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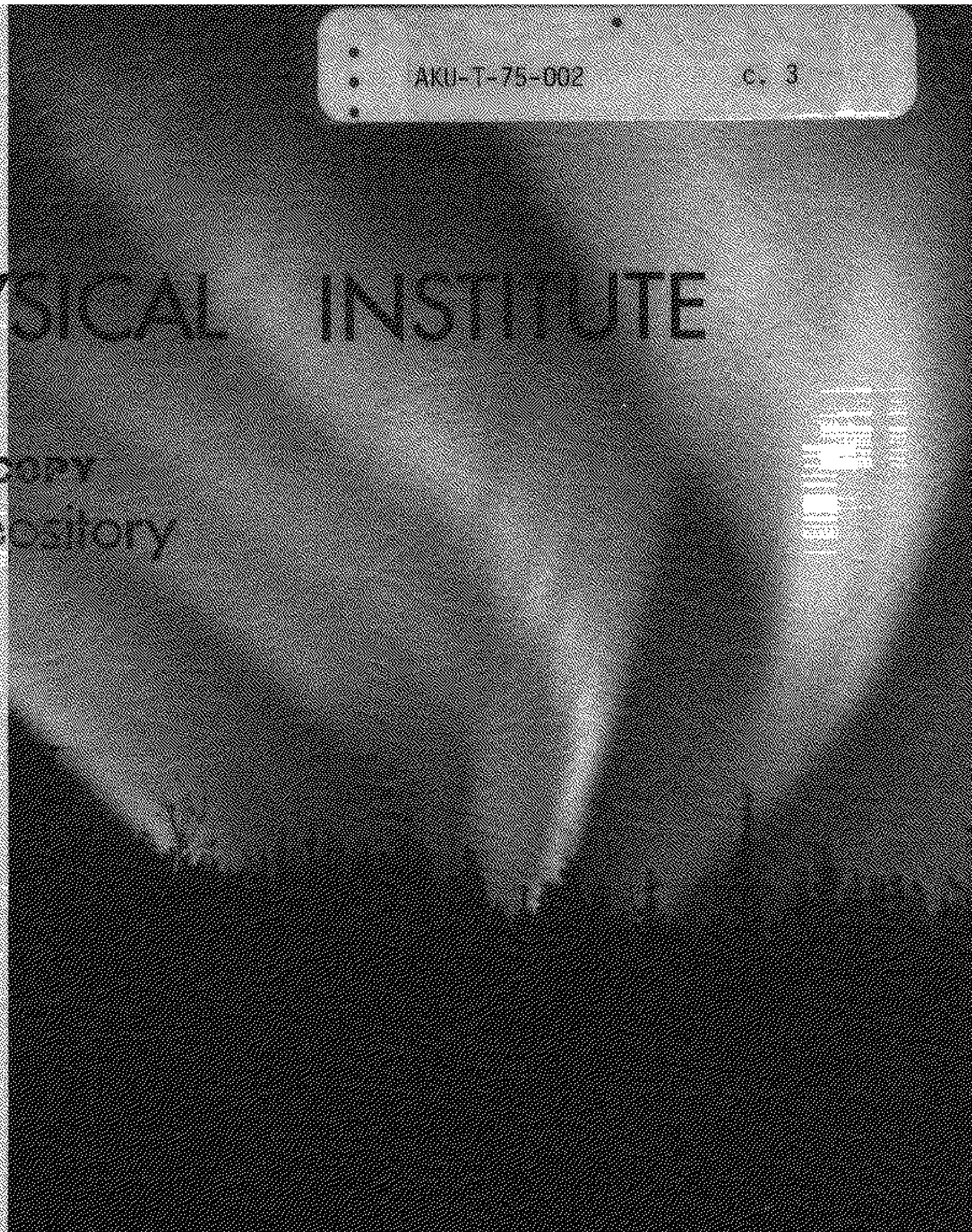

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UAG R-234

A CONCEPTUAL MODEL OF OFFSHORE PERMAFROST

by

T. E. Osterkamp

SCIENTIFIC REPORT

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Sea Grant Report No. 75-3

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Report Approved By

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SUMMARY

The coastal erosion process has been examined for the northern Alaskan coast for the purpose of developing a conceptual model of offshore permafrost. A series of as many as five stages of coastal erosion, which are characterized by different thermal and chemical boundary conditions, are necessary to describe the physical setting of the offshore permafrost. The seasonal variations of the thermal and chemical boundary conditions are discussed and it is suggested that these varying boundary conditions can be incorporated into a model of offshore permafrost consisting of the generalized transport equations from non-equilibrium thermodynamics, by successive application of the transport equations to the five stages experienced by a vertical soil profile during the erosion process.

INTRODUCTION

Evidence has been accumulating that shows conclusively the presence of offshore permafrost (sometimes referred to as sub-sea permafrost) off the coasts of Canada, Alaska and Siberia (see the recent review by NAS Working Group on Offshore Permafrost). Offshore permafrost is potentially a greater problem for resource development than onshore permafrost due to its expected higher temperature and its state of bondedness (the presence of interstitial salt water can result in permafrost that contains ice crystals but is not ice bonded). The expected higher temperature of the offshore permafrost makes it more sensitive to thermal disturbances and its state of bondedness determines its suitability as a foundation for structures used in resource development. Due to the recent proposals to lease the Outer Continental Shelf (OCS) areas in Alaska, it has become imperative to determine the extent of offshore permafrost and its physical and mechanical properties. To do this, laboratory and field research and modeling programs have been initiated. The purpose of this report is to derive a conceptual model of offshore permafrost and to examine its implications for future laboratory and field research and modeling efforts.

