ON THE SUBMARINE VOLCANIC ORIGIN OF ROCK-SALT DEPOSITS

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ROCK-SALT is one of the commonest of minerals occurring widely distributed in the world. It is also known to have been deposited in different epochs of the earth's history. The problem of the origin of rock-salt has long been the subject of discussion among geologists but no satisfactory solution has yet been found. The general consensus of opinion, however, appears to be that salt deposits have been formed somehow through evaporation of saline waters.

The sedimentary hypothesis of rock-salt formation is probably the most obvious one since the sea is the largest repository of salt on the earth's surface. Sea water contains about 3·5 per cent. saline matter in solution. Of this, common salt forms the major portion and is estimated, in its total quantity, to exceed ten thousand billion tons.

Many lakes are highly saline and appear to be actually depositing salt layers on their beds.

Further the sedimentary origin of salt is indicated by the bedded nature of some salt deposits as also by their nearly constant association with stratified rocks.

From all these considerations it is now generally held that salt deposits owe their formation to evaporation of saline waters in sea or lake basins. The controversy which, however, still exists pertains chiefly to the actual physical conditions obtaining during the process of evaporation.

The Bar Theory of Ochsenius

The difficulty of visualising evaporation of waters in an open sea ever reaching the stage of precipitation led C. Ochsenius, to advocate deposition of salt in oceanic bays separated from the open sea by a level bar. Continuous evaporation would increase the salinity of the bay waters whereas the decrease in volume of waters in the bay would be compensated by continuous or intermittent flow of sea water over the bar. Dry warm climate and absence of fresh water tributaries to the bay were postulated as essential conditions obtaining during this process.

Increase in salinity through evaporation increased the density of the surface solutions which sank to deeper levels while fresh accession of sea water was being made at the surface. The total salinity of the bay increased gradually till saturation was reached when salt began to precipitate at the bottom.

Some Difficulties of the Bar Theory

In its fundamental principles the Bar theory as elaborated by Ochsenius furnished a possible explanation of the formation of salt deposits in sea basins whereas the classical investigations of van't Hoff and others on the Stassfurt deposits demonstrated the theoretical grounding of the chemistry of the process operating during salt formation.

It is however when we consider the physical conditions postulated by Ochsenius as essential for the process that we meet with some difficulties.

Since the total salt content of sea waters is only 3·5% a very large volume of water must evaporate before a thin layer of salt could get deposited. The influx of sea water at any time cannot be very large and for the deposition of any moderate thickness of salt a very large number of periodical influxes must be postulated. Beds of rock-salt over 1,000 ft. thick are not at all uncommon and to account for these an undisturbed repetition of evaporation-influx process must be presumed to have continued for long geological periods.

In this connection it has to be pointed out that the bar which brought about separation of the bay from the sea is by itself a very evanescent physical feature and cannot survive for the long geological time necessary for the formation of thick salt beds. The undisturbed continuity of physical and climatic conditions, *e.g.*, absence of fresh water tributaries, dry warm climate, maintenance of bar level preventing the bay waters flowing seaword, etc., for long periods is also difficult to visualise.

In a deposit formed in the manner indicated above the proportion between the various saline constituents and particularly between sodium chloride and calcium sulphate in the sea water must be maintained at least roughly in the resultant precipitates.

This relation is rarely met with in the deposits.

Salt deposits are often found in very high latitudes which have temperate or even cold climates. In these regions evaporation must be an extremely slow process and cannot, by itself, account for the formation of thick salt beds.

Besides halite the salt deposits also contain a number of other minerals some of which are typical of high temperature paragenesis. Among these may be mentioned the Hartsalz[1] Paragenesis typically observed in the Carnellite zone of the Stassfurt salt deposit. The minimum temperature of the formation of this paragenesis[1] Sylvine, Kainite, Carnellite, Halite and Kieserite, is 72° C. or about 130° F. Very few regions on the earth's surface ever reach such high temperatures. No oceanic basins can ever attain this temperature except in the vicinity of active volcanoes. It is therefore very difficult to account for the formation of such deposits through simple surface evaporation of oceanic or even inland basins.

These are some of the points which make the Bar theory not wholly acceptable in accounting for the formation of large salt deposits.

