5. Summary

1) Most of the fluorite deposits in northern Thailand are epithermal and similar in geologic setting. Most are associated with faults zones or strong tectonic zones at or near the margins of Cenozoic basins. The elevation of the top parts of the fluorite deposits are similar to the basin elevations. Most deposits consist of microcrystalline replacement, botryoidal, concentrically layered (around rock nuclei), and flat-layered fluorite ; well crystallized fluorite is rare. Gangue minerals in deposits are similar, including quartz, chalcedony, stibnite and calcite. The deposits thus belong to a single mineralized province.

2) Deposits in limestone host rocks show important differences from those in granite and other rock types. The deposits in limestone host rocks contain both high temperature mesothermal fluorite (replacement or open-space near rock nuclei), and lower temperature epithermal fluorite (botryoidal, concentrically-layered, etc.) The ore bodies are wedge-shaped, narrowing to depth. They occur at elevations similar to those of the Tertiary basins. The fluorite is grey or colorless, and the degree of crystallinity varies greatly within ore deposit. The adjacent host rock is strongly altered. Fluid inclusions are of all four types, with Type 4 inclusions concentrated locally.

In contrast, deposits in other host rocks (mainly granite) are entirely epithermal with well-crystallized fluorite common.

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The shape of the ore bodies is variable, depending on the shape of open space in fault zones. Most deposits are at elevations relatively higher than those of the basins. The fluorite varies in colour (green, purple, colorless, etc.), and is unif rm in degree of crystallinity or shows symmetry in relation to vein contacts. The adjacent host rock is relatively unaltered. Fluid inclusions are of Types 2 and 3, with a narrow range of phase ratio, evenly distributed throughout the veins. Type 1 inclusions are also found in very small amounts in some deposits, associated with Types 2,3.

These differences occur because the capacity of trapping fluorine as fluorite deposits in Ca-rich rocks is better than that of non-Ca rich rocks. Fluorine vapour can react directly with Ca-rich rock to form replacement type deposits. In Ca-rich rock (and hence Ca-saturated ground water), deposition can take place even at very low temperature (e.g. 57°c), and at a wide range of temperature. In some deposits in limestone (e.g. Pa La Door, and Mae Phu) the fluorite consists of entirely-liquid inclusions (Type 1). This indicates that fluorine can be transported in aqueous solution to deposit in limestone. Large deposits in non-Ca rich rock without any vugs or remaining open space in veins (e.g. Amphoe Pai) need very large amounts of fluorine-bearing fluids and other special conditions.

3) The associated stibnite gangue in epithermal deposits is associated with a wide range of temperatures and fluids, such as aqueous solution (Mae Phu), and low-density high-temperature fluid

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(Mae Tha) and fluids with $\leqslant$ 0-50 % gas volume in Tha Song Yang. So this gangue can not be used as an indication of fluid composition or temperature. Stibnite may also be transported in hydrothermal solution, but conditions of deposition must be different. Stibnite may deposit within wide temperature limits (100-400°c) when the stibnite-containing solution increases in CO_2 content by the reaction of associated F solution with Ca-rich rock or $CaHCO_3$ saturated water.

4) Fluid inclusions in well crystallized fluorite are much more abundant than those in botryoidal or concentrically layered fluorite. Inclusions in the well crystallized fluorite are randomly distributed, while those in botryoidal or concentrically layered fluorite are associated as zones of inclusions, or in certain parts. More abundant inclusions indicate more rapid crystallization. Layered crystalline fluorite, at Amphoe Pai, contains more inclusions than cubic crystalline fluorite. This may indicate sudden cooling during deposition of Amphoe Pai fluorite,

Shape and size of inclusions is related to degree of the crystals and the type of occurrence. Inclusions trapped between granules have irregular shape as negative of granules, while inclusions trapped in or between well crystallized fluorite have regular shape as negative of the crystals. Inclusion size varies with crystal and granule size, very small in botryoidal fluorite, medium sized in zones of inclusions, and large in well crystallized part of flat-layered fluorite or cubic crystalline fluorite. The uniformity of inclusion

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size varies with uniformity of crystal or granule size.