PHYSICAL SETTING

Alaska's shelf area in the southern Beaufort Sea from Point Barrow to Demarcation Point is extremely shallow, dotted with barrier islands and in some places has a rapidly receding shoreline. The shallow nature of the shelf area is demonstrated by the fact that the 5 m depth contour extends up to 15 km from the coast and includes all the major bays and waters inshore of the barrier islands. This is an important point, since it is the shallow water areas that are most likely to be underlain by offshore permafrost. These shallow water areas are also the most complicated due to large areas of ice frozen to the bottom in the winter, restricted circulation under the ice, warm water in the summer and their recent submergence.

The specific physical model to be used for the offshore permafrost depends largely on how we envision the ocean transgressing on the land. For areas where the shoreline recession is very fast (several m per year) or as a limiting case, the situation in Figure 1 can be considered. It should be relatively easy to develop a mathematical model for this situation and it is important to do so since this represents the limiting case. Another special case is the situation when the ocean breaks through to a fresh water lake as shown in Figure 2. Eventually, further erosion of the outlet and flushing processes change the lake into a salt water inlet or bay. The mathematical model for this situation would be similar to the one developed for the limiting case shown in Figure 1, assuming the lake was large enough to neglect edge effects but more complex due to the thaw bulb under the lake. It may be more realistic to consider the coastal erosion process in more detail as shown in Figure 3. The five stages shown in Figure 3 were chosen such that each stage represents different thermal and chemical boundary conditions for the underlying permafrost. This physical setting will now be extended and considered in more detail.

The model for the physical setting proposed in Figure 3 is time dependent with respect to a fixed point since a given vertical soil profile on land will be subjected to each stage successively because of the process of coastal erosion. It is necessary to consider onshore permafrost (stage 1) since it forms the initial condition for any model of offshore permafrost. Lachenbruch and others (see Gold and Lachenbruch, 1973) have shown that simple thermal conduction models can be used to describe the gross aspects of the thermal regime of permafrost at high latitudes. However, coupled mass and energy transport models will be necessary to understand the transport processes in the upper meter or so of soil, particularly the active layer (Guymon and Luthin, 1974)). The implications are that thermal conduction models can be used to describe the energy transfer in the offshore permafrost below the bonded permafrost table but that coupled mass and energy transport models will be necessary above the bonded permafrost table. In coastal regions, additional complications may result from the lateral infiltration and diffusion of brines under the land (Sellman and Brown, 1965) and the presence of large lakes near the coast and rivers that empty into the ocean.

Stage 2 is the beach but may also be similar to low lying land masses (e.g., points, spits, barrier islands). While salt water does not normally exist over the beach, waves, high tides and vertical and lateral infiltration and diffusion may cause significant salt concentrations in the upper regions of the soil. This salt may infiltrate the lower permafrost changing its state from ice bonded to unbonded permafrost. Because of this salt water infiltration, the active layer on the beach may be expected to differ in thickness and nature from that on land. Therefore, while the beach is subjected to the same thermal boundary conditions as onshore permafrost the chemical boundary conditions imposed by salt water infiltration are different.

In some cases, the beach will be narrow (a few m in width) with very little effect on the underlying permafrost so that stage 2 can be ignored or treated as part of stage 3. However, when the beach is wide (and also for wide, low offshore islands) stage 2 will have to be treated separately.

Stage 3 involves the area out to ∿ 2 m water depth where the ice freezes to the bottom during part of the year. As a result, this area becomes conductively coupled to the atmosphere during winter and, in the summer, it is overlain with shallow, relatively warm sea water. This setting creates a different set of thermal boundary conditions. The chemical boundary conditions are also different due to salt rejection from the ice during its growth and the restricted circulation under the growing ice in the shallow water which creates highly saline water under the ice. When the ice freezes into the bottom this highly saline water may be forced into the sediments drastically changing the chemical boundary conditions. This could produce a salt wave, with a period of 1 year, propagating into the soil. Brine drainage from the ice during the thaw season can also produce a layer of concentrated brine at the ice-soil interface. Obviously, coupled mass (salt and water) and energy models will be necessary to describe the transport processes in the soil above the bonded permafrost table in this stage.

Stage 4 includes the areas where the ice does not freeze to the bottom in the winter, but where restricted circulation still causes highly saline water between the bottom of the ice and the soil in winter and spring. In the summer, these areas are covered by normal sea water due to the mixing action of waves and surface currents. The existence of this stage depends on the flushing processes under the ice and where strong currents or steep bottom slopes are present, it may be small in extent or non-existent. The reason for including it as a separate stage in the development of offshore permafrost is that during part of the year (late spring) it is buffered from the atmosphere by a concentrated brine layer unlike stage 3 which is conductively coupled to the atmosphere at this time. This will lead to different thermal boundary conditions and, since there is a greater volume of water under the ice to absorb the salt rejected from the ice (resulting in a lower salt concentration in the water under the ice), to different chemical boundary conditions when compared to the other stages of development.

Stage 5 is the area where there is normal sea water over the soil all the year. This will cause nearly constant thermal and chemical boundary conditions at the soil surface which are fairly well defined (Lewellyn, 1972). It is probable that somewhere in this area the bonded permafrost disappears although, if salt infiltration is very fast because of special soil conditions, the bonded permafrost may disappear in stage 4 or even stage 3.

The above discussion of the physical setting has not incorporated several factors which include the effects of the geological setting, sedimentation processes and ocean currents. In addition, degradation of the permafrost from below due to the changed boundary conditions and the geothermal heat transfer to the bottom of the permafrost has not been discussed. These are important factors which must be included in any model of offshore permafrost.