Theories of Continental Deposition—Other Sedimentary Theories

The Bar Theory of Ochsenius was sharply criticised by J. Walther, E. Erdamann and others. Walther,[2] from the common occurrence of rock-salt and salt lakes in deserts, explained the salt formation by lixiviation of the saline contents of the sedimentary rocks and accumulation and evaporation of the resulting solutions in desert basins, where conditions are most favourable for rapid evaporation. The main difficulty with this theory is that there is not enough circulating or flowing water in these rainless deserts to bring about either rock decomposition or leaching of saline matter from surrounding rock formations which are generally very poor in salt content. The desert streams are therefore incapable of bringing about accumulation of salt sufficient to make the lakes highly saline unless salt occurs autochthonous in the drainage area of the lake.

I. C. Russel[3] advocated the Desiccation Theory according to which former inland lakes on extreme evaporation deposited considerable quantity of salt on their bed. According to him salt got absorbed by lacustrine clays during desiccation while the next monsoon brought fresh quantity of salt to the lake. This process was repeated and after a long period of concentration the lake waters became strongly saline and finally evaporated to dryness leaving a deposit of salt over the lake bed.

These Lixiviation and Desiccation Theories may account for a few small occurrences but are generally not applicable to larger deposits.

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[1] U. Grubenman and P. Niggli, *Die Gesteinsmetamorphose*, 1924, **46**, p. 142.

[2] J. Walther, *Das Gesetz der Wustenbildung*, Berlin, 1900.

[3] "Salt Resources of the United States," *U. S. Geol. Sur. Bull.*, 1919, No. 669.

Hypogene Origin of Rock-Salt

The fact that sodium chloride and hydrochloric acid are among the important constituents of volcanic emanations has led several geologists to assign a volcanic origin to salt beds. Some even hold that most of the saline contents of the sea are primarily of volcanic origin.

In a number of deposits salt occurs in the form of domes and plugs as in Persia,[4] Algeria, Tunisia, Andalucia, Pyrenees, Mexico, United States, etc., where salt is observed to show intrusive relations with the associated stratified formations. The salt in these 'intrusive' bodies does not show any bedding. The junction of the salt deposits with the adjoining rocks, instead of being sharp is very commonly irregular and brecciated, the fragments of associated rocks being often found enclosed within the salt deposit. This has led many investigators to assign an igneous origin to these deposits.

Middlemiss,[5] discussing the origin of salt marl in Salt Range, visualised it as a scum secreted at the surface of an ancient untapped magma which on intrusion or injection sometime during Tertiary Period consolidated as marl.

The most usual association of salt and gypsum which is commonly held as truly sedimentary could be equally of igneous origin since SO_2 which is a common volcanic exhalation would, on reaction with limestone, easily form gypsum. It is frequently seen that the two minerals occur in different proportions in different parts of the salt deposit and form irregular masses, quite unlike what one would expect from a normal precipitate formed through the simple process of evaporation.

There are again several other facts concerning association which are not easily explained on the basis of the evaporation theory but which would be normally expected on volcanic theory.

Among such evidences may be mentioned the very frequent association of volcanic rocks, ashes and tuffs as in the Carpathian mountains, United States, Persia, Salt Range, etc.

Sulphur and sulphurous gases as also the borates and nitrates are common products of volcanic activity. Their occurrence in salt beds lends a strong support to the view that volcanic activity had some significant part to play during the formation of these deposits.

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[4] J. V. Harrison, "Geology of Some Salt Plugs in Laristan," Q. *J. G. S.*, Vol. **86**, Pt. 4, pp. 463–552.

[5] *Rec. G. S. I.*, Vol. **24**, pt. 1, p. 42.

If however salt were only of igneous origin the occurrence of salt deposits should have been restricted to the immediate vicinity of igneous intrusions, a feature, which is comparatively less frequent. On the other hand the deposits are most commonly associated with such sedimentary rock formations where volcanic rather than intrusive igneous activity has played a definite but minor part.

It would then appear that salt deposits show some features which are characteristic of sedimentary deposition but they also show others which are peculiar to igneous origin. No one mode of formation can by itself explain all the characteristics of salt deposits and it would therefore be necessary to visualise a combined process where both sedimentation and igneous action play their respective roles.

