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1. Preliminary materials map of the Chester quadrangle, Hampshire and Hampden Counties, Massachusetts, by G. William Holmes. 1 map, scale 1:24,000, 1 table. Massachusetts Dept. of Public Works, 100 Nashua St., Boston, Mass. 02114; and USGS, 80 Broad St., Boston, Mass. 02110. Material from which copy can be made at private expense is available at the Broad St. address.

2. Preliminary materials map of the Massachusetts portion of the Hancock quadrangle, Massachusetts-New York, by G. William Holmes. 1 map, scale 1:24,000, 5 tables. Massachusetts Dept. of Public Works, 100 Nashua St., Boston, Mass. 02114; and USGS, 80 Broad St., Boston, Mass. 02110. Material from which copy can be made at private expense is available at the Broad St. address.

3. Marine phosphorite deposits--economic considerations, by James B. Cathcart. 21 p., 1 table.

4. Phosphate exploration in Colombia--a case history, by James B. Cathcart. 19 p., 1 fig., 1 table.

5. Florida type phosphorite deposits--origin and techniques for prospecting, by James B. Cathcart. 27 p., 1 fig., 2 tables.

6. Distribution and geologic habitat of marine halite and associated potash deposits, by Robert J. Hite. 35 p., 11 figs.

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DISTRIBUTION AND GEOLOGIC HABITAT OF MARINE HALITE AND ASSOCIATED POTASH DEPOSITS

By Robert J. Hite

Introduction

The world's most important sources of potash are deposits associated with marine evaporites. Marine evaporites are chemical rocks precipitated from sea water as the result of concentration by evaporation. The dominant rock forming evaporite minerals are precipitated in the following order as the salinity of sea water increases (Usiglio, 1849): 1) calcite and dolomite, 2) gypsum and anhydrite, 3) halite, and 4) various potash and magnesium salts. Although many limestones and dolomites are evaporitic in origin, the term evaporite is most commonly used in reference to deposits of gypsum, anhydrite, or halite.

As our knowledge of lithologic associations in the sedimentary crust has grown, we have discovered that marine evaporites are more common than previously assumed. Halite deposits are much less common than gypsum or anhydrite but even so, halite has been found on all continents of the world with the exception of Antartica. Potash deposits represent the end phase of evaporite deposition and are rare in the sedimentary column.

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Diagenesis in some degree has occurred in most potash deposits, the effects of which ultimately may greatly influence economics of a potash deposit. These effects are not considered in this paper, however, which stresses the problems related to the primary phase of exploration.

Many of the important potash deposits of the world have been found, or at least manifestations, which led to the actual discovery, by accident, in the course of exploration for petroleum. Many of these accidental discoveries have been made only after a sedimentary province has received extensive petroleum exploration. The Paradox Basin, U.S.A., is an excellent example. Early indications of potash were found in this basin in 1924 by petroleum exploration. Although this led to some direct exploration for potash, which was not too successful, it was almost another 30 years before the discovery which is presently being exploited was made. Again, the later discovery was made by a petroleum test hole. The lag in discovery is primarily a function of drill hole density. Also the pattern of drill holes favored by petroleum exploration may not provide optimum coverage of potential potash target areas.

The world's present and rapidly growing needs for new potash resources cannot be satisfied by accidental discoveries. Direct exploration for new potash deposits must be undertaken if the world's needs are to be met. Since direct exploration for potash involves expensive drilling programs, every effort must be made to narrow down the target area. For that reason this paper attempts to indicate

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the frequency of occurrence and the geologic habitat of marine potash deposits with particular emphasis on the relationship to paleoclimate. It is hoped that from this discussion some preliminary guidelines may be drawn concerning the direct exploration for potash deposits.

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Basic Principles of Formation of Marine Evaporites and Potash Deposits

Many of the fundamentals of marine evaporites and potash deposition are well established in geologic literature. Space limitations prohibit a detailed discussion of the theories of evaporite deposition in this paper, but some coverage seems desirable.

Various schemes of classification have been proposed for marine evaporites. One of the earliest classifications was made by Grabau (1920) who suggested four types of depositional sites. 1) Marginal salt pans; 2) marine salinas, 3) lagoonal or barred basin, and 4) relict seas. Grabau's classification was based primarily on the conditions effecting circulation between the evaporite pan and the open sea. More modern classifications, notably Krumbein, 1951, Sloss, 1953, and Ivanov and Levitskii, 1962, have applied a tectonic approach. For the sake of simplicity, the genetic scheme of Grabau, with one additional category (shallow shelf), is used in this paper. These depositional sites are discussed in order of their geologic importance.

Lagoonal or barred basin

The basic factors involved in the formation of marine evaporites and associated potash deposits are constant source of sea water and solar energy. In hot, arid climates evaporation concentrates the salt content of the surface layer of the ocean. This water of higher salinity and density gradually sinks and remixes with water of open ocean salinities. If some type of topographic barrier slows or prevents the return of this water to the open ocean, an increase in salinity of water behind the barrier will result (Bischoff-Ochsenius theory). The accessway of a barred basin may be so constricted that its flow capacity only equals the volume of water lost by evaporation in the basin. Since a constant load of dissolved salts is brought into the basin through the accessway, the water of the basin will eventually become salt-saturated and evaporite deposits will form. If the accessway to the basin is widened or deepened so that its flow capacity is increased beyond the volume needed to balance evaporation, then a return flow (reflux) of brine to open sea can take place. When reflux occurs equilibrium between inflow salt load and outflow salt load is achieved and there is no further increase in salinity. An excellent modern example of this is the Mediterranean Sea. Sea water of near normal salinity (3.6%) flows into the Mediterranean through the Straits of Gibraltar at the rate of $1.75 \times 10^6 \times 10^6 m^3$/sec. to replace the loss by evaporation. Simultaneously water of a higher salinity (3.8%) is refluxed back to the Atlantic by an underflow at the rate of $1.68 \times 10^6 m^3$/sec. (Fischer, 1964, p. 571). These figures

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indicate a near balance between incoming and outgoing salt loads. The slightly greater amount of salt being refluxed probably represents additions made by river waters. Unless there is either a climatic change, lowering of sea level, or a rise in the floor of the Straits this salinity budget will remain constant. If equilibrium is reached during the halite phase of concentration, only halite mixed with the less soluble phases will be deposited and the potash-rich brines will be refluxed to the sea. Any change in the volume of inflow and outflow, caused by raising or lowering of barriers or sea level, will upset this depositional equilibrium and either regressive or transgressive phases will be deposited. Thus, potash deposits should be expected to form only in basins where evaporation rates are high and severe restrictions on circulation minimize or prevent reflux.

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In the barred basin the most dense brines are concentrated by gravity into the lowest parts of the depression. For this reason the most soluble evaporites accumulate in the deepest water. The distribution of evaporites in the barred basin is also influenced by the location of accessways. Briggs (1958) has shown in his studies of the Michigan Basin that lobes of normal marine or penesaline facies project into the saline facies along accessways.

Most of the world's important deposits of halite and potash were formed in barred basins. Notable examples include the deposits in the Permian, Paradox, and Michigan Basins of the U.S.A., and Zechstein Basin of Europe.

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Shallow shelf

Although barred basins have probably made the most significant contributions of marine evaporites, other depositional environments can provide the necessary conditions for evaporite formation. A very convincing discussion by Shaw (1964) shows how marine evaporites can be deposited from epieric seas on shallow shelf areas even though no physical barriers to circulation are present. According to Shaw (p. 5) the bottom slopes of these epieric seas must have ranged from about 0.1 to about 0.5 feet per mile. When the sea moves hundreds of miles inland across such gentle and shallow slopes where a hot arid climate prevails sea water can become very concentrated. This highly saline water, which would normally return to the open ocean as a density underflow, is effectively held in place since it lacks enough hydrostatic head to overcome the friction imposed by the gently bottom slope and the push of inflowing water (Scruton, 1953). Thus, these dynamic conditions can cause a strong salinity gradient with greatly elevated salinities in the neritic zone and eventually the deposition of evaporites. Bathymetric relationships would be just the reverse of the barred basin, and the most soluble evaporites would accumulate near shore. The evaporite facies of the epieric seas would develop in broad bands (Shaw, 1964, p. 13) and these bands should parallel shorelines. Again, this contrasts with facies distribution in the barred basin. Shallow shelf evaporites are markedly affected by conditions of regression and transgression. The lowering of sea level only a few feet can shift facies belts many miles seaward and

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expose previously deposited salines to erosion. Conversely, if sea level rises, an onlap of less saline facies will occur and dissolution of the more soluble facies will occur along their previousmost seaward development.

