent different stages of sinkhole topography; the former represent the younger stage and the latter the older stage. Fig. 17 illustrates a schematic map on the distribution of different types of sinkhole topography in Khorat Plateau; (1) well defined sinkholes, (2) diffusely defined sinkholes, (3) anticlinal domes due to salt dome development.

The concept of sinkhole topography raises a key question concerning to the geology of Khorat Plateau. Are salt beds limited to Mahasarakham formation? Or are they contained in other formations as well? At present moment, geological evidences for clear conclusion are not at my hand. But, I have an impression that other formations also contributed to the development of sinkhole topography. In order to draw a schematic diagram on the development of well-defined sinkholes in Phu Phan range, for example, we need to assume that evaporites had existed in Phu Phan formation even before evaporites of Mahasarakham formation deposited. Fig. 18 illustrates a schematic diagram on the development of sinkhole topography. This figure presumes: (1) the uplift of phu phan range took place after the deposition of major part of Mahasarakham formation, (2) thickening of clastic member having salt lenses, (3) development of salt domes, translocation of salt lenses and subsequent upwarping of the clastic members, and (4) corrosion of salt lenses and salt domes, and subsequent subsidence of warped clastic member.

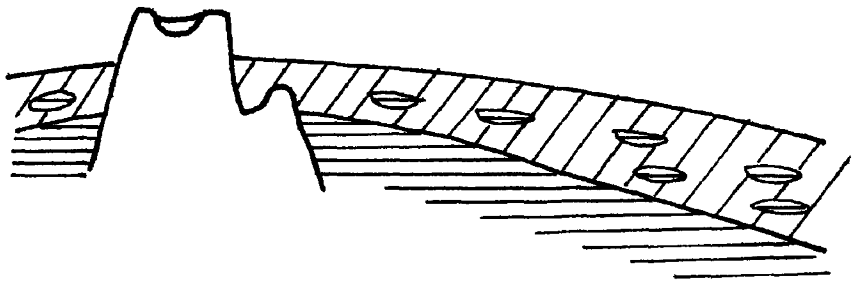
3. *Sinkhole Topography as Viewed in Airphotos*

In the preceding section, sinkhole topography was divided into three categories and demarcated on LANDSAT imageries. Observation of airphotos reveals the features more in details. Fig. 19 illustrates three scenes from different topography; hill and flat basin. One common pattern is distinctly recognized in all categories; that is, polygon assemblage. Turtleback-shaped polygon assemblages are figured out by troughs arranged in centripetal and tangential direction. Polygon assemblages are demarcated with broad lines in Fig. 19. As mentioned before, I suppose that these assemblages were caused by anticlinal warping due to salt dome development. One assemblage may correspond to one salt dome. The size of assemblage is from 5 to 10 km, and presumably indicate the diameter of salt dome.

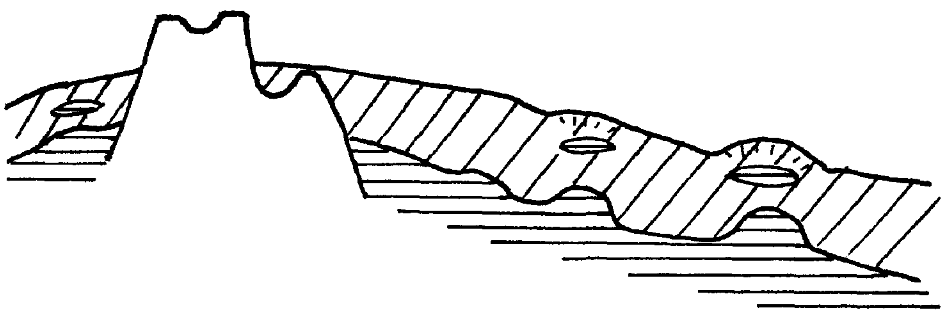
Then, what is the cause of different topography, hill and flat basin? The difference is not due to the gradation or denudation in a conventional concept, but due to the different stage of



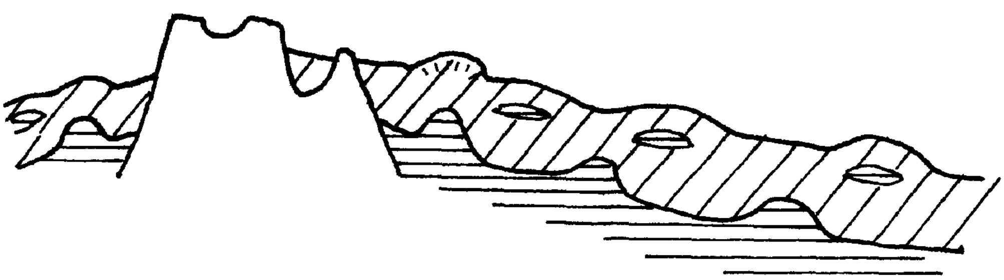
(1) Uplift of Phu Phan range at later stage of Mahasarakham formation.



(2) Corrosion and sinkhole development on mountaines; Thickening of clastic members in basin.



