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PHYSICAL ENRICHMENT——A NEW THEORY ON THE GENESIS OF INDUSTRIAL PHOSPHORITE DEPOSITS

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INTROOUCTION

Sedimentary mineral deposits were not formed simply as product of simple reactions through a single kind of factors, but were outputs of intricate reactions among a complex set of evolutionary natural environmental agents. They were formed at least through three different stages, viz., the imbibition and concentration of ore forming materials; the geochemical enrichment; and the physical concentration stages (Fig. 1). As to industrial phosphorites, physical enrichmnt is of paramount importance. It seems, almost all of the world industrial phosphorite deposits were formed as such.

Our idea of physical enrichment was first set up in 1980, during the 2 nd National Symposium on Mineral Deposits at Hongchow. Since then, lots of new evidences had been added up.

In this paper, only those of phosphorite deposits are described.

TEXTURAL CONSTITUTION AND CHARACTERISTICS OF THE CHINESE PHOSPHORITES

Chinese phosphorites are almost and always made of carbon-fluorapatite intraclasts of various kinds, being either rudaceous, sandy, silty or clayey in size. This is nothing strange as to the world known huge deposits such as the Middle Cambrian deposit of Karatau,the Permian deposit of Western U·S·A·, the Midde Cambrian deposit of the Georgina Basin of Australia,the Cretaceous-Eogene deposit of Morocco,etc. This means that phosphorite deposits were actually products of repeated sedimentation or resedimentation; and thus, mechanical enrichment can never be despised in their genesis.

The phosphorite intraclasts were came out from the desruption and resedimentation of what we termed "the primary or embryo ore beds", which are of several kinds in origin, i.e. : ——

(1) Phosphate pellets, concretions or micro-concretions formed within blackish clayey or silty shale formations during different episodes of diagenesis.

(2) Replacement of precursor dolomite crystals by phosphate-rich pore water.

(3) Replacement and sedimentation of phosphorous marine bottom water. This includes;

(a) Phosphate coatings or "coagulating concretions" on hardground or "omission surfaces", as seen at the Lower Cambrian deposit of Kunyang.

(b) Collophane cement of quartzose sandstone as seen in the Lower Cambrian phosphorite of North China.

(c) Phosphate replacement of the adjacent dolomite country rock, as seen at the Sinian Kaiyang phosphorite deposit. (Fig. 2)

(4) "Clean" phosphorite sand made all of tiny phosphate shell fragments. such as seen at the Lower Cambrian phosphorite deposit of Kunyang, Phosphatic stromatolite either in isolated cones, columns, mats, or reefs are also quite familar in the Sinian deposits of Wengan and Kaiyang.

It can be realised, that all the "embryo ore beds" enumerated above, possess two points in common, i. e.:

(1) They all belong to sediments rich in organic material.

(2) The concentrations of their phosphate content are all related to certain diagenetic process, especially related to porc water of the early stage of diagenesis.

The intraclastic phosphorites are predominately texture mature, being very much similar to the texture of clean sand. Their cementing material is mostly minor in amount. Nevertheless, in occasional cases, "ghosts" of limpid translucent collophane lumps can be encountered with, such as in the Sinian ore of Kaiyang. Under microscope these lumps are isotropic in nature, and under cross-nicol, contraction, in which fractures were shown, looks very much like the aging fractures of colloidal sediments. The same kind of collophanitic material also made up the vein-let swarms within the capillary fringe zone,that formed right above the boundary line of the silty band and its underlying sandy band of the Lower Cambrian Kunyang phosphorite layer (Fig. 3). Apparently, these phosphate veinlets were formed through pumping of the phosphorous pore water from the underlying sandy phosphorite, whenever they were temporarily emerged. All these collophanite materials, although looking limpid under microscope, are made of micrite aggregate of 2-4 μm under SEM.

All the phosphate intraclasts, including even the nuclear part of phosphate oolites, are made predominately of silty or clayey phosphorites, being more or less similar to the collophanite just described above, except they usually contain more nonphosphorous impurities such like illite or carbonate tiny fragments. Then, what made the tenor difference between clayey phosphorite and the different kinds of intraclastic phosphorites? For the elucidation of this problem, we examined petrographically the ores from both clayey and pelletic clastic ones from Kunyang, Kaiyang, Wengan and Xiangyang etc., and singled out under microscope those "pure" or uncontaminated "apatite", and sent for chemical analysis. This is tablized in Table 1. As shown in the table, the P_2O_5 content of all the "apatite" dressed out from the clayey phosphorites is much lower than those from the pelletic clasic phosphorites; but, at the same time, their Al_2O_3 content is much higher instead. The reason under these divergence, as shown under microscope, lies chiefly upon the difference in their relative contents between apatite and illite (Al_2O_3). As shown in Fig. 4, Al_2O_3 and P_2O_5 possess obviously a negative relation. And Fig. 5 compares the difference between those of the Cambrian and Sinian phosphorites. Fig. 6 shows the mutual relation of the system P_2O_5--Al_2O_3--SiO_2.