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The evaporite facies in the Holbrook Basin of east-central Arizona may be an example of halite and potash deposition on a shallow shelf. On the basis of isopach data, Pierce (1966, p. 4) believes that the evaporites occur in a depositional basin. If this is true then the depositional site may represent a small local depression on the shallow shelf. This type of modified shelf site has been described by Landes (1963, p. 7).

Marginal Salt Pan

Besides the shallow shelves of epieric seas, other deposition sites for marine evaporites include what Grabau (1920) has described as the marginal salt pan. The marginal salt pan depositional site is a shallow depression which borders the sea and which periodically is flooded by high tides. These depressions generally are of insufficient capacity to produce any appreciable quantity of evaporites. Even when sea water fills the depression to capacity and then completely evaporates only a thin crust of evaporites results. The modern-day example of a marginal salt pan cited by Grabau (p. 116) is the Rann of Cutch located on the southwest coast of India. However, recent work by Platt (1962) shows that most of the water that collects in the Rann is not sea water but rain water which falls during the Monsoon season. A possible fossil representative of the marginal salt pan type is the Danakili Depression on the Ethiopian coast of the Red Sea. The great thickness of evaporites plus the presence of potash deposits in the Depression suggest, however, that these are more closely related to the barred basin type.

Marine Salina

The marine salina of Grabau is similar to the marginal salt pan. It differs in that instead of periodic overflow from the sea into a depression, sea water seeps in through permeable barriers. Again it is unlikely that this type of depositional site contributes significant quantities of evaporites. Two modern examples have been described, Lake Larnaka on Cyprus (Grabau, 1920) and Lake Assal in French Somaliland (Borchert, 1964). No fossil evaporites from this type of depositional site have been reported.

Relict Sea

According to Grabau's usage relict seas are disconnected arms of the ocean. Without replenishment from the ocean these seas eventually are desiccated and evaporites are deposited. Even though the volume of water trapped in these relict seas may be large, they could not be expected to furnish important quantities of evaporites. This point is forcefully made by Borchert (in) Muir (1964, p. 67) who states that "complete desiccation of the Mediterranean whose mean depth is 1,431 meters would yield only 24 meters of salt." No clear-cut examples of evaporites formed under these conditions are known.

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Evaporite Facies

The presence of strong salinity gradients at the sites of evaporite deposition (i.e., shallow shelf or barred basin) causes an orderly arrangement of facies belts. If a complete development of facies is present the following lateral arrangement of successive facies will be achieved: 1) limestone, 2) dolomite, 3) gypsum or anhydrite, 4) halite and 5) bittern salts. Each facies belt will be positioned on the salinity gradient according to the saturation field of that particular salt (Scruton, 1953). The same succession is repeated vertically in cyclic fashion if there have been several periods of transgression and regression. The vertical succession of an evaporite cycle will not be complete at all points (Hite, 1961). The completeness of the vertical facies will depend on the degree of on-lap and off-lap. Shelf evaporite deposits, because of their large scale lateral shift of facies belts during regression or transgression, should exhibit the most complete vertical sequences over large areas. Conversely, evaporite basins, particularly those with relatively deep water, prohibit large lateral facies shifts unless there are periods when inflow almost completely flushes out the basin. One important point that is sometimes overlooked by geologists unfamiliar with principles of evaporite deposition is that any basin with halite or bittern salts must also contain the lateral equivalents of the less soluble phases. Occasionally, geologists have found it difficult to explain the unusual volume, purity and seemingly monomineralic occurrence of a halite deposit (the Louann Salt of the Gulf Coast area, U.S.A. is a good example). In most instances the other facies are present, but simply have not yet been drilled. This may be particularly true in areas of salt tectonism where halite, because of its susceptibility to flowage, may be far removed from its original position with the less mobile facies.

Geographic Distribution of Marine Halite and Potash Deposits Through Geologic Time

Marine evaporites containing a halite facies have been found in all geologic periods, with the possible exception of the Precambrian, and on all continents except Antartica. The most complete study of worldwide evaporite distribution has been made by Lotze (~~1963~~ 1964). Lotze's distribution maps, on which he shows both chloride and sulfate facies, were used extensively by the author in preparing the distribution maps included with this paper. Lotze's work, in addition to a great number of other publications used in the preparation of these maps, is listed separately at the end of this paper under a selected bibliography of the world's marine halite and potash deposits. The maps shown here depict only those areas containing halite with or without potash deposits along with paleolatitudes from Briden and Irving (1964). The author realizes that these maps leave much to be desired in completeness and accuracy, but hopefully they are adequate for making a few basic deductions.

Precambrian

At present there are no reliably dated halite deposits of Precambrian age in the world. Several deposits thought to be Precambrian in age because of their stratigraphic position such as those in the Salt Range of Pakistan, on the basis of pollen content or other evidence, are now thought to be much younger. The apparent stratigraphic position of such deposits may be misleading. The great mobility of halite and gypsum creates an effective lubricant along glide planes of thrust systems as that juxtaposition of older strata is not uncommon where evaporites are involved. The occasional presence of thin beds of gypsum or anhydrite and salt casts in rocks of Precambrian age indicate that beds of halite could have been deposited. That these highly soluble deposits did not survive the ravages of geologic time is not surprising.

Cambrian

Halite deposits of Cambrian age are found only in Asia and Australia (Figure 1). Despite the limited geographic distribution, these deposits are large and of great geological importance. These deposits show a pronounced clustering near the paleoquator. In Siberia deposits of Cambrian halite collectively form one of the most areally extensive salt accumulations in the world. Significant deposits of potash are also present, although it isn't known whether these are being exploited. Other important deposits of halite occur in the Salt Range of Pakistan where minor amounts of potash salts have also been reported. The actual age of the Salt Range deposits has not been completely resolved. Other significant Cambrian deposits include the salt of the Amadeus Downwarp, Northern Territory, Australia. The extent of this salt basin is still relatively unknown.

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Ordovician

The Ordovician Period easily ranks last from the standpoint of important halite deposits. To the author's knowledge the only known marine halite deposits of this period occur in the McKenzie Basin and in the Norman Wells area, Northwest Territory, Canada, some distance north of the paleoequator (Figure 2).

Silurian

Halite deposits in the Silurian period are also rare (Figure 3). The only known deposits occur in the Salina Group in northeastern U.S.A. and southeast Canada. The deposits are extensive in the Michigan Basin and they spread into the States of New York, Pennsylvania, Ohio, West Virginia, and into the Province of Ontario, Canada. These deposits fit well with paleolatitude data, falling between 0 and 10 degrees south. Some of the halite in the Michigan Basin contains traces of potash minerals but no concentrations of industrial importance are known.

Devonian

The importance of the Devonian Period as a time of salt accumulation has gone relatively unnoticed, but the Devonian halite deposits are nearly as extensive, if not equal to, those in the Permian (figure 4). These deposits, with the exception of several deposits in western U.S.S.R., are located near the paleoequator. Important deposits of potash occur in the Devonian, in the Pripiat Depression and in the Tuva Basin of the U.S.S.R. What may prove to be the largest and richest deposits of potash in the world are found in the Williston Basin of North Dakota, U.S.A., and Saskatchewan, Canada.

Mississippian

The distribution of halite deposits in the Mississippian Period contrasts markedly with the great buildup during the Devonian. Only three Mississippian halite deposits are known, all on the North American continent. These deposits, which occur within 10 degrees of the paleoequator, are in the Williston Basin, in the Maritime Provinces of Canada, and in a small area in [redacted] Virginia (figure 5). Neither the volume nor the areal extent of these deposits is particularly impressive. The deposits of the Windsor Formation of Canada do contain some potash which is complexly folded and faulted.

Pennsylvanian

Only two halite deposits of the Pennsylvanian Period are known, but each is quite significant (figure 6). One deposit, which is one of the world's thickest accumulation of halite, occurs in the Paradox Basin, Western U.S.A., where economic deposits of potash salts also occur. This salt basin is located almost directly on the paleoequator. The other halite deposit of Pennsylvanian age occurs in the Amazon Basin of Brazil and is that continent's largest halite deposit.