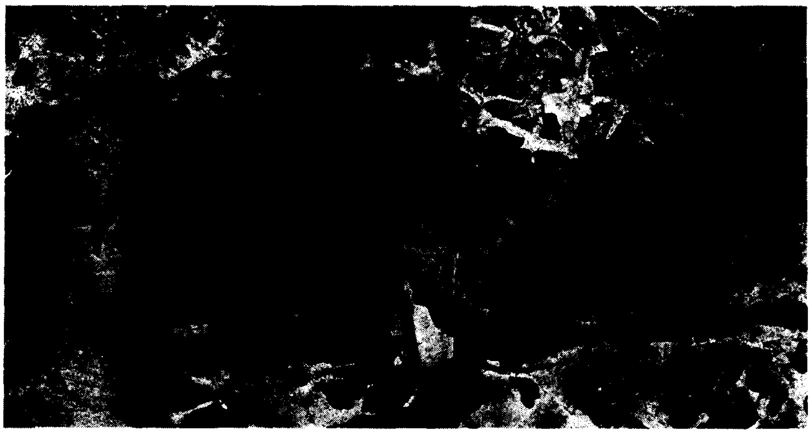
(3) Salt dome and anticlinal dome development in lower basin.



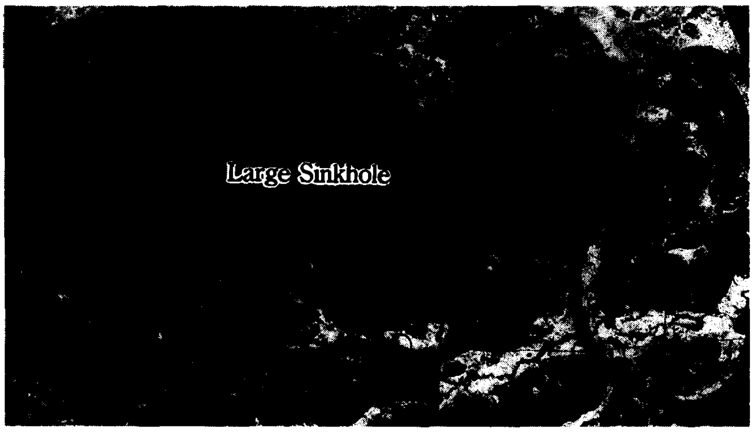
(4) Translocation and corrosion of salt beds, resulting in sinkhole in lower basin; anticlinal dome developed in the higher basin.

Fig. 18 Schematic Diagram on Evolution of Sinkhole Topography

N←　(a) Closely packed polygon assemblages on anticlinal domes at



N←　(b) Loosened polygon assemblages with broad valleyes at advanced



N←　(c) Emergence of large sinkhole at more corroded stage.

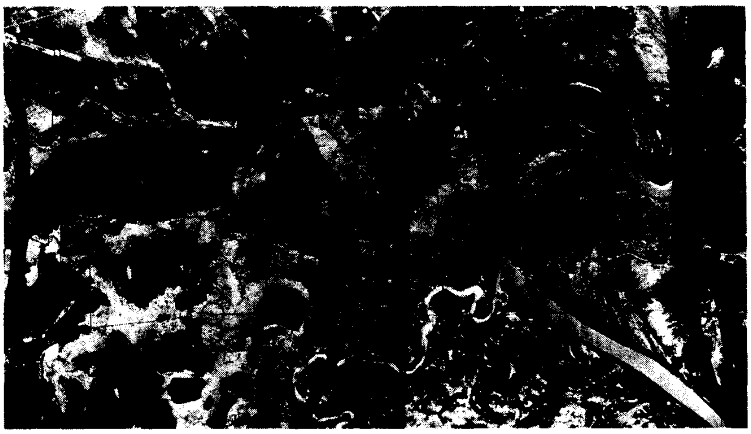
Source of airphotos:

(a) VV WWS M 76 AMS 15 Jan. 54; 12379, 12381, 12383, 12385, 12387.
(b) VV WWS M 113 AMS 24 Mar. 54; 19860, 19858, 19856, 19854, 19852.
(c) VV WWS M 55 AMS 29 Dec. 53; 8378, 8380, 8382, 8384.

Fig. 19 Polygonal Assemblage Observed in

younger stage. N-S transect from South of Tha Pra.

stage of corrosion. N-S transect at 12 km East of Mahasarakham.



N-S transect at 7 km West of Ubon.

Airphotos (approximate scale 1:180,000)

corrosion process. An incipient stage, as represented by a close packing pattern in Fig. 19 (a), shows separate small sinkholes and trough-shaped valleys. On the other hand, advanced stage as represented by Fig. 19 (b) and (c), shows the widening of valley floor, linkage of separate small sinkholes, and emergence of a large sinkhole. It may be assumed that the salt dome development took place earlier at the lower part of the basin because the critical load to cause the flowage of rock salt was attained earlier there. On the other hand, upwarping in the upstream started much later. The fact that hill topography shown in Fig. 19 (a) is an incipient stage is reflected in many aspects: (1) valleys are yet narrow, (2) each polygon unit is well preserved, (3) polygon assemblage also holds well defined shape, (4) active release of salt to the valley slope is remarkable than in more corroded topography.