Now, it is obvious that the tenor of any kind of phosphorites is intimatey related to the amount of terrestrial non-phosphorous contaminations. And the divergence of tenor of the pelletic intraclastic phosphorites and the clayey micritic phosphorites is probably due to the replacemnt of illite and the like by phosphate rich pore water during the early diagenetic stage.

DYNAMIC REGIME AND ENVIRONMENT OF SEDIMENTATION OF INTRACLASTIC PHOSPHORITES

Basically the Chinese phosphorites fall into two categories, viz., clayey concretionary phosphorites,that akin to black shale formations,and the bedded intraclastic phosphorites that used to accompany carbonate formations. The bedded intraclastic phosphorites form almost solely within inner continental shelf, above the wave base zone, and are thus products of tidal or storm induced currents. Clayey concreetionary phosphorites, generally with micritic texture, are mostly formed within the offshore or transitional zones,although occasionally could be encountered also within restricted shallow seas or lagoons. Phosphorite forms always within an eustatic movement period and occur always within the lower part of a transgressive series, while the rate of sedimentation was slow and intermittenly quick. But, the phosphorite-bearing series are prevailing retrogradational instead of progradational. The phosphorite ore-beds themselves are mostly polycyclic, and different kinds of "omission surfaces" used to occur.

Almost all the phosphorite-bearing beds are blackish in color and rich in organic material. And, quartzose sandstones, made almost all of quartz sands usually occur somewhere below the phosphorite horizon. The paleoclimatic condition of phosphorite sedimentation seems to be hot and humid. But, pseudomorphs probably of anhydrite and celestite were encountered with occasionally in Kunyang andKaiyang. And,above the phosphorite-bearing series,gypsum and rock-salt layers generally occur in the red beds both of the Cambrian and Sinian in North and South China as well. Thus, the paleoclimate background of phosphorite deposits may either be hot and humid or transitionary between humid and dry. Recent results of paleomagnetic survey give the paleolatitudes of both the North and South China's Cambrian phosphrites as around from the equator to 35°s. The Sinian ones are in continuous deposition with Cambrnian, so, they must fall into the same latitudinal position.

Chinese phosphorites are all shallow marine deposits formed above the wave base zone. This is clearly shown by their sedimentary structures such as: crossbedding, rolling crossbedding, flaser bedding, herringbone crossbedding, hummocky cross bedding, omission surfaces, cut and fill, flat topped ripple mark, birdeye structure, mudcracks, rip-up clay chips and edgewise conglomerate, graded grain bedding, and tepee structure, etc. They are mostly intertidal, estuary, and subtidal shoal deposits. This can be inferred by the paleogeographic and isopach maps of Figs. 7 & 8. Within the phosphorite beds themselves or the strata right above or below them, there are customarily stramatolite mats, bioherms or reefs. Therefore, the water depth of phosphorite deposition must be something around 30-50 m. As to the depth of deposition of the micrite concrctionary phosphorite of the blacke shale formation, it may not quite as deep as customarily envisaged. Because the black shale formation iucluding the phosphorite is generally laminated and shally bedded, but as soon as they drew near the phosphorite, the lamination structure generally soon disappears, and becomes massive in bedding. This may indicate that they had been exposed to shallow depth, and the lamination was destroyed through bioturbation. Even mudcracks and tepee structures can be seen both in the black shales and the phosphorite themselves.These, of course, are extreme cases.

As stated above, the Chinese phosphorites are chiefly shallow marine deposits, mostly in intertidal zone. And during their deposition temporary exposure often occurred as shown by the mudcrack, tepee, birdeye structure, and the capollary fringe zone phosphorite veinlet swarms as shown in Fig. 3. Exposure of even a longer duration is recorded by the silicified paleokarstic omission surface shown at the base of the Sinian B-layer phosphorite of Wengan. The episode of temporary exposure is an indications of the intermittent sea level oscillation.These oscillations movement was able to induce and strengthen the erosive power of the bottom current. This is well shown at the base of the phosphorite bed at Kunyang. There, a swale of about 400 m in width and about 1 m in depth was excavated by the bottom current, and left with phosphorite lag pebbles incoperated into the basal part of the overlying phosphorite bed. Bottom current, being as strong as this, must be somewhat like a sort of storm induced current. This can well be proved by the existence of graded grain bedding (Fig. 10), hummocky cross-bedding, rip-up clay chips, lag conglomerate etc.