Geological and Geographical Distribution of Rock-Salt Deposits

In order to arrive at a proper understanding of such a comprehensive process it may be helpful to study, in general, the geological and geographical distribution of rock-salt deposits of the world.

Rock-salt is known to be associated more or less with rocks of all ages right from Cambrian down to Recent. Cambrian age has been attributed to the salt deposits of the Punjab Salt Range, and of Persia. This age, however, has been seriously questioned.

Salt deposits are known from Upper Silurian formation (Onondago Salt Group) of New York State, Michigan and Ontario where they are associated with red marl and gypsum.

A Carboniferous age has been assigned to the salt deposits of Nova Scotia and Montana in United States and to those of Kimberley District of Western Australia.

Permo-Trias is the period of intense salt formation and some of the largest rock-salt deposits are found associated with formations of this age in Central Germany, Russia, southern Scotland and the eastern and central parts of the United States (Fig. 1). More than half of the world's annual output of rock-salt comes from these deposits. It may be remarked here that the region extending from eastern United States on the west to the Urals on the east forms a zone of Hercynian mountain activity and that the salt beds in this zone appear to be intimately connected with this late Palæozoic orogenesis.

Leaving the Westphalian rock-salt deposits of Germany which are associated with upper Jurassic (Purbeck) limestones, the next important period of salt formation is the Tertiary when rock-salt got extensively