Permian

Conditions favoring evaporite deposition apparently reached their zenith in the northern hemisphere during the Permian Period (figure 7). Extensive halite deposits occur in a belt extending in a north-south direction across the entire Western U.S.A. The well-known potash deposits of the Carlsbad District are located at the southern end of this belt. Newly discovered potash deposits also occur in a small halite basin near Holbrook, Arizona. In Europe widespread halite and potash deposits of the Zechstein Basin cover parts of Denmark, England, Germany, the Netherlands, and Poland. In the U.S.S.R. a vast area underlain by halite deposits in several formations extends along the western edge of the Ural Mountains from the Barents Sea on the north to the Caspian Sea on the south. Potash deposits are present through much of this area. The largest deposits occur in the Cisural Depression (Upper Pechora Basin, Upper Kama Basin, and Orenburg-Aktivbinsk area), where the well-known Solikamsk District is located. Other important deposits are known in the Sterlibashevo District and in the Caspian Geosyncline. Although extensive deposits of halite are present in Permian rocks on the North American and European continents, such deposits are lacking or unknown on the other continents. Halite deposits of Permian age suggest by their locations a broadening of the belt favoring evaporite deposition. In Europe, for example, the deposits occur through a range of 30 degrees paleolatitude.

Triassic

Another period of important halite deposition in Europe occurs during the Triassic (Figure 8). Halite of Keuper age is probably the most extensive and can be found in separate basins in Britain, Germany and France. In the Mediterranean area Keuper salt is also extensively developed in the Pyrenees, the Iberian Peninsula, Italy, and along the North African coast in Tunisia, Algeria and Morocco. Many of the European and North African deposits show the effects of diapirism. Halite of Triassic age is also found in the Szechwan and Yunnan Provinces of China. A small halite deposit of questionable Triassic age occurs along the coast of Tanzania. Traces of potash salts have been found in a few localities, but no deposits of industrial importance are known. The locations of the European and African salt deposits fit reasonably well with paleolatitude. Most of the deposits are located within 10 degrees of the paleoquator.

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Jurassic

Halite deposits of Jurassic age are known on all the continents with the exception of Australia (Figure 9). The greatest accumulations of halite are in North America. The largest of these deposits is the Louann Salt of the Gulf Coast. The age assignment for the Louann has been a source of controversy for many years. Now, however, most American geologists place it tentatively in the Jurassic. In North America all the deposits, with the exception of the Williston Basin, are involved in salt tectonism. The Louann and the deposits on the Isthmas of Tehuantepec are involved in a myriad of salt domes. In the Western U.S.A. halite of the Preuss Sandstone and the Arapien Shale is complexly folded and squeezed in the large belt of overthrusts extending from Idaho into Utah. Diapirism of an unknown scale is also involved in the Jurassic deposits of Peru. Another extensive halite deposit has been recently discovered on the Khorat Plateau of Thailand. Potash deposits are known in the Louann Salt in the domes of the Gulf Coast area. These deposits are complexly deformed and are of questionable value. Important deposits of potash occur in the U.S.S.R. in the western Gissar Mobile zone and in the Kugitang-Guardak District. Insufficient data on paleomagnetism prevent any speculation on the relationships of the geographic distribution of Jurassic deposits to paleolatitudes.

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Cretaceous

The distribution and form of halite deposits of Cretaceous show a distinct departure from the patterns of previous periods. (Figure 10.) Most of the deposits are small and are located along continental margins. For the first time halite deposits are more common in South America and Africa than in the other continents. Potash deposits of industrial importance occur in the Congo and also in the small Serpie and Alagoas Basins of Brazil. The distribution pattern of the Cretaceous deposits suggests paleolatitude had only a weak influence on their locations.

Tertiary

With the exception of a small deposit in the Dominican Republic the deposits of marine halite of Tertiary age are located in a belt extending northwest from Asia Minor to Europe (Fig. 11). Many of these deposits are associated with rift systems such as the Red Sea, Dead Sea and Rhine Graben. Several important potash deposits of Tertiary age are located in Europe. These include the well known deposits in Alsace in the Rhine Valley, the deposits in the Ebro Basin of Spain, and several along the flanks of the Carpathian Mountains in the U.S.S.R., Poland, and Rumania.

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<u>Conditions Favoring Potash Deposition</u>

The preceding discussion has shown that halite deposits, particularly those containing potash, are by no means ubiquitous in time or space. This implies a restrictive framework of conditions within which such deposits are likely to form. From observations made concerning these deposits some of these conditions can be summarized as follows:

1) Paleoclimate must be a factor in the distribution of halite deposits. This is suggested on the North American continent where most of the salt deposits show a successive northerly migration with increase in geologic age. This distribution pattern corresponds rather closely in most places with shifts in the paleoequator. Similar distribution patterns are not so evident on other continents. This may be due in part to continental drift, or it may be due to the fact that many salt deposits have not yet been discovered. Paleoclimate may have been a factor in determining the position of potash deposits within areas where large-scale deposition of halite was taking place. One notable exception occurs in the Permian halite deposits of the western U.S.A., which extend almost continuously from the south border of Canada to the north border of Mexico. The paleoequator during Permian time was positioned very close to the Williston and Alliance Basins, but the only potash deposits are located hundreds of miles to the south.

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2) Regions of hot, arid climates alone do not suffice as depositional sites for evaporites. If restrictions of sea water circulation within these arid belts are imposed by tectonic controls or broad shallow shelves, then evaporites will form. If these circulation restrictions are severe enough, halite and potash deposits will form.

3) Tectonic events have a strong influence on evaporite deposition. Although favorable climatic belts shift through geologic time, sites of evaporite deposition may persist where downwarping is continuous. A good example is the Williston Basin, U.S.A., where evaporites of Ordovician, Devonian, Mississippian, Pennsylvanian, Permian and Jurassic age are present. Halite was deposited in four of these periods, but potash deposits are known only in the Devonian.

4) In comparing the four environments of evaporite deposition, barred basin, shallow shelf, marginal salt pan, and marine salina, the first type seems most favorable for accumulation of potash salts. Most of the world's richest deposits are of this type. Potash deposits can form with shallow shelf evaporites; however, their survival in this environment seems highly unlikely. Because shelf environments are characterized by oscillatory movements of the sea, potash deposits which would be located near shore, are subject to dissolution either by emergence during marine regression or by undersaturated waters of the transgressive phase. Only

deposits of appreciable thickness are likely to survive unless a protective layer of clay is rapidly deposited. Marginal salt pans as a rule do not favor the formation of significant potash deposits. A great thickness of evaporites can accumulate under these conditions but the percentage of potash salts in each evaporite layer resulting from flooding the pan with sea water is small. Thus, the accumulation of salts can be great, but the potash is so dispersed that it cannot be recovered economically. If, however, during each period of inflow the preceding layer or layers of salt were taken back into solution, the potash concentration in the last deposited layer would be high. This final potash-rich layer could be preserved if covered by an impervious layer of wind-blown sediment.

5) Deposits of halite and potash are found in both oxygenated (red-bed) and euxinic (black shale) environments. Apparently neither environmental parameter has any direct influence over potash deposition. If the euxinic environment can be interpreted to mean deeper water conditions, then it may indirectly favor potash deposition simply because deep water brines are less susceptible to dilution during sudden freshening conditions which would result in dissolution of potash if shallow water conditions prevailed.

Exploration Guides

The search for potash deposits in marine evaporites can be considered as two phases of exploration. Rather obviously, the initial phase is first finding evaporites containing a halite facies. The second phase of exploration involves specific examination of each individual halite deposit.

In areas of the world where drill hole data is sparse, the problem of locating marine halite deposits in the subsurface can be extremely difficult. There are, fortunately, some geologic criteria which may indicate halite deposits at depth. One strong indication of subsurface deposits, and probably the first geologic criteria employed in man's earliest search for salt, [are] saline springs whose waters contain a high percentage of sodium chloride. Such springs may be the result of active dissolution of underlying salt deposits by ground water and subsequent rise of this chloride-rich water along fault planes. The ionic ratios in such waters are usually quite different than waters which have obtained a high salt content by other means. The Na/K, or Na/Mg ratios in salt springs may indicate leaching of halite containing appreciable amounts of potash salts.

The presence of subsurface halite deposits may be indicated by surface structure suggesting salt tectonism. The most typical form is the salt diapir whose most readily identifiable surface features consist of intrusive masses of residual gypsum, resulting from dissolution of halite as the salt mass intrudes into the active ground water zone. Other less spectacular displays of salt tectonism may consist of small simple non-diapiric folds. These folds, in contrast to other folds of the region, many show the influence of repeated upward movement of salt by numerous unconformities and thinning in flanking and overlying sediments.