TRANSPORT PROCESSES

Frozen ground and permafrost allow salt and water transport, especially at temperatures near 0°C (say -5°C to 0°C). The physical mechanism for this salt and water transport involves the unfrozen water film adsorbed on the soil particles and ice crystals (Hoekstra and Chamberlain, 1964). In addition, some vapor transport may occur in unsaturated soil pores and Osterkamp (1975) has shown that ice lenses near their melting point contain liquid 3 grain boundaries which may make them permeable to water. When potential gradients (osmotic, matric, pressure, temperature and electrical) are impressed on a frozen soil the unfrozen water film (and, in some cases, the water vapor) responds and is set in motion. Since the unfrozen film may contain soluble salts it is apparent that the salt will also move through the soil with water. In addition, the salts may also move by diffusion along concentration gradients and thermal gradients. It is important to recognize from this physical discussion that, in the active layer and unbonded permafrost, the fluxes of mass (salt and water) and energy (heat) are all coupled so that it is necessary to use coupled mass and energy transport models to describe the transport processes in the active layer and unbonded permafrost.

In some cases, determined by the soil type and ice content of the permafrost, gross infiltration of sea water into very porous permafrost may be a factor in changing bonded permafrost to unbonded permafrost. Permafrost with low ice content and consisting of unsaturated coarse gravel may be an example of this situation.

SOME APPLICABLE THEORIES

Consideration of the physical setting proposed in Figure 3 and the above transport processes suggests that the bonded permafrost can be treated with a heat conduction model but that it will be necessary to use coupled mass and energy transport models for the active layer and unbonded permafrost. The heat conduction models are well established (Gold and Lachenbruch, 1973) and will not be discussed. Coupled mass and energy models do not appear to have been applied to unbonded permafrost although much effort has been devoted to the problem in unfrozen soils (see Taylor and Cary, 1964; Philip and DeVries, 1957). In addition, Hoekstra and Chamberlain (1964) and Cary and Mayland (1972) have performed laboratory experiments on salt and water movement in frozen soils.

The most general approach which appears to be applicable to mass and energy transport in unbonded permafrost is based on the general transport equations developed from non-equilibrium thermodynamics by Taylor and Cary (1964). Their flux equations are

$$J_i = \sum_{k=1}^{n} L_{ik}\left[F_k - T\frac{d}{dz}\left(\frac{\mu_k}{T}\right)\right] - L_{iu}\frac{d}{dz}(\ln T) \qquad (1)$$

and

$$J_u = \sum_{k=1}^{n} L_{uk}\left[F_k - T\frac{d}{dz}\left(\frac{\mu_k}{T}\right)\right] - L_{uu}\frac{d}{dz}(\ln T) \qquad (2)$$

where J_i is the flux of the i^{th} component in the soil (e.g., salt or water), J_u is the energy flux, L_{ik} are the Onsager coefficients, F_k is any external force acting on the k^{th} component, μ_k is the chemical potential of the k^{th} component, and T is the temperature. Equations (1) and (2) are coupled through the F_k and in a multicomponent system any given flux will depend on the F_k and on the fluxes of all other components. These equations reduce to the usual flow laws (Fourier's Law and Darcy's Law) when only temperature gradients or hydraulic gradients are present in the soil.

Equations (1) and (2) may be used for steady state transport or for predicting instantaneous flow across a cross-section in a transient system. In a transient system, the equations may be combined with the equation of continuity to obtain a set of coupled, time-dependent, second order equations of motion. These equations of motion will be the generalized equations governing the mass and energy transport in the coupled transient case. Fick's second law and the transient heat flow equation are special cases of the generalized equations.

Cary and Mayland (1972) have applied Equations (1) and (2) to the special case of the flow of soil water solution and salt in unsaturated, frozen soils. Since Equations (1) and (2) have not been applied to unbonded permafrost, their specific forms need to be evaluated for the components, driving forces and saturation conditions present in unbonded permafrost. Also, present data on unbonded offshore permafrost are not complete enough to apply the equations to it.

The special case of unbonded permafrost with low ice content and coarse gravels may be treated using infiltration theories (Baver et al., 1972) developed for unfrozen soils since the effect of a small amount of ice in the pores would be to reduce the pore space. However, a complicating factor will be the possible phase change when the salts contact the relatively fresh ice in the permafrost.

The problem of defining the motion of the bonded-unbonded permafrost boundary after the sea water encroaches on the land has not yet been solved. This appears to be a Stefan-type problem and some initial attempts at solving it have been made (Rogers et al., 1975) and it will not be further addressed here.

This preliminary consideration of the theories suggests some measurements that should be made in the field and/or laboratory. The thermal and chemical boundary conditions must be known to solve any equations describing the heat, salt and water transport. In addition, it will be necessary to know (Cary and Mayland, 1972) the hydraulic conductivity and thermal conductivity at given water contents, and handbook information on the soil exchange reactions and salt solubilities.

DEVELOPING A MODEL

It should be recognized that the problems of coupled mass and energy transport in freezing and frozen soils and permafrost are extremely complex and satisfactory solutions will require the combined efforts of numerous investigators over a period of many years. The purpose of this section is to suggest one method of attacking the problem in the case of offshore permafrost based on the physical setting suggested in Figure 3 and using the generalized equations developed from non-equilibrium thermodynamics.