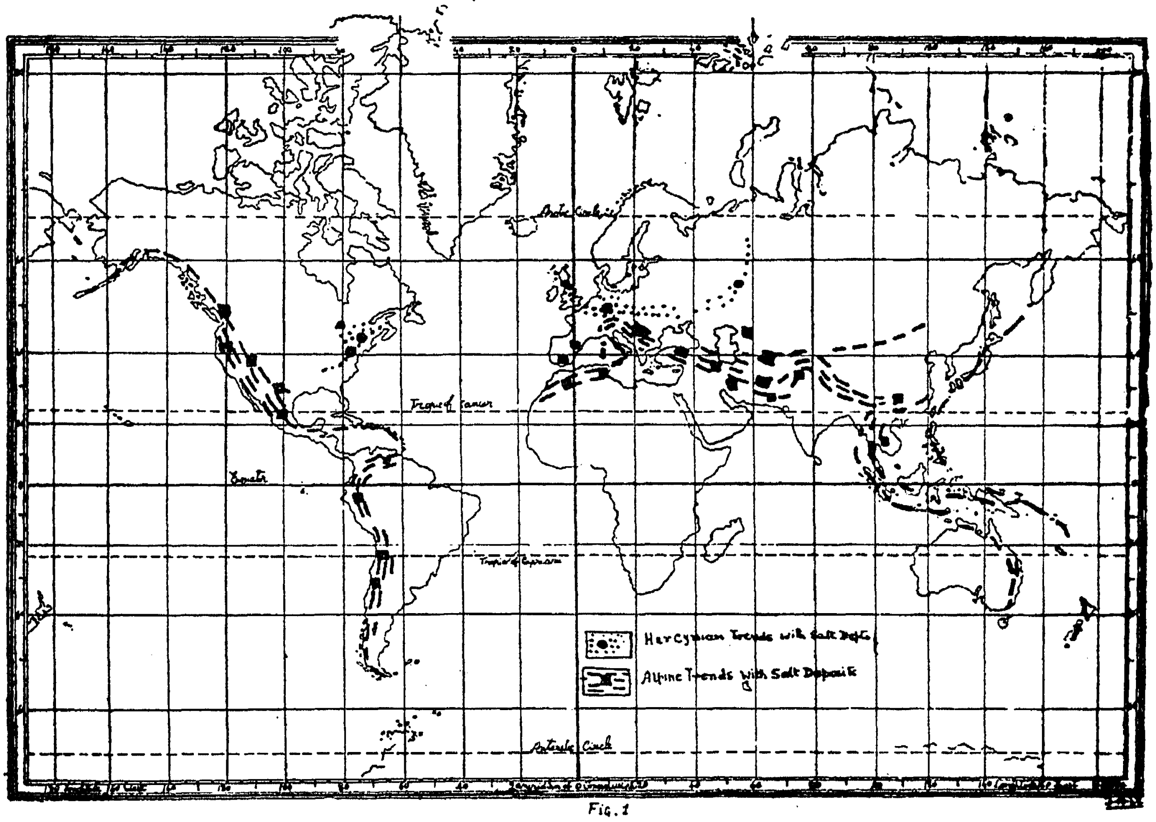

Fig. 1

deposited all along the western sea board of the Americas from Br. Columbia in the north to Chile in the south and also along the Atlas ranges, Spanish Meseta, the Carpathian and the Caucasus ranges, the Aral-Caspian depression, Turkish and Persian ranges extending up to the Punjab Himalayas. Tertiary rock-salt also occurs in parts of China and Thailand.

From this distribution it is quite obvious that the Tertiary rock-salt has closely followed the trends of the Tertiary orogenesis represented by the Andean and the Alpine-Himalayan mountain systems (Fig. 1). In several regions these salt formations have been intricately involved in the mountain folding while they are also seen at places to be intimately associated with eruptive sheets.

In post-Tertiary period there are no indications of extensive rock-salt formation; the few stray deposits found associated with saline lakes in the present desertic regions, *e.g.*, Sambhar lake in Rajputana, India, appear to the author to be formed largely through solution and reprecipitation of Tertiary or older salt deposits found *in situ* in these deserts.

From this review it would be seen that the rock-salt formation is closely related, both in geological time and geographical distribution, to the orogenic upheavals particularly of the Hercynian and the Alpine movements, both of which are accompanied by extensive volcanic action.

Theory of Submarine Igenous Activity

The Theory of Salt Formation suggested here is based on the apprecia- tion of the fact that a preponderant number of Tertiary salt deposits of the world are confined to a narrow belt running parallel to, and closely following on either side, the Alpine-Himalayan and the Andean chain of mountains. These salt deposits represent nearly the last marine sediments (precipitates) deposited in the Tethyan seas. These salt beds have further been involved in the complex orogenic folding which the region has undergone. There is therefore a possibility that the salt formation particularly of the Tertiary period marks a closing event in the depositional history of this Mesozoic geosyncline.

It may be presumed here that for millions of years during the geosyn- clinal phase the Tethys was continually receiving sediments and saline con- stituents from the continental regions (Fig. 2*a*). The suspended and the

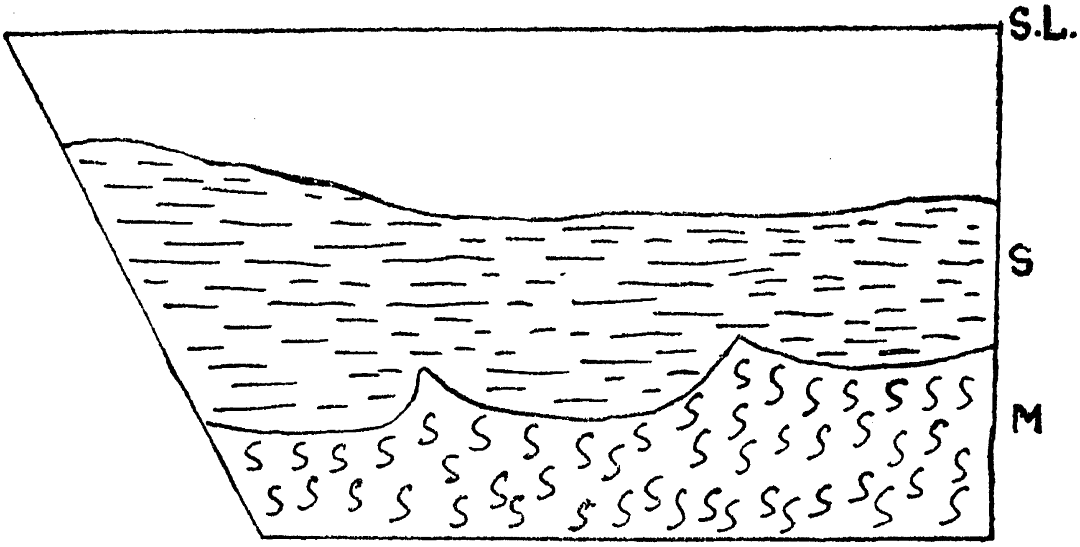

FIG. 2*a*. Geosynclinal Phase
M., Metamorphic basement ; *S.*, Continuous Deposition of Sediments

less soluble materials got deposited, but the more soluble ones like sodium chloride remained behind in solution. The sea water was thus constantly, though inappreciably, getting richer in certain dissolved salts.