Primary, pseudo-secondary, and secondary inclusions are easily identified. Primary inclusions usually have regular angular shape as negative of crystals, or irregular shape as negative of granules, or occur as zones of inclusions. Secondary inclusions usually occur as groups with irregular shape and uniform phase ratio in cleavage planes or some fractures of fluorite crystals. Pseudo-secondary inclusions are usually found near fractures in fluorite, and are usually rather large, with a shape which is partly negative of the crystal and partly a fracture plane.

It is useful to classified inclusions into four types depending on their phase ratio : Type 1-entirely liquid ; Type 2 (0-5 % gas); Type 3 (5-50 % gas) ; and Type 4 (> 50 % gas by volume). Phase ratio shows a close relation with density of ore fluid, and hence composition of ore fluid. This aids interpretation of the ore genesis. Shape and size have no direct or important relation to the ore fluid, and are probably both affected by other external factors.

The phase ratio of inclusions in each deposit enables deposits to be divided into three groups. Deposits containing entirely liquid inclusions (Type 1) are Pa La Door, Mae Phu, and Chom Thong deposits. Homogenization temperature cannot be measured for these inclusions, but these deposits are believed to have formed at very low temperature in aqueous solution. Deposits containing only gas-liquid inclusions (Types 2,3) are Tha Song Yang and Ban Sop Lan. Amphoe Pai

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deposits are similar to these, but they also contain Type 1 inclusions. Deposits containing all types of inclusions (Type 1 to 4) include Fang, Mae La Noi, Mae Tha, and Ban Hong. For these last two groups, Type 2 and 3 inclusions gave homogenization temperatures ranging from 57.4 to 274.2°c. Mean temperatures for the deposits range from 115 ± 27.5°c to 179.6 ± 12.9°c. Histograms for homogenization temperatures indicate the modal classes ranging from 110-160°c. Type 4 inclusions gave homogenization temperatures ranging from 251.3 to 410°c. Mean temperature for the deposits range from 300.5 ± 34.2°c to 355.8 ± 39.5°c. The second group of deposits formed at moderate temperatures from aqueous-vapour ore fluids. The third group of deposits formed in two stages : from a high temperature vapour phase ore fluid, and from a moderate temperature aqueous-vapour phase ore fluid.

Temperature of homogenization of inclusions in well crystallized fluorite is uniform for each deposit. Temperature for botryoidal,concentrically-layered and granular fluorite, which can be found in the same deposit, show a wide range of homogenization temperature for each variety.

Zones of inclusions are related to degree of crystallinity of fluorite. Outside the zones, inclusions are very rare. This indicates that supply of the ore fluid was not continuous. Samples with two zones of inclusions indicate at least two pulses of mineralization of fluorite. The mean temperature of the inner zone of inclusions is usually higher than that of the outer zone. This indicates temperature drop during crystallization.

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The pressure and salinity corrections for the formation temperature could not be determined. However, it is estimated that the combined correction would be less than ± 25°c.

6) Colour variation is a very distinctive feature of the fluorite deposits. It would be useful to relate colour to the temperature and history of mineralization in the deposits. In several deposits, well crystallized cubic fluorite and flat-layered fluorite show a narrow range of homogenization temperature but reveal many shade of colour. Colour in these deposits can not be used as an indication of mineralization temperature range, and there is also no specific rule concerning the order of temperature range between colours. But in some deposits, different colours of fluorite do show different mean homogenization temperatures ; for example, in Ban Sop Lan (Omkoi), mean homogenization temperature decreases from deep green to pale yellow to sky blue fluorite. Deep green fluorite always shows the extreme value (highest or lowest ranges) of homogenization temperature in fluorite deposits.

Fluorite of similar crystal size but different colour commonly differs in abundance of inclusions. Purple fluorite usually has very few or no inclusions. The ratio of number of inclusions between purple fluorite and fluorite of other colours can be as high as 1 : 10, although they have the same degree of crystallinity. Abundant solid inclusions are commonly present within purple fluorite. Purple fluorite may crystallize at a slower rate than fluorite with other

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colours. Colorless and green fluorite usually contain abundant inclusions. Sky-blue fluorite contains extraordinarily large amounts of small secondary fluid inclusions in every cleavage plane of the crystals. In Amphoe Pai Vein No. 3, there are many colours of fluorite, but the less-transparent pale green fluorite usually contains oil inclusions, with some probable organic matter associated. In zones of inclusion of concentrically layered fluorite, the zones usually have brighter refracted colour, and are more transparent.