As shown in Table 2 and Fig. 12, the cumulative probabillity curves of grain size analysis of phosphorites are mostly composed of 3 or 4 segments. This indicate that they are most probably intertidal, subtidal shoal or estuary deposits. Their suspension fraction is low, being mostly only several percent. The intersection point of the suspension segment and the saltation segment falls mostly above 3.5 ϕ or 4 ϕ, and the percentage of saltation fraction is generally rather high, being largely above 90%. Hence, they are apparently shoreline deposits. Nevertheless, exceptions do at times exist, such like curves Nos. 3, 25 and 15, which are probably due to sampling in lower energy position as came from the upper part of the sedimentary package. Some curves show two saltation segments, this is probably due to the effect of the on and back flow of tidal currents. These characteristics comply with the direction of paleocurrent as shown in Fig. 13, and the paleogeogaphic maps of Fig. 7 and 8. The traction load of phosphorites is usaully very low, being only several to at most around ten percent. And even nil in some samples.

As judged from the curves presented here, Chinese phosphorites have the following characteristics:

(1) The peak values of the frequency curves fall mostly in the vicinity of 1-3 ϕ, i.e, a grain size between 0.5-0.1 mm.

(2) The frequency curves are mostly bimodal or polymodal. This means the direction and speed of the sea water current vary constantly. This coincides with the salient features of coastal sedimentation.

As seen from table 2, the sorting coefficients of phosphorites are predominantly median to comparatively good. Their kurtosis fall mostly between 0.90-1.11 and 1.11-1.50, i. e., mostly median to narrow. Their skewness falls into two kinds, one is from near symmetrical (-0.10—+0.10) to positive (0.10—0.30), most of the huge industrial phosphorites of China, suck as Xiangyang, Yichang, Wengan, Kaiyang, etc., belong to this category. The other is near symmetrical to negative (-0.10—-0.30) or extreme negative (-0.30—-1.00), like the Deze and Chadian deposits. It seems, that all the huge deposits with good tenor belong to the first group and all the minor deposits with poor tenor belong to the second group, which generally possesses a negative skewness. Thus it is obvious, deposits of good quality and large magnitude belong mostly to the first category, whereas those of minor quantity and poor quality belong mostly to the later one.

As to the Sinian and Cambrian phosphorites of China, it seems that their quality and magnitude could roughly differentiated from their granularity and character of their frequency curves. For instance, the range of grain size of the Chadian deposit is largely between 0 ϕ to 6 ϕ, and with a very wide despersion, being no any size fraction occupies more than 15% in quantity. Its sorting coefficient is extremely low, ranging from 1.00 to 2.00, And, it has generally a high percentage of suspension fraction. Most of the Lower Cambrian phosphorites of North China are quite similar to the Chadian deposit in character. It is necessary to idenify the strength, direction and character of the paleocurrent that transported and deposited the intraclasts that constituted the phosphorits, for the understanding of the process and procedure of phosphorite formation. But, this is not an easy task, because lots of critical phenomena had been lost in the past. So what we are talking here, is just a try.

We took the Wengan deposit as an example to determine the direction of the paleocurrent. We measured 8 localities of conglomerate deposits, 1 locality of crossbedding, 5 localities of flute cast and ripple marks. For crossbedding and conglomerate we measured more than 100 readings at every locality. After stratigraphic bearing recorrections, the final approved directions of paleocurrent were depicted on Fig. 13. As seen from this map, the flow direction as determined from flute casts and ripple marks are predominantely from East to West, varyiug between 250°—300°; as from crossbeddings, the direction is from West to East, being roughly around 77° 06′; as from pebbles of conglomerate, the resulting direction is twofold; one portion is from East to West, being 291°42′ to 329°35′; the other portion is from West to East, varying between 67°09′ to 126°30′. The two portions are just opposition to each other.

As seen from the map, within the two gulf areas of both the south and north ends of this pericontinental sea, the flow direction is abnormally N—S. This is probably due to the deflection of the topographic boundary effect. On the whole, the main prevailing flow direction of the paleocurrent was apparently east-westward and against the coast. And apparently, they are tidal or storm induced current of the coastal neritic zone. And it was just due to the back and forth winnowing effect of this kind of shallow marine process, clastic phosphorites of high quality were finally formed.