Towards the close of the marine period when due to orogenic movements the sea floor with its thick series of sediments got heaved up and thrown into folded wrinkles (Fig. 2*b*) the Tethys Sea was diminishing in depth and extent and at certain periods accommodated itself in detached longitudinal synclinal basins (Fig. 2*c*). It is these basins which appear to have served as sites for the formation of large Tertiary salt deposits.

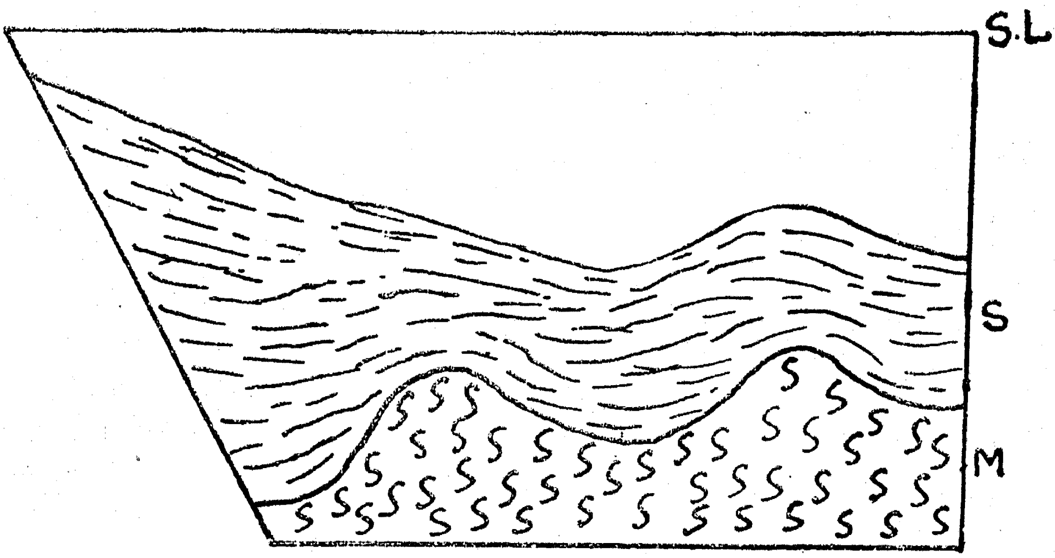

FIG. 2*b*. Embyronic Orogen
Gentle folding in bedded deposits

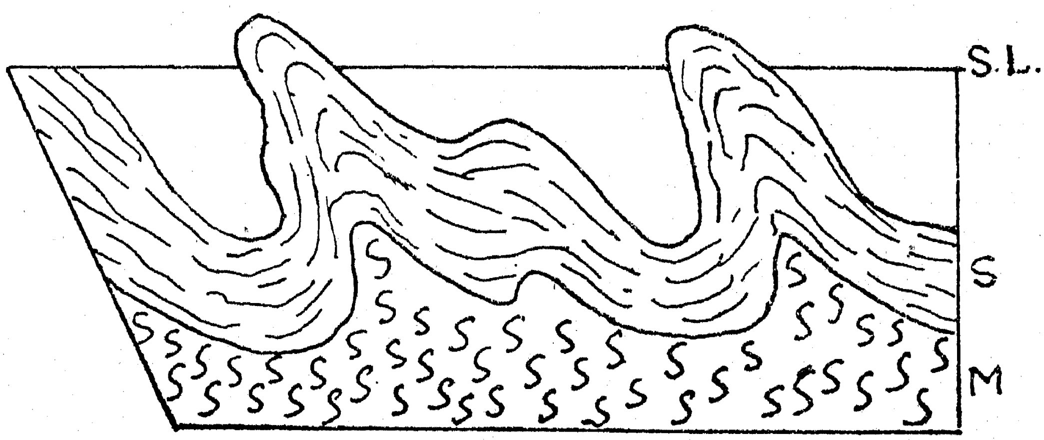

FIG. 2*c*. Mid-Orogen
Intense folding and upheaval ; shallowing and partitioning of the Geosynclinal sea into separate longitudinal basins