I suppose that those hills in Chatturat–Dan Khun Thot–Choho–Bua Yai area are at a similar incipient stage. These anticlinal domes are rather young, and now releasing salts from the fractured clastic members.

4. *Other Features Related to Sinkhole Topography*

I will describe some features related to sinkhole topography and corrosion process.

4.1 Mesozoic Nam Dung

In many outcrops of older Khorat formations, we can notice frequently small mounds which are quite similar to the present *nam dung*. Polygonal mudcracks are also observed. One example illustrated in Fig. 20 was observed at Wat Prabat Phu Phan Khan, C. Khon Kaen, along HWY 2109 to Ubon Rattana dam. Various rock forms and rockfall are displayed by coarse-

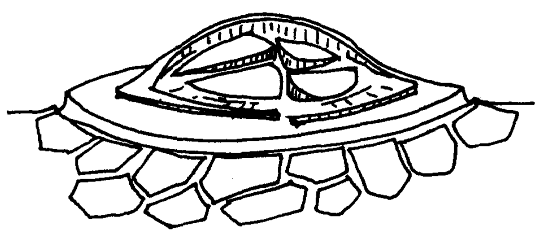


Fig. 20 Mesozoic *Nam Dung* and Mudcracks at Wat Prabat Phu Phan Khan, C. Khon Kaen near Ubon Rattana Dam

grained sandstone (Phra Wihan formation?). On a huge slab which supposedly exposes a ground surface of Mesozoic era, there are Mesozoic *nam dung*, polygonal mudcracks, and some trace fossils.

This *nam dung* which is moribund of course is hardened with unknown cementing material. The lime nodules were not found, and the crust did not react with HCl. Nearby, rock surface is featured by polygonal mudcracks formed in great number. The polygon units are surrounded by shallow ditches. The interstice between polygons is 5 cm deep.

All the features strongly suggest that the slab surface represents former ground surface in Mesozoic era, on which *nam dung* and mudcracks had been formed under similar conditions as are operating now. Since the present *nam dung* formation is closely related with sinkhole topography, Mesozoic *nam dung* suggests that sinkhole topography was present in Mesozoic era, too.

At this site, there is a big 'ghost bridge', that is, a shaft cave (Ø 5 m and 4 m high), the roof of which makes a gently curved bridge. This rock feature is often interpreted as a pothole. In my view, this is a corrosion cave, which was a salt plug formerly.

These features strongly infer the relation with some sort of salt beds. And if my observation is correct, Phra Wihan formation should have some evaporite lense.

4.2 Fracture of Slab

Another feature related to sinkhole topography is fracture of slab, which is frequently observed at rockland in mountainous areas of Khorat Plateau. An observation illustrated in Fig. 21 was made at 8 km south of Mukdahan along HWY 2034. A rocky ground is exposed in a corrosion valley between Phu No and Phu Chom. A huge slab of sandstone is fractured into four blocks. Two blocks on northern half dips more strongly than the southern half. At the same time, western wing is 40 cm lower than the eastern wing.

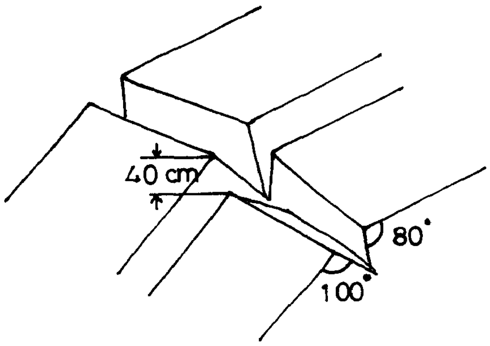


Fig. 21 Fracture of a Slab, in Relation with Development of a Corrosion Valley (South of Mukdahan)

This fracture can be interpreted in relation with rockfall or subsidence due to corrosion. The valley located to the north shows U-shaped cross section. The most probable implication is that the valley was formed as a result of corrosion. Subsequently the subsidence of bedrock increased in the northern half, and the slab, yielding to self weight, underwent fractures into two blocks. Due to the unequal subsidence of a wing, blocks were further fractured to eastern and western wings.

Similar fracture was observed at the outlet of

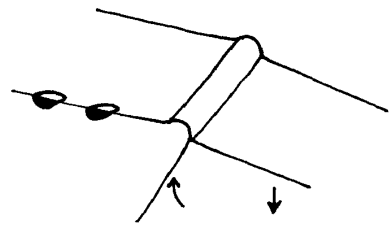


Fig. 22 Sliding and Fracture of Slabs, in Relation with Sinkhole Development (South of Waritchaphum)

B. Thung Chuak sinkhole along HWY 2093, south of A. Waritchaphum, C. Sakon Nakhon. Slab surface dips about 15°. Northern half has subsided much largely, and shows surface gap of 3 cm at the fracture line. Rotational movement of northern block generated upward pressure to the fracture surface of the southern block, on which slight, linear bulge was formed.