Figure 3 suggests there are, in principle, at least 3 distinct soil regimes in which the transport problems must be solved, the active layer, unbonded permafrost and bonded permafrost. Pure conduction models appear to be sufficient for the bonded permafrost leaving the first 2 regimes. In the case of stage 3 the active layer may be expected to freeze in the usual sense but in the case of stages 4 and 5 it may be somewhat different from what is usually envisioned (i.e., the sea bottom in much of these shallow water areas may be expected to be warmer than 0°C in later summer and colder than 0°C in winter, but not necessarily ice bonded). In fact, if the sea bottom temperature in winter is > -1.8°C the soil on the bottom may not even contain ice.

Time dependent boundary conditions which occur over several time scales will be important in developing the model. While daily variations in the thermal and chemical boundary conditions can probably be ignored, it will be necessary to take the seasonal changes into consideration. Figures 4-8 are each of the stages shown in Figure 3, illustrating the expected seasonal variations. In addition to the seasonal variations, there will be long-term changes in the boundary conditions due to the fact that as coastal erosion proceeds past a particular soil profile, that profile will be successively subjected to the boundary conditions of each stage. Therefore, each stage may be expected to contain a certain "memory" of its previous stages which must be considered in the model.

These memory effects, due to the differing thermal and chemical boundary conditions of each stage shown in Figure 3, can be readily incorporated into a model. When the transport equations (Equations 1 and 2 in a form applicable to offshore permafrost), thermal and chemical boundary conditions and the necessary soil properties have been determined a fairly detailed model of offshore permafrost may then be developed. The procedure would be to start with stage 1 in the time frame $0 < t < t_1$ and to solve the transport equations for an appropriate set of boundary conditions and soil properties (determined by meteorological data and a shallow drilling and sampling program). This solution would be the thermal and chemical condition of the soil in a vertical profile and would also constitute the initial conditions for stage 2. The next step would be to consider stage 2 in the time frame $t_1 < t < t_2$ and to solve the transport equations for the initial conditions (determined by the solution for stage 1) and the appropriate boundary conditions and soil properties (again determined by meteorological data and a shallow drilling and sampling program). Continuing in this way, in principle, it should be possible to determine the thermal and chemical condition of a vertical soil profile as it is successively subjected to each stage in Figure 3.

A procedure of this type includes many assumptions which may invalidate the final results or make it impossible to obtain results. For example, the length of time to which the vertical soil profile is subjected in each stage may not be obtainable, the thermal and chemical boundary conditions determined for each stage may have been different at an earlier time due to unknown climatic changes, the unknown sedimentation processes and ocean currents may be major factors in determining the thermal and chemical boundary conditions, and the geological setting and soil types in some areas may require the use of empirical infiltration equations rather than Equations (1) and (2). In addition, it may not be possible to solve the coupled transport equations in reasonable time periods even with the use of large computers. These factors indicate that it may be more realistic to attempt to solve relatively simple problems (e.g., limiting cases, degradation of the permafrost from below, pure diffusion of salt into the permafrost, etc.) in place of attempting a full solution of the coupled mass and energy transport problem in offshore permafrost.

ACKNOWLEDGMENTS

I wish to acknowledge numerous discussions with L. H. Shapiro, J. C. Rogers and W. D. Harrison on the problems of offshore permafrost. This publication is the result of research sponsored by NOAA, Office of Sea Grant, Department of Commerce, under grant number 40-3-158-41 and by the Alaska Oil and Gas Association.

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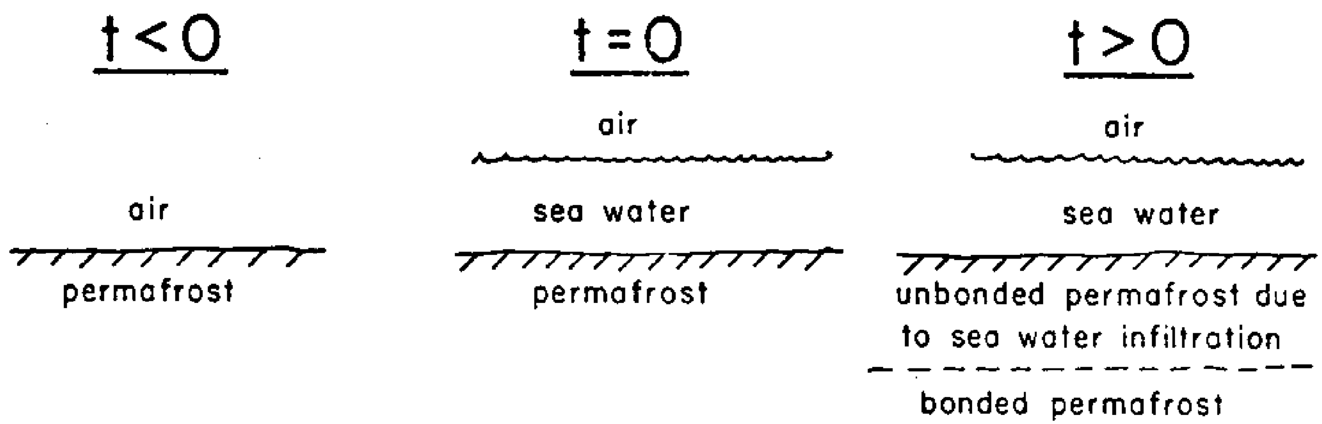

FIGURE 1. A model to be used of offshore permafrost in areas where shoreline recession is very fast (several m per year) or as a limiting case for calculational pu-poses.