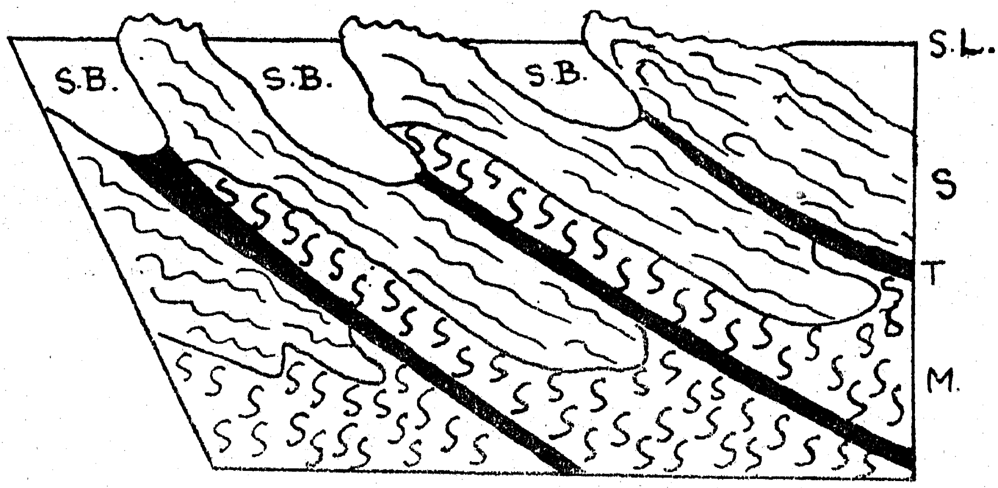

FIG. 2*d*. Mid-Orogen, Eruptive Phase
SB., Sea Basins ; *T.*, Thrusts. Further compression and development of deep-seated ırusts. Ascent of the magma along Thrusts. Submarine Vulcanism

The view advocated here is that though some of these shallow longitudinal seas on drying up may have left sheets of rock-salt, most of these however were by themselves not sufficiently rich or concentrated to give rise to large salt deposits. During certain phases of the orogenesis, however, further compression of the belt led to the development of longitudinal thrust planes some of which extended in depth right to the magma-zone itself (Fig. 2*d*). As a result of intense crustal compression and aided possibly by radio-activity the magma-zone at the base of the geosynclinal belt became heated and mobile and got involved in the general folding of the region. The thrust planes served as easy channels of escape and an eruptive activity ensued giving rise to thick dikes and sills and extensive trap formations. Every orogenic zone is replete with such magmatic manifestation nicely illustrated by the ophiolites of the Pennine Alps and by the extensive Tertiary and post-Tertiary volcanic activity in the Circumpacific mountain ranges. It is quite possible that certain deep synclinal basins occupied by the sea had become seats of such fissure eruptions wherein most of the magmatic gases and vapours got absorbed in the sea water. This accession of magmatic emanations to the salts already existing must have violently disturbed the chemical equilibrium of the sea water, whereas the heat of eruption must have raised the temperature of the sea water abnormally high leading to rapid evaporation and even to boiling. This led to the copious precipitation of particularly those salts which were being added from volcanic vents.

Volcanic exhalations include a large number of gases which are given out at different periods according to the phases of the volcanic activity.[6] During the earlier-acid fumarole-phases, sodium chloride and hydrochloric acid are the chief components which are given out abundantly. These are followed by sulphurous acid and at still lower temperatures by hydrogen sulphide when native sulphur gets crystallised. During the later-alkaline fumarole-phases ammonium chloride is the main constituent while carbon dioxide represents nearly the last phase of igneous activity.