There are small pebbles embedded in this sandstone. These pebbles are cut into halves, and cut surfaces are exposed on the slab. This indicates that other slab which had overlied slided down, splitting the pebbles into halves.

4.3 Cave

There are many "caves" in mountainous areas. Two types of cave are identified. Dominant one is rock shelter type which is formed due to rockfall or displacement of rockmass. Other type is corrosion tunnel or replica of salt dykes. One examples may be given below.

Cave at Wat Tham Khon Pheng, A. Nong Wua So, C. Udon Thani, on the way from Udon to Nong Bua Lamphu has been formed jointly through dislocation of rockmass and corrosion (Fig. 23). Cave at Wat Tham Kham at B. Kham Kha, 21 km from HWY 22 has a similar structure. The sandstone at the cave roof has lime precipitates.

Seri Thai cave near to Phu Phan National Park office, C. Sakon Nakhon, is a beautiful corrosion tunnel. The cave is surrounded by

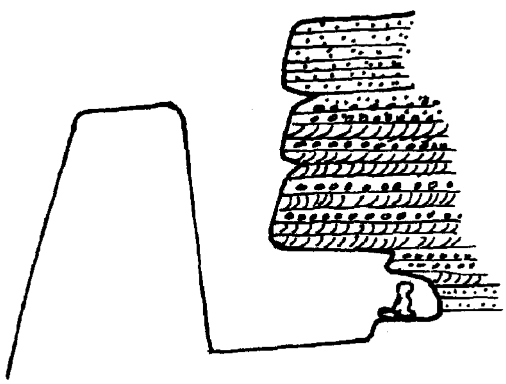
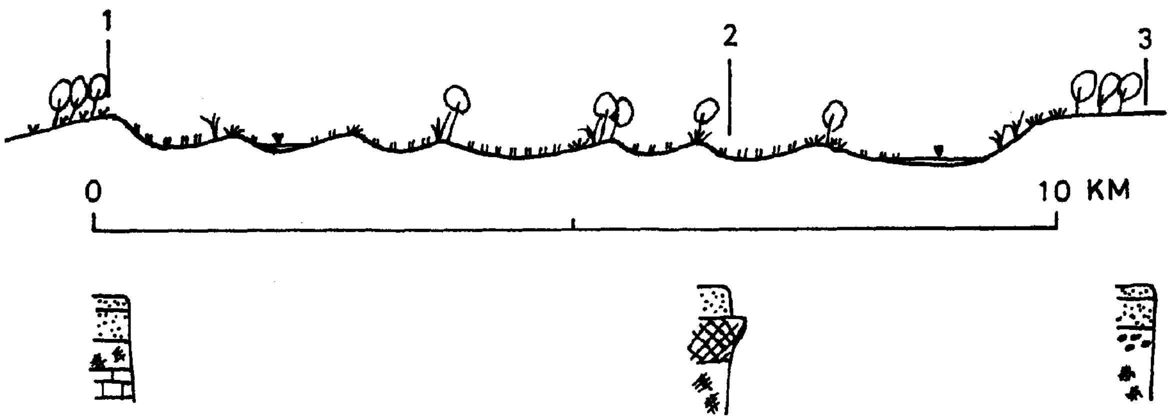


Fig. 23 A Cave Formed through Joint Action of Rock Dislocation and Corrosion, at Wat Tham Khon Pheng along HWY 210

purplish red siltstone, presumably containing anhydrite veins. Cave is 4 m in diameter and continues tortuously about 50 m in length. Nearby the cave, there are alternating beds of purplish red siltstone and greyish white sandstone which contains small rounded pebbles together with petrified wood. There are remnant hills with purplish red soils, and small sinkholes in great number on the ground nearby.

These features indicate that many caves were formed as a result of corrosion of evaporite dykes; caves are replica figures of the dyke.



Profile 1 under dry dipterocarp forest has:
(1) 15 cm dark brown LFS.
(2) 40 cm grey LFS.
(3) 30 cm dark reddish brown HC; common yellowish brown mottles.
(4) 30 cm+purplish red claystone of Mahasarakham formation.

Profile 2 at well wall in rice field has:
(1) 50 cm pinkish grey SiL.
(2) 50 cm loosely indurated laterite pan.
(3) 60 cm+mosaic of purplish red and white HC; saprolite of claystone.

Profile 3 has:
(1) 20 cm dark brown LFS.
(2) 40 cm yellow LFS.
(3) 30 cm nodular ironstone layer
(4) 30 cm+mosaic of purplish red, white and red yellow HC; saprolite of Mahasarakham claystone.