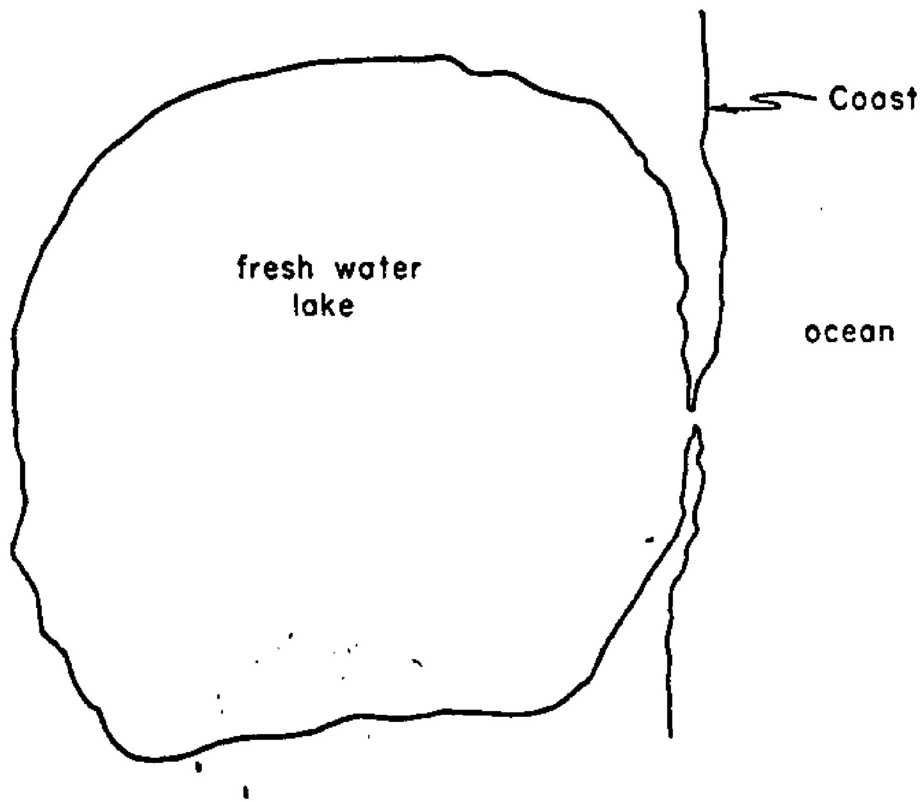

FIGURE 2. The case where the ocean breaks through to a fresh water lake.

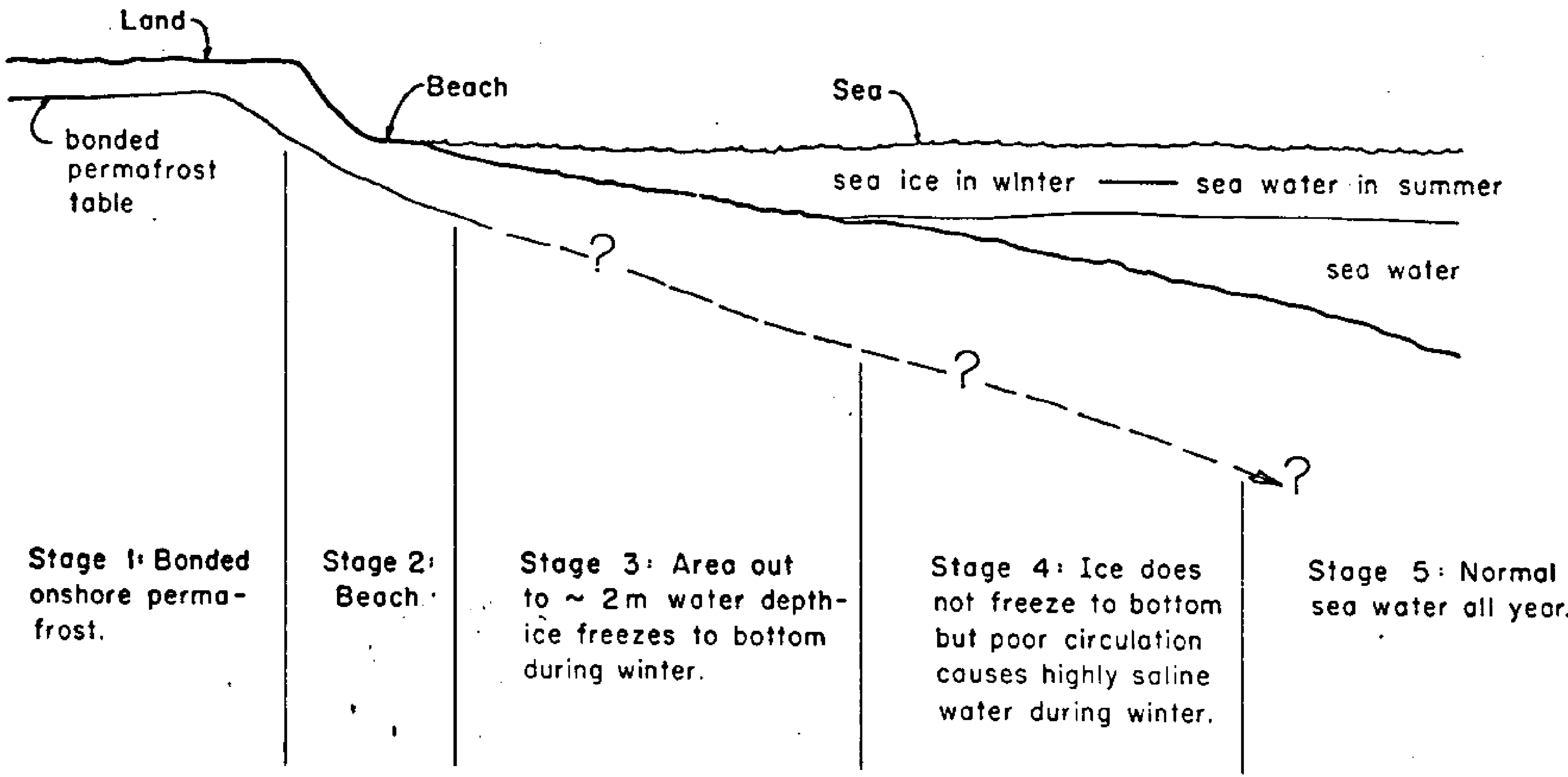

FIGURE 3. Coastal erosion model of offshore permafrost. The system is time dependent and moves to the left by erosion of the coastline.