In the case of submarine volcanic activity such as we are visualising here the various exhalations are being absorbed by the sea water at different times, and in accordance with the well-known Common-Ion effect, the first salts to get deposited from the sea water are those whose common constituents are being added to the solutions by the magma. Thus during the period when, for instance, volcanic hydrochloric acid is being added to the sea water rock-salt would get precipitated in preference to the less soluble ones

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[6] Clarke, F. W., *Data of Geochemistry*, 1924, p. 266.

like calcium sulphate. This principle is actually being commercially utilised in the patented Margueritte process[7] of manufacturing pure common salt from sea water. In the succeeding phases of igneous activity addition of SO_2 or H_2SO_4 would lead to the precipitation of anhydrite (or gypsum) whereas H_2S would deposit sulphur.

In this manner large quantities of different salts would get precipitated from the sea water at different periods and in proportions which are in no way related to the original composition of the sea water.

Under the simple evaporation process as visualised by Ochsenius and others the variation range of temperature is comparatively small allowing only a small number of minerals to be formed under this restricted range.

Under the present theory, however, the sea water would receive heat as well as saline constituents of magmatic origin in a large measure. The sea water would therefore show a much wider range of variation in temperature concentration conditions. This would facilitate crystallisation of a large number of minerals with widely different degrees of solubility and temperatures of crystallization.

A study of minerals actually found in salt deposits shows that besides rock-salt and gypsum a large number of minerals, simple as well as complex, are found which are either hydrous or anhydrous, chlorides, sulphates and often borates and nitrates of sodium, potassium, calcium and magnesium. They show widely vaiying degrees of solubility at different temperatures in simple or mixed solutions. It is, therefore; clear that these minerals will find their appropriate conditions of precipitation much better realised under submarine volcanic conditious than under atmospheric conditions prevailing in shallow evaporating basins.

Salt deposits are very commonly associated with effusive rocks rich in alkalies like the rhyolites, ceratophyres, phonolites, etc. It is therefore possible that the volcanic emanations, liquid as well as gaseous, would bring about extensive chemical alterations of these alkaline lava flows and sediments and thereby release abundant materials which would ultimately go into the composition of and add to the quantity of the salts thus formed in the sea. This metasomatic alteration may be so intense that the original identity of the rock may be completely lost. Salt marl which is so constantly seen associated with rock-salt, may owe its peculiar nature to this alteration process.

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[7] Thorpe, *Dictionary of Applied Chemistry*, Vol. VI, p. 202.

Structural Relations of Rock-Salt

During the later phases of orogenic activity the whole region would suffer further compression, bringing about intense folding and over-thrusting in the component rock formations.

Nappe structures may be developed in a larger or smaller scale in which some of the salt beds thus entrapped might serve as gliding planes (Fig. 3).

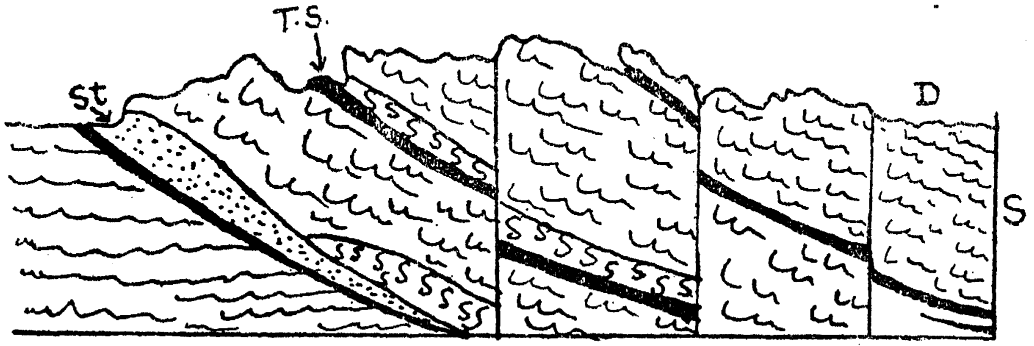

FIG. 3. Post-Orogenic Subsidences
Salt Deposits associated with thrusts, and deserts. *St.*, Salt Deposit; *Ts.*, Trap sheet; *D.*, Desert.