We tried this same kind of measurement also at the Kaiyang deposit. But the main point we did there is to further determine the current intensity and the slope of the littoral zone. As seen from Table 3, the grain size from south to north decreases gradually. This can be inferred from the paleogeographic map of Fig. 7 There it can be seen, an "oldland" was located right down south of Kaiyang, and, northwards as up to Zunyi the corresponding phosphorite-bearing series gave rise to a black shale formation. Thus, apparently, the grain size of the phosphate intraclasts decreased as away from the paleocoast. This just coincides with the measured grain median size array; and it shows the direction of the paleocurrent was also roughly perpendicular to the coast.

We used the equation and method of Bascon (1951) and Wiegel (1964) to compute the paleobeach slope of Kaiyang. The final result we got is between 1:31 to 1:60, and the averge is 1:46. It belongs to a kind of moderate to gentle slope of the modern beach.

For solving the intensity or flow velocity of the paleocurrent with a load of grains less than 0.5mm in diameter, we adopted the equation of Komar and Miller (1973), and the results are shown in Table 3.

Now, if we take T as 10 sec., then the flow velocity of the southern part of the Kaiyang deposit is 26.67 cm/sec., and of the northern part as 21.35 cm/sec. And, if we take T as 16 sec. then we got 31.19 cm/sec.for the southern part, and 24.97 cm/sec. for the nortern part. These are all shown in Table 3.

If the diameter of the intraclasts is greater than 0.5mm., we used the equation of Rance and Warren (1969). The results are shown in Table 4. It can be seen when the grain diameter is 3 mm, and the wave period is 10, then the flow velocity would be 183.87 cm/sec., and if the wave period is 16, the velocity would be 196.63 cm/sec.

Thus, it can be seen during the deposition of the Kaiyang phosphorite the velocity of the tidal current was generally above 22—32 cm/sec ., This is the lowest velocity, and is quite similar to the modern shore velocity of 30—50 cm/sec.But, during storm weather, the velocity must be much higher, As shown above, if we take the grain diameter as 3 cm, then the corresponding value of paleocurrent velocity would be 183.87 cm/sec. to 196.63 cm/sec. This is similar to the maximum velocity of recent shore current. Of course, grain diamter as big as 3 cm is rare in the Kaiyang deposit, but it does occur at the base of the phosporite layer. and, at the same time, rip-up clay chips existed occasionally also. Therefore, storm induced current must had occurred intermittently during the phosphorite deposition.

CONCLUDING REMARKS

(1) Almost all of the Chinese phosphorites are intraclastic bedded phosphorite. They were products of the disruption, transportation, and re-deposition of the "embryo ore Beds". They were formed through repeated winnowing above the wave base zone and finally deposited within foreshore and transitional zone.

(2) The formation of phosphorite deposits is always related to eustatic movement and used to occur at the base of a transgressive series. Their hydrodynamic condition varied intermittently both in space and time. This is expressed clearly by its changing character of granularity. The ore beds are always polycyclic.And the cycles are constantly separated from each other by some kind of "ommission surfaces". The omission surfaces may represent subaquatic erosion, subaerol denudation,or at times only the transformation of the velocity of sea current. This means that oscillations of sea level were quite often during genesis of phosphorites.

(3) The paleoclimatic condition of phosphorite genesis is hot and dry, or transitionary between wet to dry. The paleomagnetic data set up recently indicate that the Sinian and Cambrian phosphorites were located from the equator to 35° S.

(4) The frequency curves of the Chinese phosphorites are mostly bimodal or polymodal. Rich ores mostly sorting better, and with narrow or median spread, and symmetric to positive skewness. They are chiefly made of saltation fraction, whe-

reas suspension fraction is always minor. On the opposite, ores of poor quality are largely with wide spread, poor sorting, symmetrical to negative or extremely negative skewness, and comparatively richer in suspension fraction.

(5) The transporting medium of industrial phosphorite deposits is mostly bi-directional tidal or storm induced current that is oridinarily perpendicular to the coast line. Their current velocity ranges generally above 22—32 cm/sec., quite similar to the 30—50 cm/sec. of modern shore line current. But, if we take grains, with 1-3 cm in diameter, then the computed results give 114.82—196.63 cm/sec.. This is apparently storm current in nature. Thus, the dynamic condition of the formation of phosphorites is surly tidal current or storm induced current.