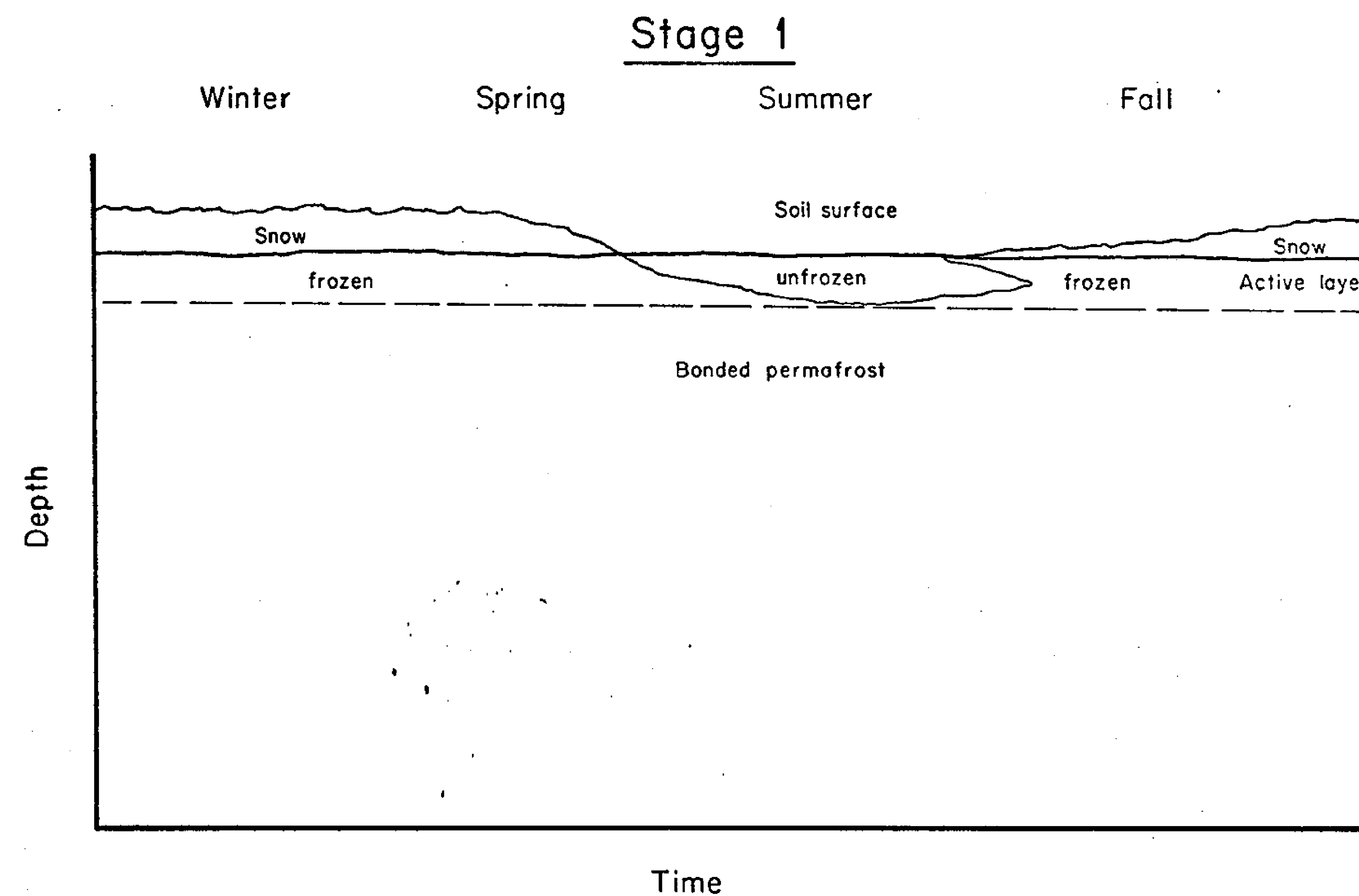

FIGURE 4. Seasonal variations in stage 1.