Red beds may be indicators of evaporites in the subsurface. There are, however, tremendous volumes of red sediments in the world that are totally unassociated with evaporites. Furthermore, additional data suggest that black shales are very commonly associated with evaporites.

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In the preceding discussion on the occurrence of halite and potash deposits it was shown that the distribution of many deposits correlates with reconstructed paleolatitudes for the time of deposition. Thus for some areas of the world prospecting for buried salines could be narrowed to localities where marine sediments were deposited in low latitudes. It may also be possible to further appraise the favorability of these sites by lithofacies studies. If for example the rocks exposed on the margins of a sedimentary basin are of favorable age they should be examined for lateral facies changes of the type described earlier in this paper. For example normal marine limestones of a high-energy environment grading basinward into dolomites may indicate a paleo-salinity gradient and the possibility of an evaporite facies deeper in the basin.

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When the presence of halite deposits has been established by direct exploration, (often through petroleum exploration) an examination of each halite unit or units can begin by employing several tools. If by good fortune, there are petroleum test holes in the area, a great deal can be learned by close study of mechanical logs run in wells which have penetrated halite. The great number of lithologic parameters measured by the various types of mechanical logs available today, allows an accurate interpretation of the lithologies and mineralogy penetrated by the drill hole. This is particularly true if several combinations of logs are run in each drill hole. There is of course no substitute for core from the interval of interest, but coring is expensive and should perhaps be resorted to only after the presence of potash minerals has been established. Then cores will be necessary for an accurate assay of the potash deposit.

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A new tool of great value to potash exploration is the study of bromine distribution in halite deposits. During the last decade much work has been done on the geochemistry of bromine in chloride evaporite minerals. Extensive application of bromine distribution to exploration problems has been made in Germany and Russia and on a limited scale elsewhere in the world. Space does not allow a complete description of the literature available on bromine geochemistry. Some of the more recent works pertaining to exploration (Baar, 1966; Braitsch, 1966; Holser, 1966; Ogienko, 1959; Raup, 1966; and Valyashko, 1956) are recommended. Bromine is present in trace amounts in all marine halite deposits. The element substitutes for chlorine in the crystal lattice of halite. This substitution is proportional to the amount of bromine in the solution depositing the halite. The higher the salinity of the solution, the more bromine present in the solid phase. For this reason bromine can be used as a salinity indicator in halite deposits. By establishing a salinity gradient in a halite deposit through the use of bromine distribution maps, areas favoring potash deposition can be outlined.

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In summary, one of the greatest problems facing potash exploration is the immense size of some potential target areas. This problem can be illustrated by reference to the halite deposits of Permian age in western U.S.A. An area of about 140,000 square miles covering parts of Colorado, Kansas, New Mexico, Oklahoma and Texas contains a series of overlapping halite deposits. These deposits occur in several formations each of which has its own particular areal extent, and range in age from Wolfcamp to Ochoa. The only potash deposits (Carlsbad District) occur in the Salado Formation of Ochoa age and are restricted to an area of about 3,400 square miles in southeast New Mexico and southwest Texas. If the first discovery of Permian halite in this vast area had been made in Kansas, and no other well data was available, the eventual discovery of the potash deposits, nearly 500 miles distant, might have come only after a long and expensive search. Should situations like this exist in the world today, and there is every reason to suspect they do, it is hoped that some of the discussion presented here will enable a more efficient approach to the problem.

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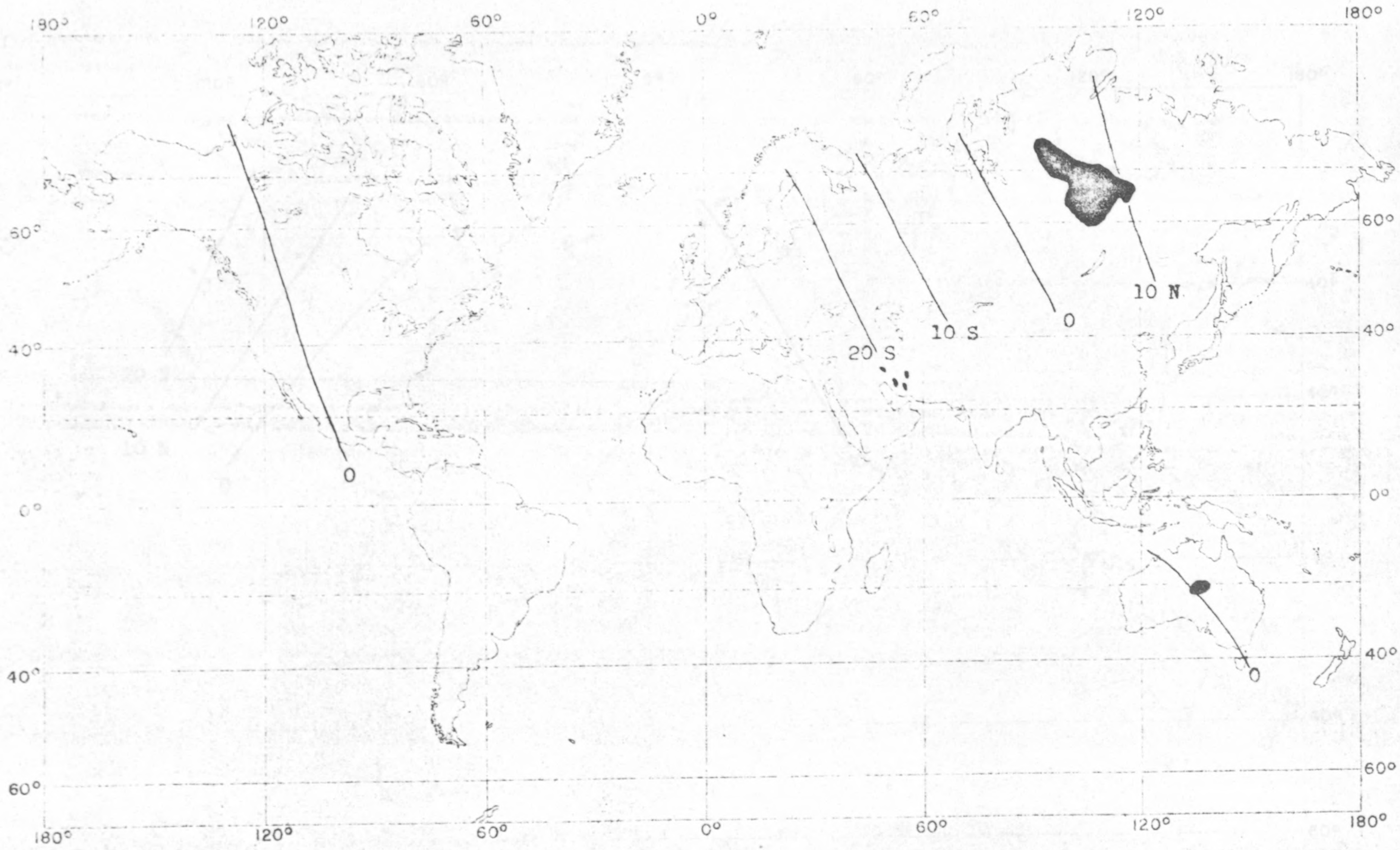

Figure 1. Marine halite deposits and paleolatitudes for the Cambrian.