Fig. 24 Gentle Undulation as Representing Sinkhole Topography, B. Don Daeng, A. Si Songkhram, C. Nakhon Phanom

5. *Oxbow Lake or Sinkhole?*

Gently undulating topography is characteristic of Northeast Thailand. One example is illustrated in Fig. 24. The transect is taken from B. Don Daeng, A. Si Songkhram, C. Nakhon Phanom. The topography used to be interpreted as being formed by fluvial processes and erosion; the lows were formed as floodplain in which some oxbow lakes were left by meandering of rivers, and the highs were formed as riverine terraces, and so on. I propose a different view that this undulation is characteristic to sinkhole topography; the lows represent subsided trough and sinkhole, or synclinal depression related to salt dome, and the highs represent resistant beds, sometimes more stabilized by laterite capping, or anticlinal dome related to salt dome. This view is based on the fact that recent fluvial deposits are quite shallow, or restricted to narrow belts along the present streams, and clastic members of Mahasarakham formation lie at shallow depth. Some observations along the transect in Fig. 24 are given below.

The depression has dark clay, and is occupied with rice fields or lakes. Since Mahasarakham bed is frequently exposed at a shallow depth even in rice fields located at depressions, we may expect that it makes continuous bedrock lying at a shallow depth through the whole transect. It seems to me that the lakes are small sinkholes which collapsed due to corrosion, and remnant hills are resistant to the collapse. Anyway, Si Songkhram basin itself is a large sinkhole.

V Mass Movement

1. *Soil Distribution Pattern at Sinkhole Bottom*

If the gentle undulation is derived from fluviatile process, sediments at flat basin should show rather homogenous composition on wider area. If mass movement is significant we may expect that a newly formed sinkhole would receive creeping sand from the surrounding high ridge, and keep a graded slope. Actually, this kind of expectation is not rewarded. The actual situation shows a quite high heterogenity. It is rather usual to find clay spots distributed in isolated patches among sandy terrain, and *vice versa*. Bottom floor of small sinkholes is frequently covered by clay soils in spite of the abundant source for sand on the surrounding sandy hills.

One example is illustrated in Fig. 25. The transect was observed at B. Niu, A. Muang Chaiyaphum, C. Chaiyaphum.

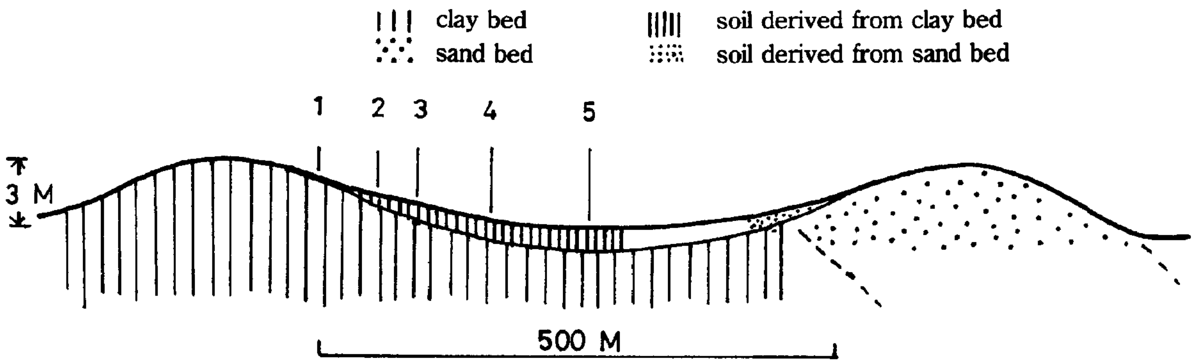
These profiles indicate that saprolite of Mahasarakham claystone lies at shallow depths, even at the center of the depression. Texture and reaction of soils are predominantly controlled by the nature of clay bed saprolite, less influenced by the sandy ridge located at the other end of the transect.

Layers with many pisoliths may reflect the influence of local transport, which is, however, rather limited in extent and depth.

2. *Laterite Pan*

Various laterite beds, such as indurated laterite pan with tortuous pores filled with clay, botryoidal laterite, and ironstone or pisolith layer, are more pronounced in Sakon Nakhon basin. This is probably related with more pluvial climate in this basin. Leaching of evaporites proceeds deeply, and this induces segregation of iron compounds in thick saprolite.

Laterite pan modifies the stability of ground



Profile 1:

(1) dark reddish brown HC; saprolite of Mahasarakham claystone; laterite crust remains sporadically; water of dug-up pond indicates 0.6 mS, on June 20, 1987.

Profile 2, 20 m from profile 1:

(1) 10 cm dark brown HC; with iron pisolith.

(2) 10 cm+dark reddish brown HC; saprolite.

Profile 3, 60 m from profile 1:

(1) 15 cm dark brown HC; with iron pisolith.

(2) 15 cm+dark reddish brown HC; saprolite.

Profie 4, 150 m from profile 1:

(1) 15 cm grey brown HC; with small rounded pebbles:

(2) 35 cm mosaic of grey brown and reddish brown HC; many manganiferous pisoliths (Ø 3 mm).

(3) 20 cm+brigth reddish brown (2.5YR5/6) HC; pH 7; common soft manganiferous pisoliths (Ø 2 mm); with lime nodules; this layer is saprolite.