The salt masses would be pressed forward while the overlying rocks would simply slide *en mass* over the smooth gliding planes. Rock-salt on the other hand, would get squeezed out into huge masses in the frontal portions of the thrusted strata.

In this manner translation of rock-salt and of the overlying rocks may be effected for varying distances from their original places of deposition.

The existing field relations of salt and the associated strata in any folded region would thus get highly complicated and would in no way be related to their original stratigraphic sequence.

Field Distribution of Salt Deposits

On the basis of this tectonic theory of rock-salt formation as outlined above it is quite easy to explain the more or less restricted development of salt deposits within the belt of orogenic activity. It is also conceivable that rock-salt may have developed extensively all along this mountain belt. However, when we study the actual field distribution it is seen that the deposits are found not quite within the region of high mountains but only along the low lying flanks of the ranges.

This is naturally to be expected since owing to the excessive erosion taking place in the mountain regions all the salt which may have been formed in those parts would get easily washed off. On the other hand at the flanks of the mountain ranges the areas are undergoing frequent subsidences through block faulting as a result of post-tectonic (Insubrian) readjustments. There are therefore much better chances of preservation of salt deposits in these low-lying sub-mountain tracts.

Rock-Salt in Deserts

Rock-salt is found extensively distributed in deserts and this fact had led Walther and others to postulate the formation of rock-salt as a consequence of the extremely favourable conditions of evaporation obtaining in these regions.

It is worth noting in this connection that nearly all the important deserts are situated not far away from the hill ranges in a belt more or less parallel to the Tertiary mountain belt. This is the region which, most likely, has suffered extensive subsidences as a result of the post-tectonic block faulting.

If this is true it is obvious that the desert formation is consequent on the subsidences of those regions. It is not difficult to follow the steps which culminated in the formation of these deserts. We can quite visualise that as a result of subsidence the rivers of the area would turn into inland drainage system giving rise to numerous lakes, a process which is observable in actual progress in some parts of Tibet.

At some stage the underground waters tapped some rock-salt deposits occurring at some depth below the subsoil and as increasing quantities of salt began to go in solution the subsoil waters became more and more saline. This immensely affected the growth of vegetation and desertic conditions set in. The passing over of monsoon winds without precipitation in these barren subsiding tracts accelerated the process and we now see a full-fledged desert topography developed in areas which even in historic times were luxuriant and productive.

From this it is now easy to explain the common occurrence of salt in deserts where salt, as a primary deposit, has largely brought about the formation of desert and not *vice versa* as has been commonly believed so far.

Merits of this Theory

This theory of rock-salt formation explains satisfactorily the following features which are commonly observed in salt deposits:—

1. Sedimentary characters like bedding, association with normal stratified rocks, occurrence of normal saline precipitates in salt deposits.

2. Characters peculiar to igneous origin like intrusive and corroded contacts with associated rocks, frequent association with traps and other

igneous rocks, occurrence of free sulphur, sulphurous gases, boric salts, nitrates, etc.

3. The frequent complicated folding and over-thrusting undergone by salt and associated rock beds, whereby they often show anomalous stratigraphic sequences.

4. The extraordinary development of these deposits in certain geological periods like the Permian and the Tertiary which are also the closing period of major Orogeneses.

5. The geographical distribution of rock-salt deposits along definite belts irrespective of latitudes or climatic zones.

6. The parallelism of the salt belt with the belt of the major tectonic mountains, which is also the belt of intense eruptive activity during that orogenic period.

7. The common occurrence of rock-salt and saline lakes in deserts flanking the Tertiary mountain ranges.

Summary and Conclusion

From the foregoing treatment it is clear that though some salt deposits may possibly have been formed by simple precipitation in sea or lake waters, brought about by evaporation, lixiviation or by desiccation process, the formation of most of the principal salt deposits of the world is brought about by intra-tectonic submarine igneous activity in geosynclinal basins.

This theory satisfactorily accounts for the various characteristics—chemical, structural, associational and distributional shown by most rock-salt deposits.

If we now extend the scope of this theory, we can also apply it to the formation of certain other saline residues particularly the Borate and the Nitrate deposits, such as those of Chile, which show many characteristics in common with rock-salt.

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