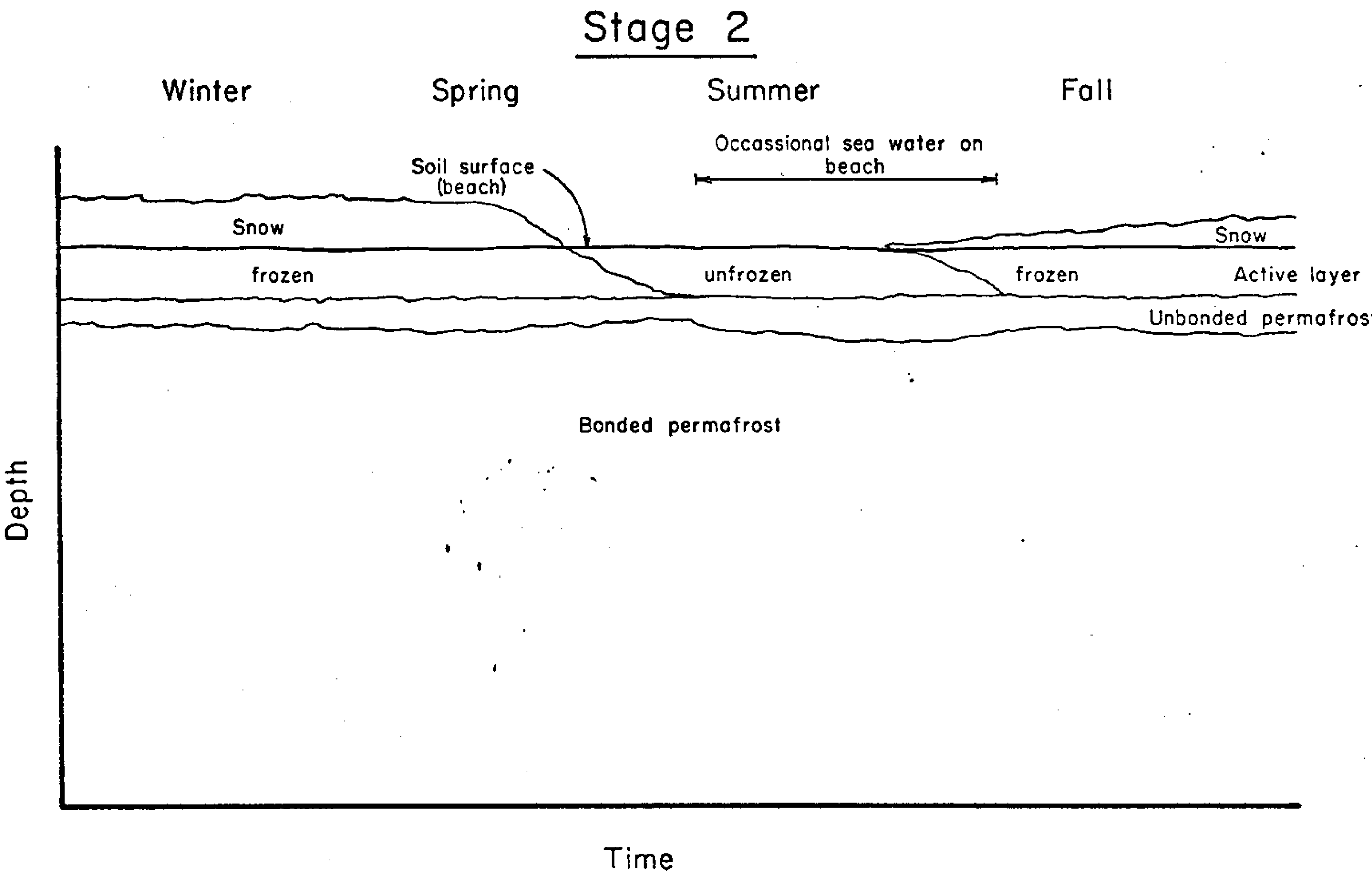

FIGURE 5. Seasonal variations in stage 2.