Profile 5, 250 m from profile 1:

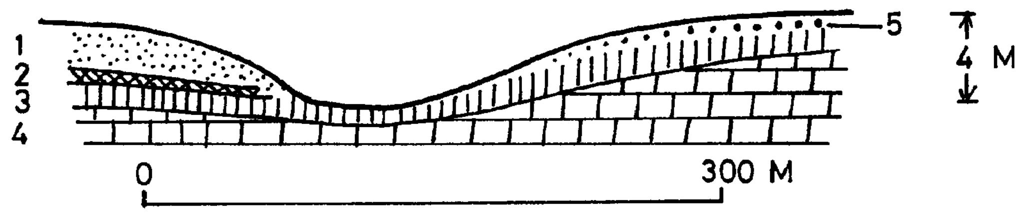
(1) 15 cm grey HC; pH 7.

(2) 55 cm grey brown HC; pH 7; many iron and manganiferous pisoliths (Ø 5 mm); very stiff.

(3) 30 cm mosaic of yellowish brown and grey brown HC; common pisoliths; possibly saprolite.

(4) 60 cm+dull orange (2.5YR6/4) HC; many yellowish brown mottles; many lime nodules; saprolite.

Fig. 25 Control of Soil Properties by bedding Layers



A profile observed at well wall is as follows:

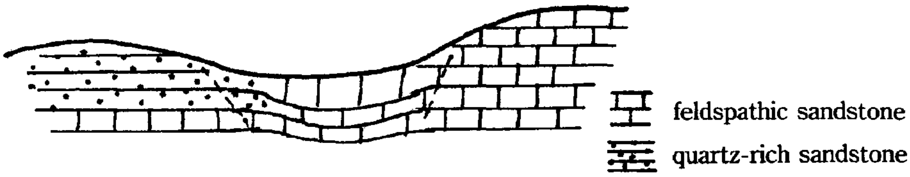
(1) 150 cm white LFS; podzolized.

(2) 50 cm indurated laterite pan with tortuous pores filled with pale yellow clay.

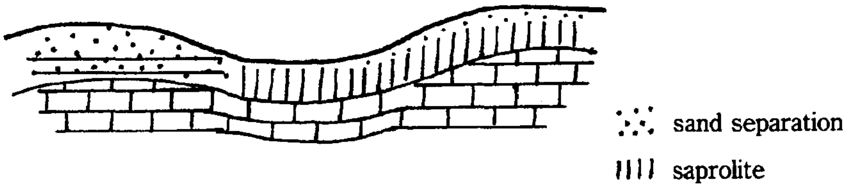
(3) 50 cm mosaic of purple red and white HC; saprolite of feldspathic sandstone.

(4) 50 cm+ purple HC; saprolite of feldspathic sandstone, preserving bedding structure.

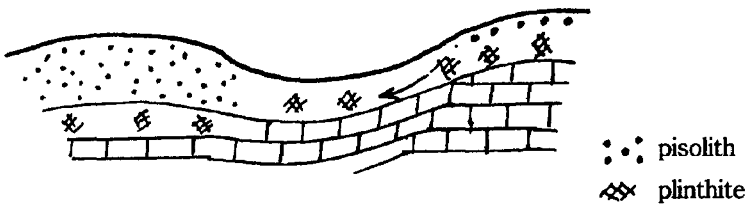
Fig. 26 Laterite Pan Stabilizing the Ground Surface (B. Na Pho, A. Si Songkhram, C. Nakhon Phanom)



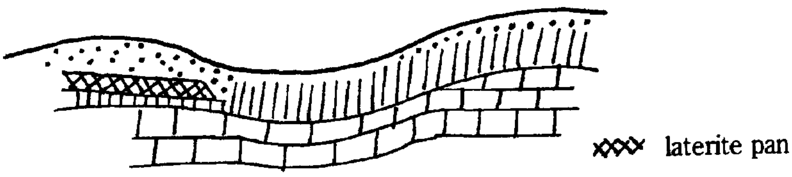
(1) Gentle undulation is formed due to sinkhole topography.



(2) Separation of sand and clay-iron takes place in the feldspathic saprolite; separation of quartz sand takes place in the quartz sandstone.



(3) Segregation of clay and iron compounds proceeds; seepage rich in iron compounds flows down along the topography.



(4) Laterite pan is formed in the lower terrain; iron pisoliths are formed on the crest.

Fig. 27 Laterite Pan Formation on Gentle Undulation

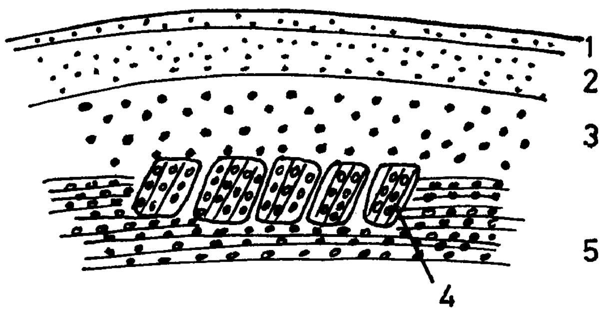
surface. The following cross section illustrates the residual alteration products from Mahasarakham sandstone, and the resulting laterite pan stabilizes the otherwise erodible sandy ridge. Because of this, mass movement is retarded and depressed. Topography is governed only by corrosion. The observation was done at B. Na Pho, 11 km ENE from A. Na Wa on the way to A. Si Songkhram, C. Nakhon Phanom.