Therefore, colour and abundance of inclusions in fluorite are commonly related. The inclusions influence the optical properties of the fluorite directly. More significantly, both are related to processes of mineralization through differences in composition and rate of crystallization.

7) Inclusions in most fluorite deposits in northern Thailand, do not show observable necking down, except for those in the Amphoe Pai deposit, especially in Vein No,5. The degree of necking down is different from vein to vein. The necking down in Amphoe Pai caused differences in phase ratio of adjacent inclusions, indicating that necking down occurred after cooling to below homogenization temperature. The necking down process is therefore caused by recrystallization of the fluorite host crystals, and may indicate that there were tectonic events in the Amphoe Pai region. Most deposits do not show any necking down process probably because they are very young and have not been disturbed by tectonic events.

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8) Age of mineralization is very cleary evidenced as Pleistocene to Recent. Some deposits show direct evidence for this age (fluorite in gravels, relation to present topography, fluorite deposited at hot springs), and other deposits are similar to them in geologic setting. The young age of mineralization is also confirmed by absence of necking down in most deposits except for that in Amphoe Pai.

The immediate source of fluorine probably was younger granites associated with thermal events during Cenozoic time. The fluorine was probably obtained from the older granites which are abnormally F-rich because of time strong mantle control of the province, as in western U.S.A. (Shawe, 1976). The fluorine may have risen from part of a mantle wedge underlying a back arc continental margin.

9) The evidence strongly suggests fluorite deposition by mixing of magmatic water with shallow ground water near the surface, or surface water. Some parts of fluorite deposits were deposited by fluorine-bearing vapours in the range of temperature 410-250°c as mesothermal deposits by reaction with Ca-rich rock or Ca-saturated solution. Other parts were deposited on mixing with ground water, and form epithermal fluorite in the range of temperature 57-210°c. The tempera- dropped between the two modes of deposition to about one half to one third of its initial value.

The presence of gaseous inclusions indicates that low density volatile fluorine-rich fluid came from the upper part of a magma chamber during thermal events in Cenozoic time. Some fluorite was

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deposited along structural faults through to the surface but most was deposited very close to the surface due to the sudden release in pressure and drop in temperature. The amount of fluorite deposited depended on the nature of the country rock and the condition of Ca-saturated ground water. Study of critical points suggests that volatile fluorine -rich fluid was similar in different deposits. After this stage, hot-spring processes - relatively nimportant at the time of volatile fluorine mineralization - played an important role by convection-circulation of very concentrated brine using energy from remaining magmatic heat. This process would have been operating since the release of heat from magma into the rocks above the magma chamber. Initially, the temperature of hot springs was very high, and the thermal water very saline. Some magmatic water was present in this brine. The hot strong brine redissolved the primary deposits of fluorite above the magma chamber and along channel ways (faults), and on mixing with shallow ground water, precipitated fluorine again as an epithermal deposit. This process would have been less active with time due to the decrease in amount of heat energy. At present, small amounts of fluorite are still being precipitated from hot springs. At Ban Kong Khak, Pa La Door, and Mae Tha, some recent hot springs differ from hot springs depositing fluorite in that they contain less magmatic component, less F, and are of lower salinity. This shows that the hot springs can not deposit fluorite, if they have no source of fluorine, even though they are high in temperature and contain very strong brine. This source of fluorine should have been deposited above the magmatic chamber and along the channel ways during the period of fluorine mineralization.

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The presence of immiscible liquid (oil?) in some inclusions also supports mixing of fluids during deposition of fluorite. However the original fluid may also have contained immiscible components.

Mesothermal and epithermal fluorite deposits occur typically in fault zones at the margin of Cenozoic basins at nearly the same basin elevation. This sites are suitable for depositions of fluorite :

1. The fault zones are usually close to or above the younger granites which intruded into older granite. Younger granite is the immediate source for fluorine mineralization.