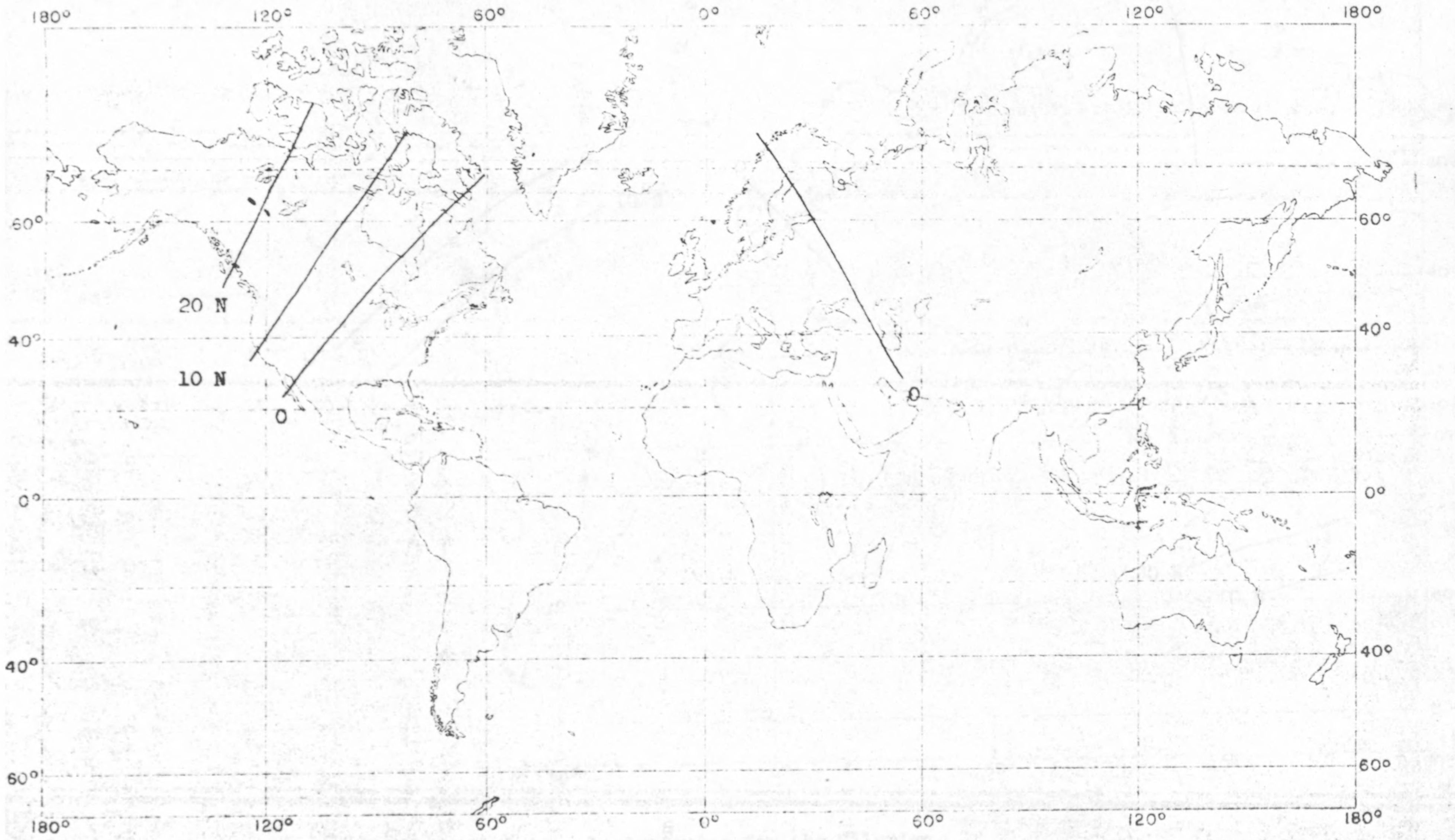

Figure 2. Marine halite deposits and paleolatitudes for Ordovician.

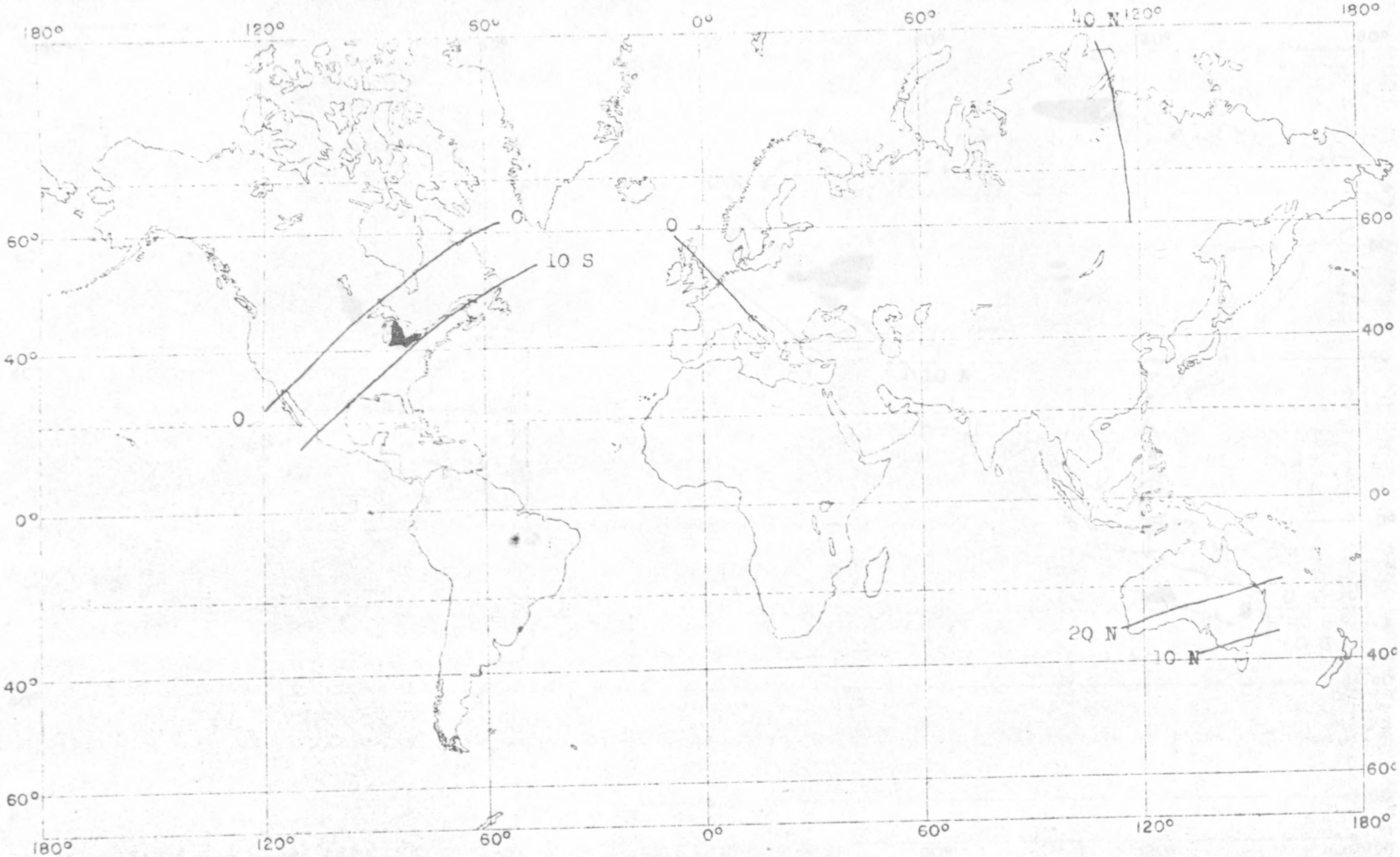

Figure 3. Marine halite deposits and paleolatitudes for the Silurian.

Figure 4. Marine halite deposits and paleolatitudes for the Devonian.