Clay hill on the opposite side of the trough shows topsoil (5) which has loose nodular iron stone layer resting on (3) and (4).

The layering of alteration products is supposed to have proceeded as follows shown in Fig. 27.

3. Rockfall

Although I stated in the preceding sections that mass movement is depressed, it does take place when induced by sinkhole emergence. The following outcrop indicates that there was a rockfall because of a steep escarpment generated by an abrupt subsidence. The observation was made on a gently rising hill at 22 km north of Nam Phong River along HWY 2, C. Udon Thani.



(1) 10 cm grey yellow LFS.
(2) 30 cm light yellow brown LFS.
(3) 80 cm pisolitic layer; with common quartzitic pebbles.
(4) 60 cm sandstone blocks (60 cm×30 cm) with small pebbles laminated; blocks are in a 'standing position' tilting 70° to NE.
(5) sandstone in 'bedding' state; with small pebbles laminated; apparently Phu Phan formation.

Fig. 28 Rockfall Induced by Abrupt Subsidence, at 22 km North of Nam Phong River

The rockfall may be related to a cavity development on Phu Phan sandstone. The cavity was caused by some agent operating in sinkhole topography. Rock mass was unstabilized and fell down to the cavity. The cavity was buried by creeping material like pisoliths and sand.

Rockfalls are frequently observed in hilly and mountainous area. High slope gradient and relief are continuously regenerated in sinkhole topography. Local creep and sheet erosion are activated subsequent to the increased slope gradient.

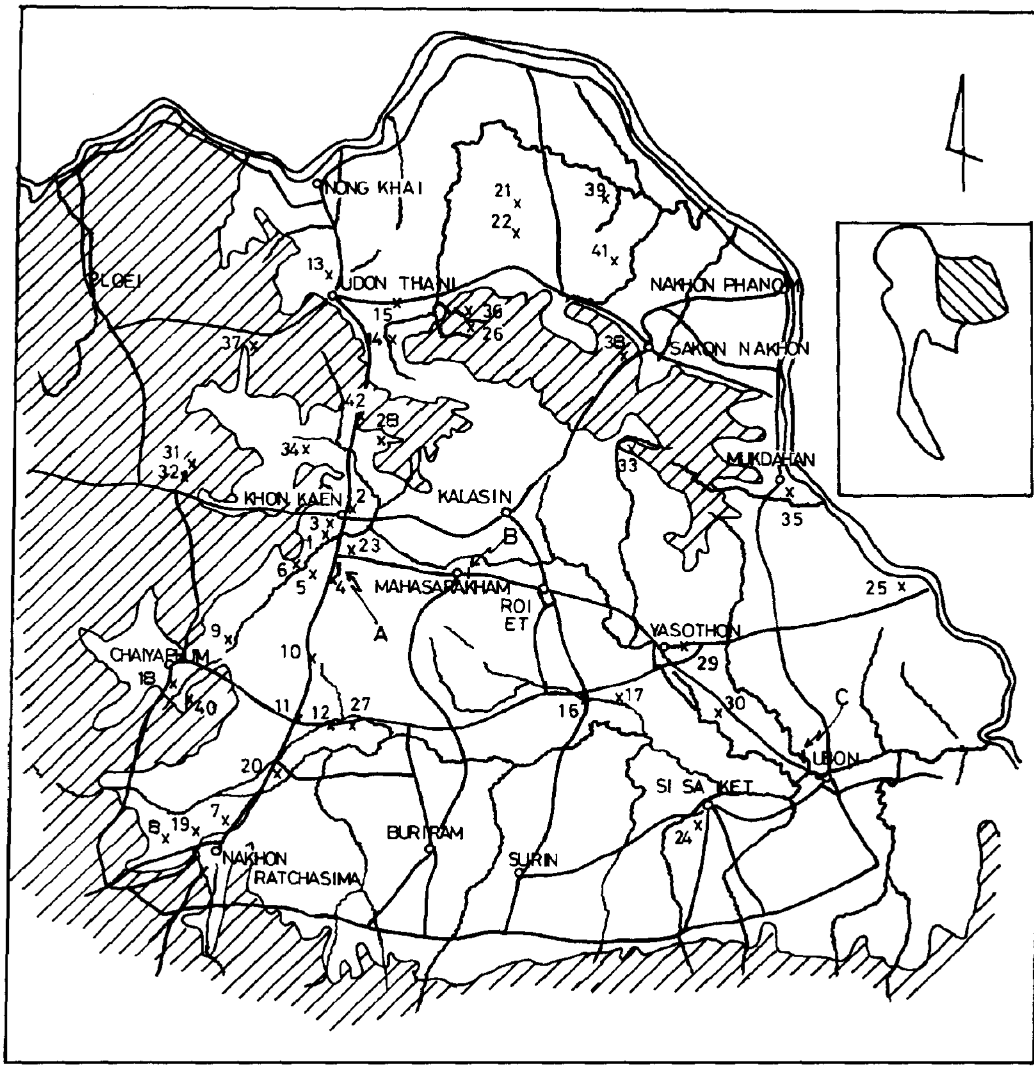
VI Summary and Conclusion

Salt in Northeast Thailand has been exploited since ancient time, probably-even from B. C. periods. People collect salt crusts which are formed in sandy spots. The leachate obtained from sandy salt crusts is boiled to salt. After a prolonged period of salt-making, the waste sand made high mounds.