2. The deep seated faults serve as channel ways for fluorine transportation from the magma chamber, and also from the site of initial deposition.

3. Fault zones at the edge of Cenozoic basins intersect the ground water level near the surface and before the ground water has flowed laterally on the surface to the river in the basins. Mixing of magmatic water and ground water can thus occur along the fault planes.

4. The fault blocks commonly contain limestone on the surface which are useful in deposition of fluorite.

The very young ore bodies in these locations have been little eroded as indicated by their close relation to recent topography.

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10) The genesis and tectonic setting of fluorite previously discussed has direct relevance to future exploration work. Many geologists have been puzzled about fluorite ore bodies which are usually

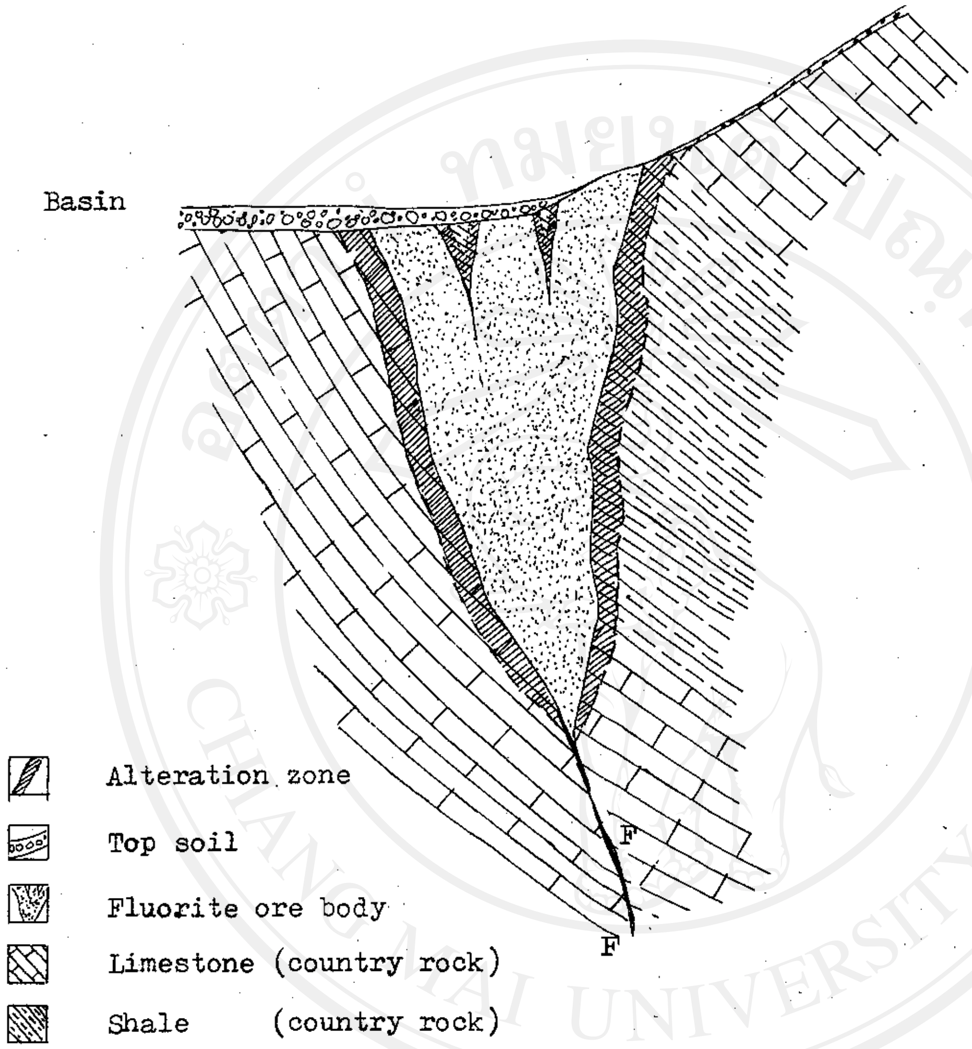

Fig. 5.1 Ideal cross section of fluorite ore body. The ore body is wedge-shaped or axe-shaped, deposited in fault zone at the edge of basin. Major part of the top part of the vein may be hidden because of top soil. (Note : the wall rocks are altered.)