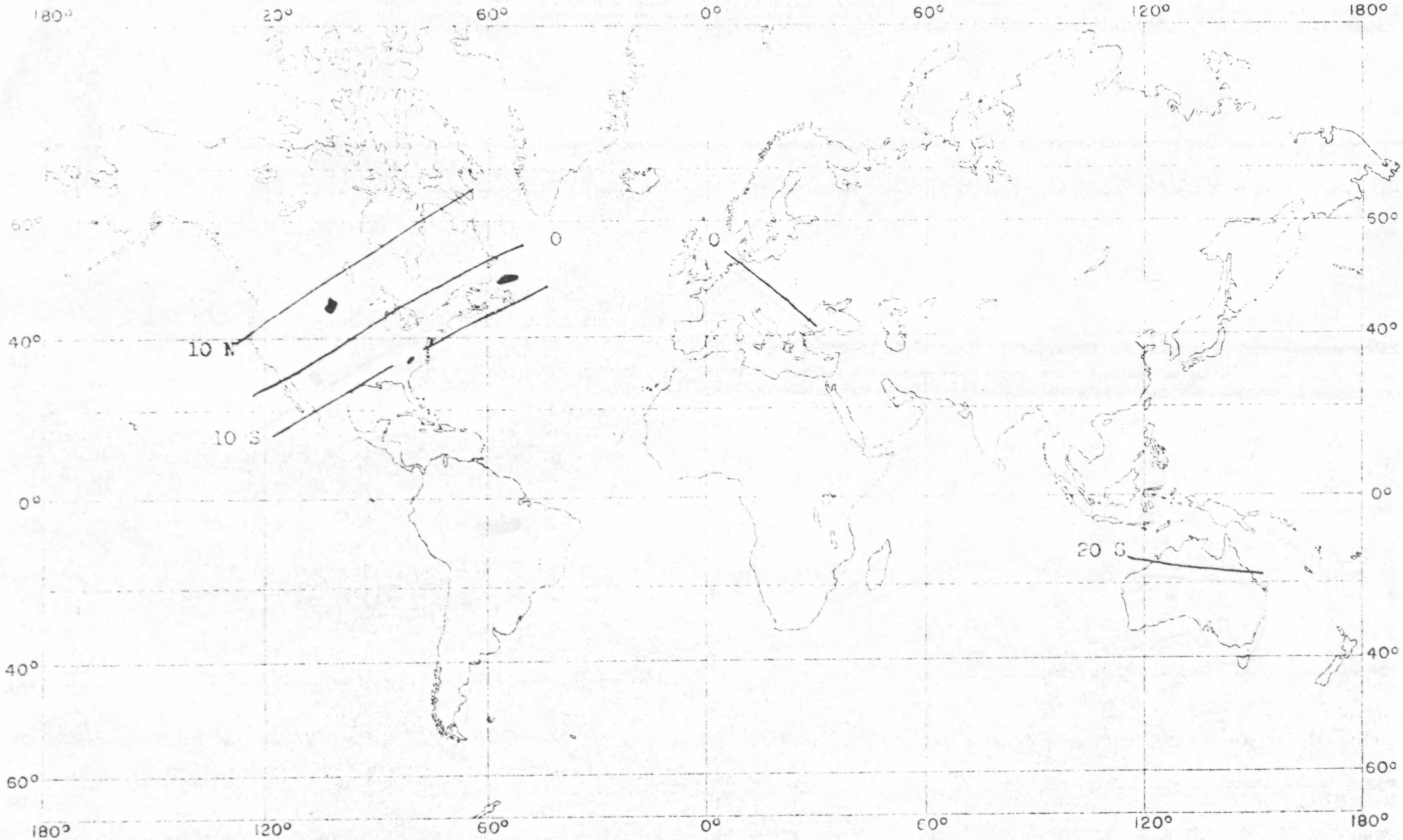

Figure 5. Marine halite deposits and paleolatitudes for the Mississippian.

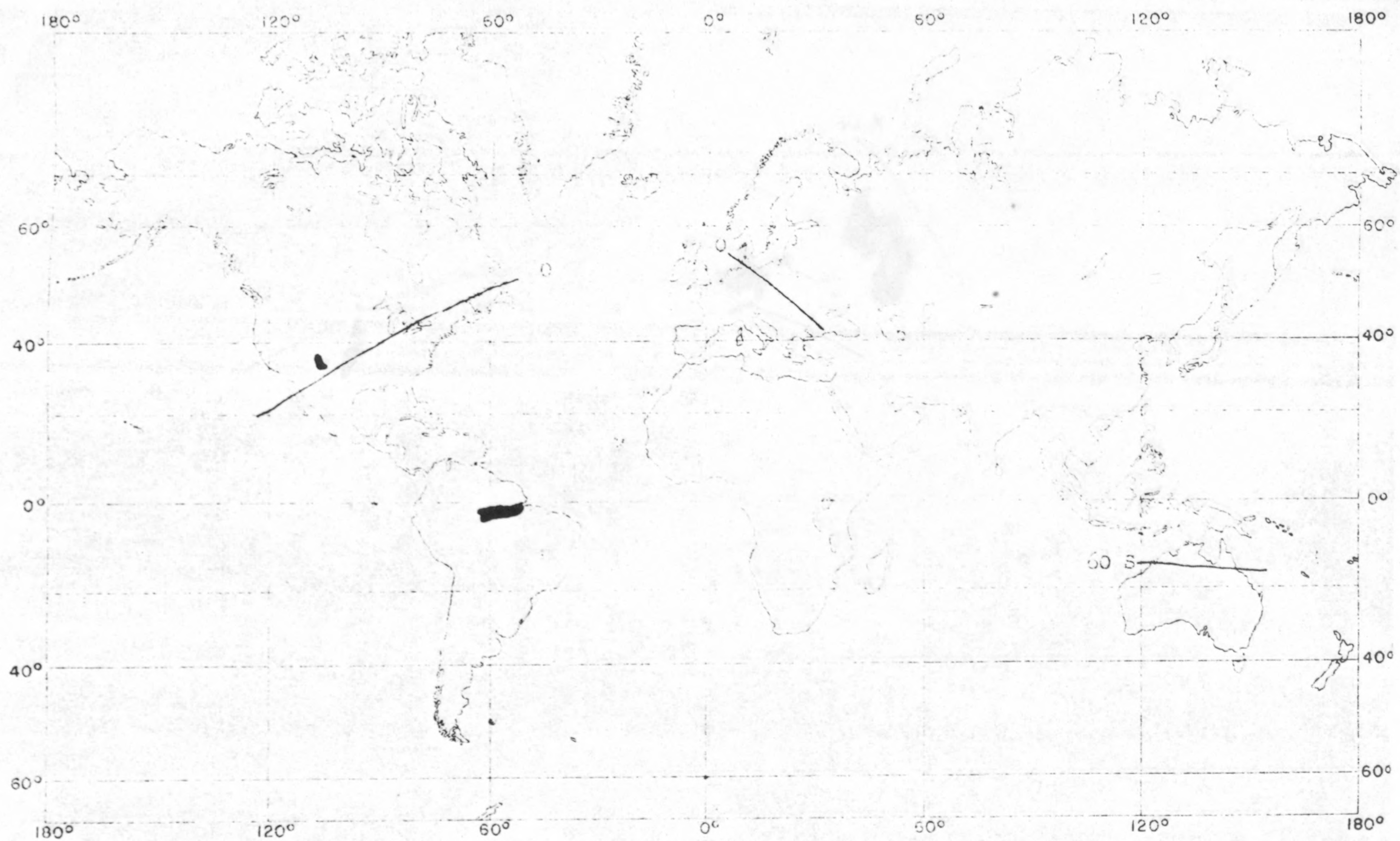

Figure 6. Marine halite deposits and paleolatitudes for the Pennsylvanian.