An innovation of salt production appeared recently. That is to pump up natural or artificial brine from rock salt bed. In this method, the amount of brine taken out is huge. It is not rare to cause a catastrophic subsidence of the ground. This fact inspired me to propose a hypothesis that the subsidence has proceeded under natural conditions, and induced the development of sinkholes.

Observation of LANDSAT imageries, with this hypothesis in mind, reveals the presence of many large sinkholes in Khorat Plateau. Actually, field observations reveal that topography of Khorat Plateau is governed by corrosion process, and can be termed as sinkhole topography. LANDSAT imageries reveal that sinkhole topography has three elements; (1) well-defined sinkhole such as Phu Wiang, Nam Phong, Waritchaphum, Khao Wong and so on, around Phu Phan range, (2) diffusely defined sinkholes, such as those in flat Mun-Chi basin, and (3) anticlinal domes due to salt dome development, such hilly area as are found in Sakon Nakhon basin, Khon Kaen–Phon area, and Dan Khun Thot–Choho area.

Well-defined sinkholes in Phu Phan range are understood as the result of corrosion of rock salt after the uplifting of Mahasarakham formation. In addition, corrosion of evaporite beds in older formations needs to be assumed. Other



1 B. Khok Sung shown in Fig. 1 & 2. 2 B. Nong Yai 3 B. Si That 4 A. Ban Phai 5 A. Chonnabot 6 A. Mancha Kiri 7 B. Don Kwang 8 B. Nong Suang shown in Fig. 3. 9 A. Khon Sawan 10 A. Ban Phon 11 B. Sida 12 A. Prathai 13 B. Nong Samlong 14 B. Kho Noi 15 A. Nong Han 16 A. Suwannaphum 17 Non Pha Khan 18 B. Nong Na Saeng 19 B. Khok Sung 20 Asahi salt Co. shown in Fig. 5. 21 B. Champadon 22 B. Non Kuam 23 *Nam dung* site shown in Fig. 6. 24 Outcrop shown in Fig. 7. 25 Outcrop shown in Fig. 8. 26 B. Thung Chuak 27 Outcrop shown in Fig. 10. 28 Outcrop shown in Fig. 11. 29 Outcrop shown in Fig. 12. 30 B. Bung Khrua 31 B. Muang Mai 32 Tham Kwang shown in Fig. 14. 33 Outcrop shown in Fig. 15. 34 Wat Prabat Phu Phan Khan shown in Fig. 20. 35 Outcrop shown in Fig. 21. 36 Outcrop shown in Fig. 22. 37 Wat Tham Khon Pheng shown in Fig. 23. 38 Seri Thai cave in Phu Phan National Park. 39 B. Don Daeng transect shown in Fig. 24. 40 B. Niu transect shown in Fig. 25. 41 B. Na Pho transect shown in Fig. 26. 42 Outcrop shown in Fig. 28.

A: Airphoto mosaic shown in Fig. 19(a) B: Airphoto mosaic shown in Fig. 19(b) C: Airphoto mosaic shown in Fig. 19(c)

Fig. 29 Location Map of the Sites Mentioned in the Text; Site Number is Arranged in the Order of the Reference in the Text two types of sinkhole topography have been initiated by anticlinal upwarping of clastic members by salt dome development and subsequent corrosion of salt beds; numerous fractures developed in the upwarped clastic members, which released salt through the percolating water to the valley slope. Corrosion caused cavity to be formed underground, and induced gradual subsidence of the ground to form sinkholes. This sequence is clearly recognized in airphotos. Incipient stage shows anticlinal domes of hilly topography which are fractured into several polygon units. An assemblage of polygons, easily demarcated on airphotos, has the size of 5 to 10 km in diameter, and is supposed to represent one salt dome. As the corrosion operates for longer period, topography becomes more flat.

Several other features are related to corrosion and sinkhole topography:

(1) gentle undulation, frequently with lakes and ponds at the valley bottom which have no outlet;

(2) *nam dung*, both moribund and active, which are formed by interflowing water and Na-saturated quick clay;

(3) Mesozoic *nam dung*, which indicates that sinkhole topography prevailed in the Mesozoic era, too;

(4) rockfall and slab fracture taking place in such a manner as to imply a partial subsidence of ground surface;

(5) corrosion caves in mountainous areas, which retain the replica figure of salt dykes;

(6) thin mantle covering the Mahasarakham formation also indicates that corrosion played an important role in reducing the thickness of later deposits, except the area covered by gravel beds and laterite capping.

Thus, I conclude that Khorat Plateau is a corrosion basin.

Acknowledgments

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