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wedge-shaped and become narrower at less than one hundred meters depths. The mechanism of deposition of fluorite by supersaturation and hot-spring processes at the surface by mixing of waters can explain the sudden disappearance of the fluorite ore body at depth. The ore body diminishes at 50-100 m below the surface although the fault or other structure continues to deeper levels. These deeper levels are below the mixing zone. In vertical section, the ore body is usually wedge-shaped or axe-shape (Fig. 5.1) because much more deposition occurs by supersaturation in the upper part where the temperature and pressure drops more quickly. Ore bodies with only a small-scale exposure may be larger because part of the true width is hidden by country rock or irregular fracturing of the country rock at the exposed surface as shown in Fig. 5.1. This could save expense in drilling projects for determining shape and size of ore body.

The alteration of the country rock in the deposit can indirectly indicate the scale of the deposit. Kaolinite and other clays are normally associated with fluorite, indicating thermal alteration. The scale of alteration varies directly with the scale of fluorite deposits. In any deposits with small exposure of fluorite, if the alteration of the wall rocks is very significant, a big deposit may be hidden a few meters underneath the surface.

Future effort should be concentrated in areas of strong tectonic activity such as fault zones, especially in or near the tensional faults along the edge, or within the Cenozoic basins. Those associated with granites or alkalic igneous rocks would be prime targets.

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Any area of high heat flow is of very great interest, especially where there are hot-springs or evidence of a recent high geothermal gradient. Many of the fluorite deposits contain hot springs close to or within the vein. Areas of high heat flow can be initially detected by thermal infrared aerial photographs which show hotter areas as white and cooler areas as progressively darker shades of grey. Promising photographs can be processed through densitometer, which resolves the density of the photographs in terms of ground temperature and applies a predetermined colour scheme to indicate the differences. The technique provides the first measurement of the extent of geothermal source and range of temperature in the area.

If limestone occurs at or near the hot-springs, or high heat flow area, the posibility of finding a fluorite deposit is increased. This is because fluorite can deposit in limestone during a long distance of transportation until the temperature of solution drops to 57°c, the minimum homogenization temperature recorded in northern Thailand.

The underground ore body can also be explored by analysis for the F-content in ground water from drill holes or wells. The F-content in ground water depends on the type of rock in the area. The F-content of ground water near the blind ore body will be more than that further away.

These exploration criteria can probably be applied not only in northern Thailand fluorite province, but also in other provinces such as central-western Thailand, and peninsular Thailand which show a

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similar geologic setting. The Khlong Thom fluorite deposits in Amphoe Khlong Thom, Krabi Province in southern Thailand are located near hot springs, and contain more than 1,000,000 tons of 50-75 % fluorite in similar conditions to those in northern Thailand province.

11) Future research should continue along several lines. The freezing stage must be constructed for studying the eutectic temperature of fluid inclusions, the salinity of ore fluids as equivalent weight % of NaCl. Knowledge about salinity of inclusion fluids leads to the correction of homogenization temperatures, and hence, the true formation temperature. The freezing experiment can also be used in studying the daughter minerals in the inclusions. In the deposits inwhich inclusions are entirely liquid, freezing experiments can give the composition of inclusion fluid, the weight % NaCl, while heating experiments can not be done. This method helps to understand the genesis of fluorite. The electron microprobe study and the method of LAZER probe analysis is also very important in analysing the true chemical composition of inclusion fluids in every type of inclusions, and in any small part of an inclusion. Gas chromatography and spectrophotometry would also be useful in studying the composition of the inclusions.

Decrepitation temperature of fluorite must be studied in the future to estimate the pressure of formation during fluorite deposition. The pressure during formation of the fluorite deposits can also be studied from estimation of the overburden during mineralization. This require detailed study of geology and stratigraphy of northern

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Thailand to estimate true thickness of overburden.

The age of mineralization requires further study. This involves detailed geologic correlation between fluorite and the country rocks of each deposit. Index fossils in the Cenozoic rocks close to the deposits are a major key for determining the age of the beds and hence the relative age of mineralization. Further more, oxygen isotope studies of the inclusion fluids could provide data on the exact time of deposition.

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