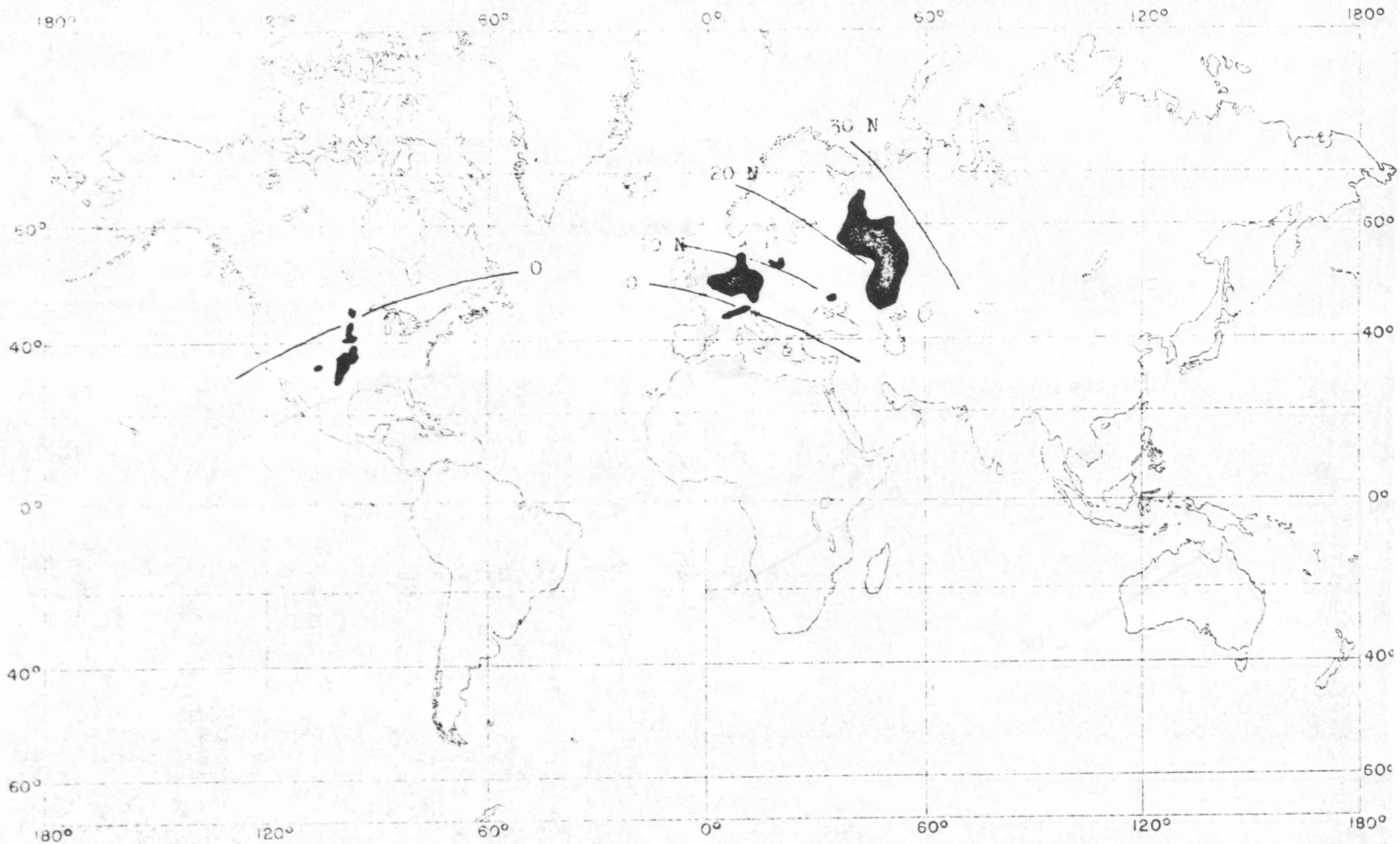

Figure 7. Marine halite deposits and paleolatitudes for Permian.

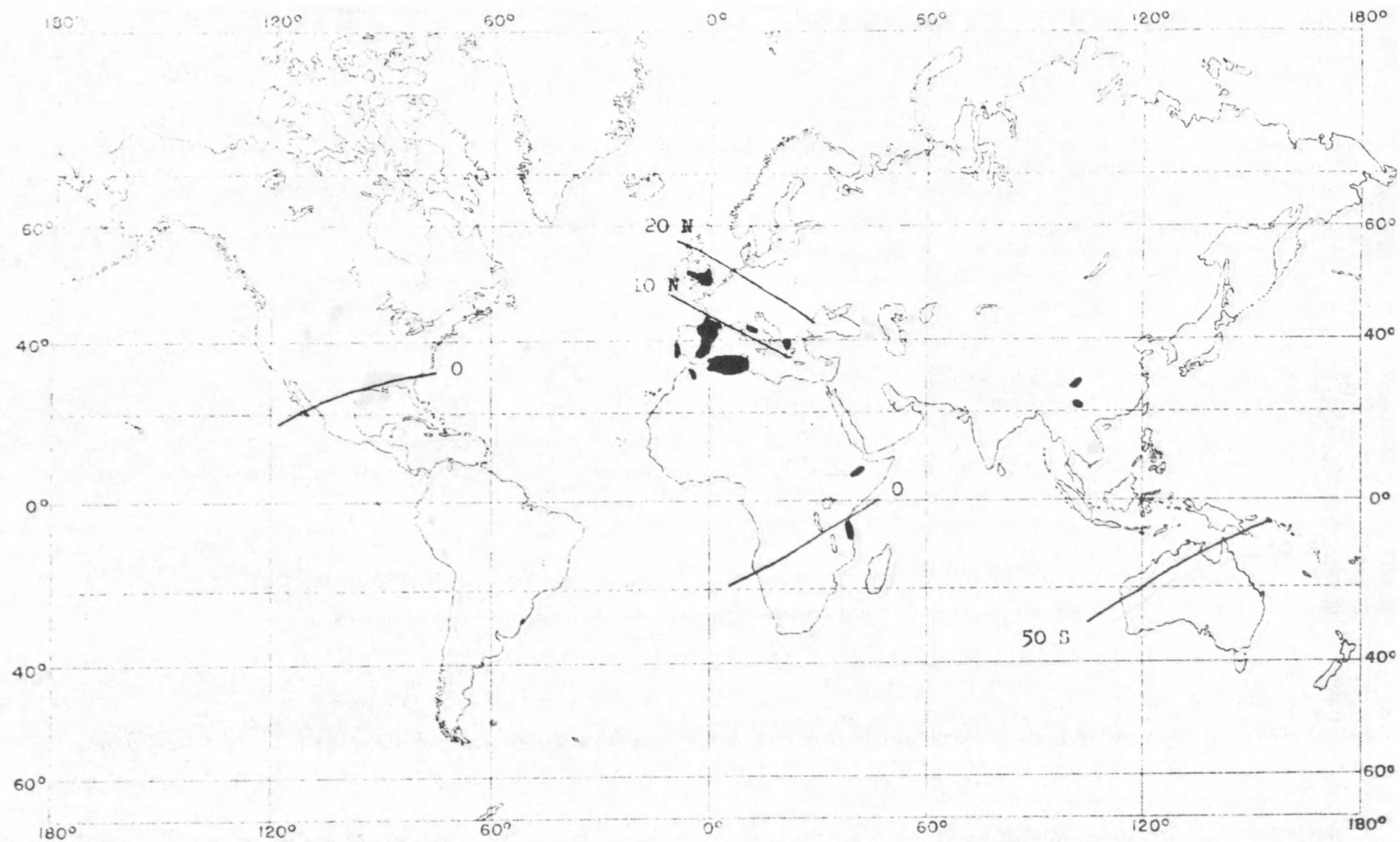

Figure 8. Marine halite deposits and paleolatitudes for the Triassic.

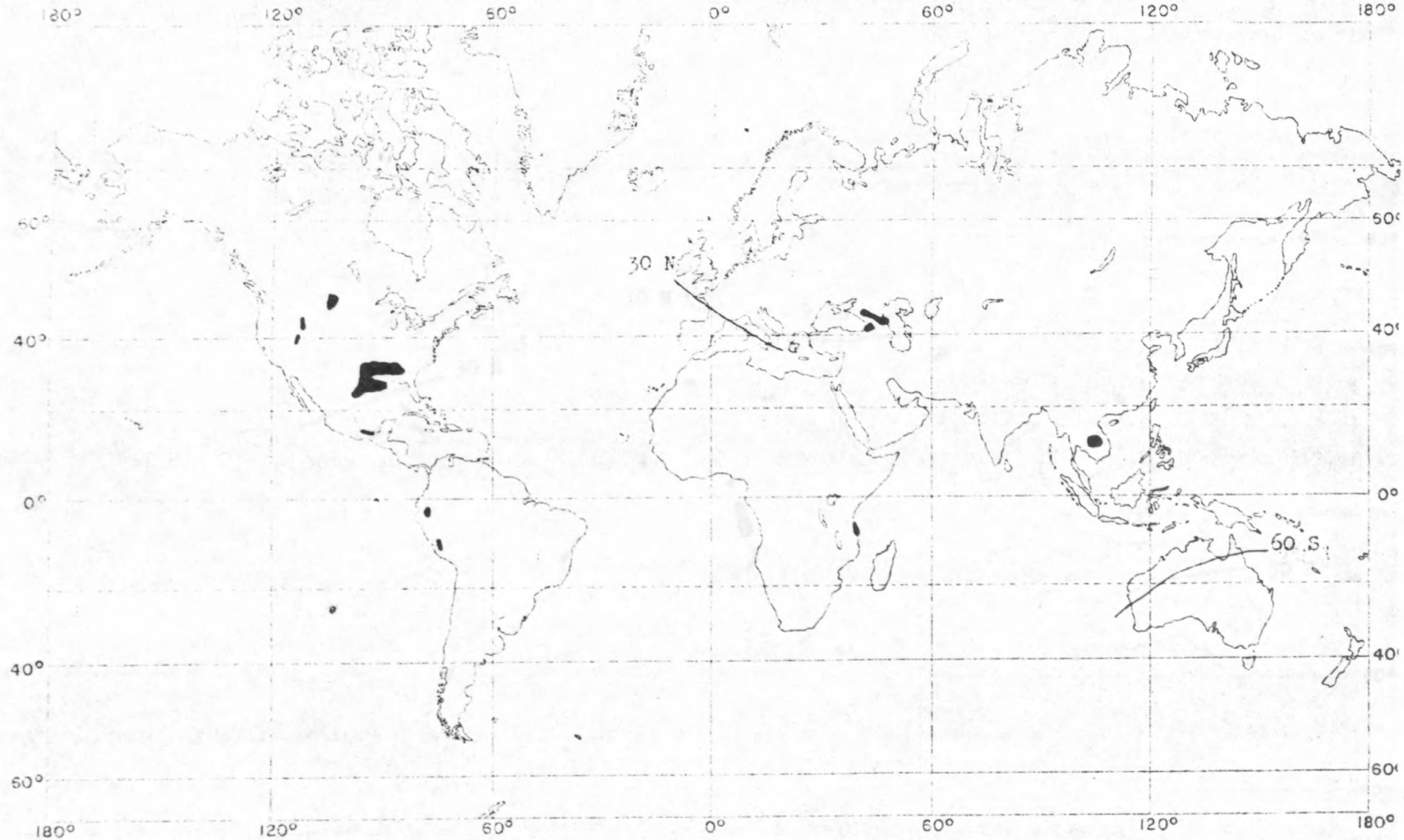

Figure 9. Marine halite deposits and paleolatitudes for the ~~Triassic~~ Jurassic.

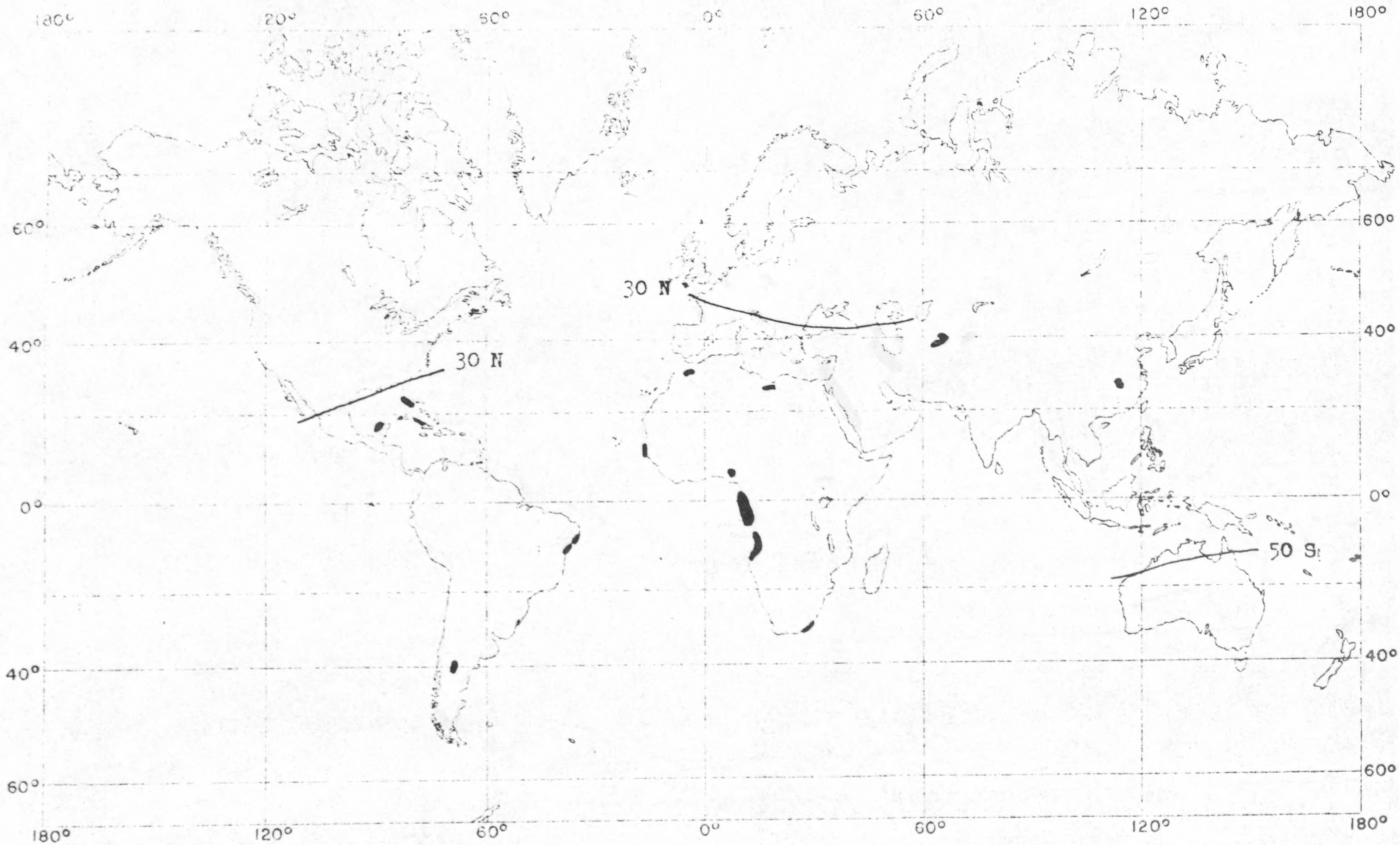

Figure 10. Marine halite deposits and paleolatitudes for the Cretaceous.

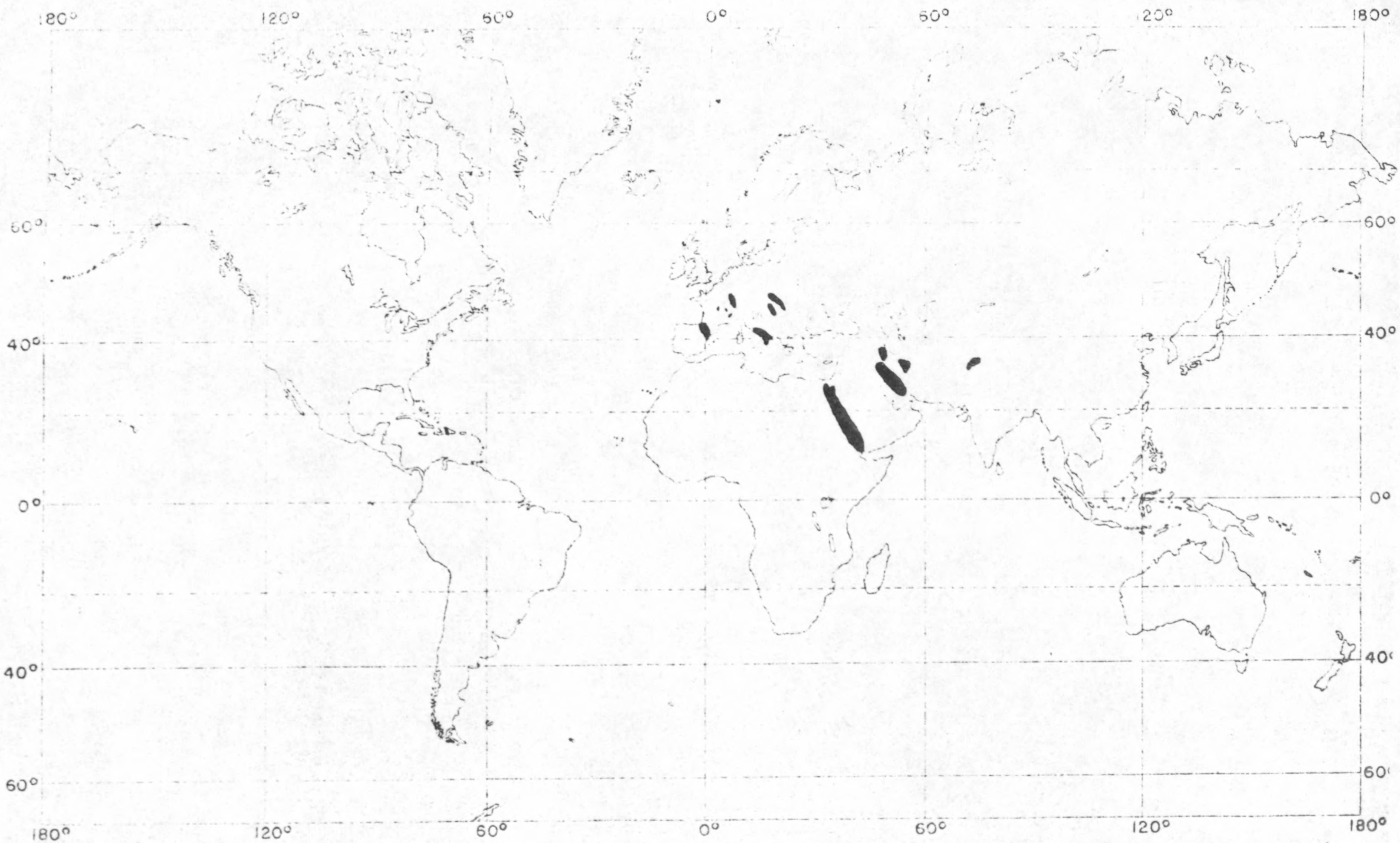

Figure 11. Marine halite deposits and paleolatitudes for the Tertiary.