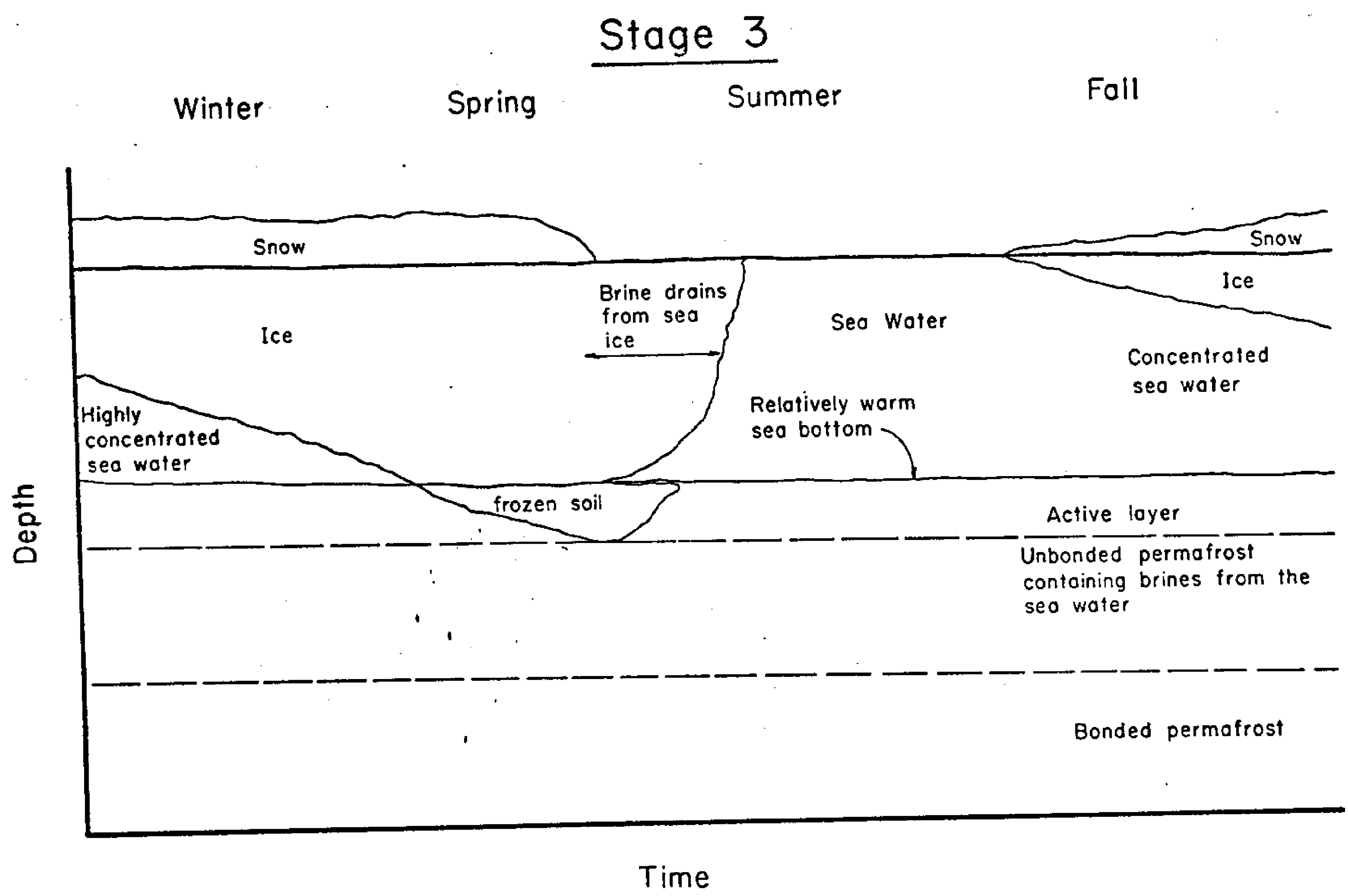

FIGURE 6. Seasonal variations in stage 3.

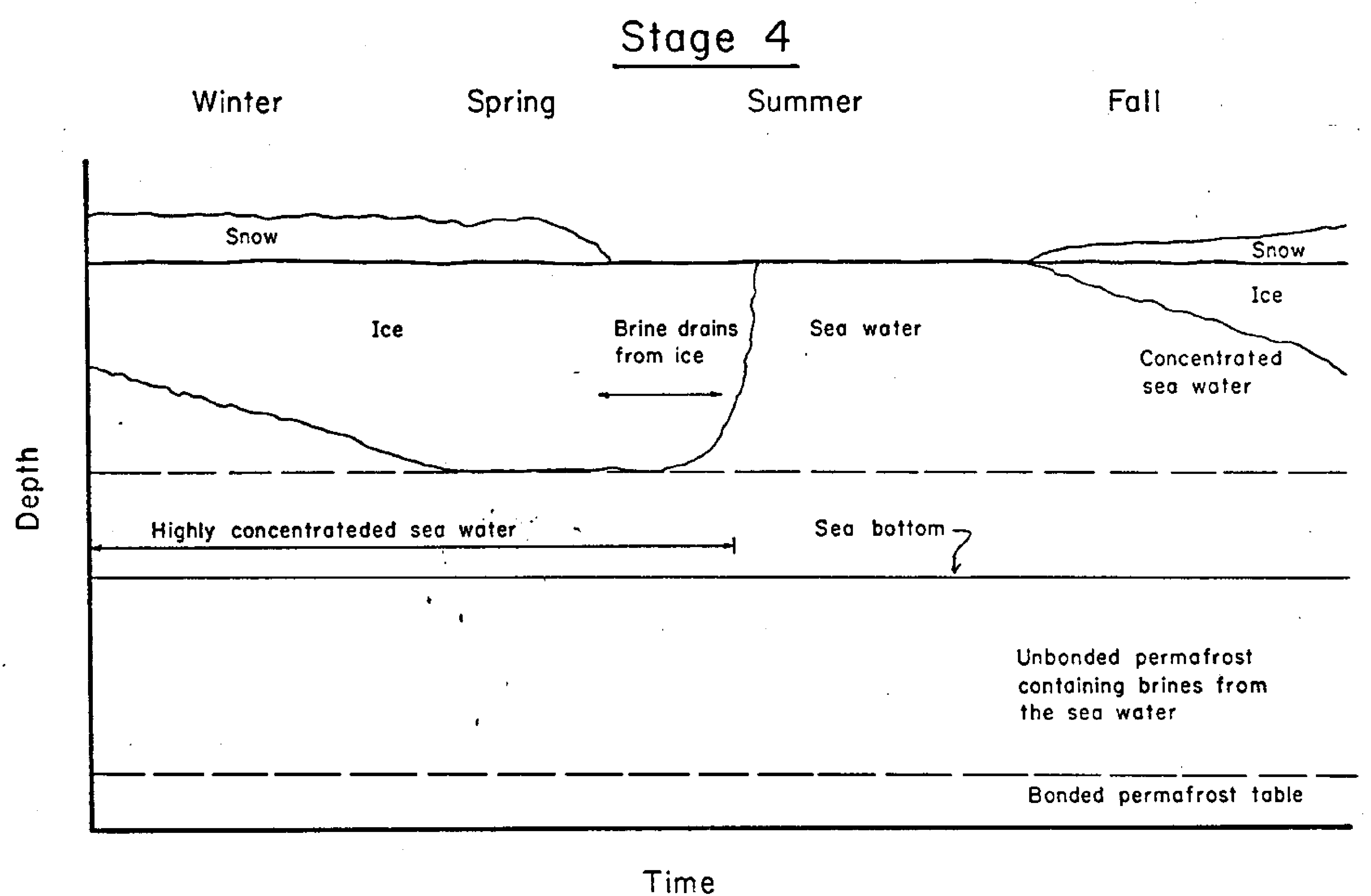

FIGURE 7. Seasonal variations in stage 4.

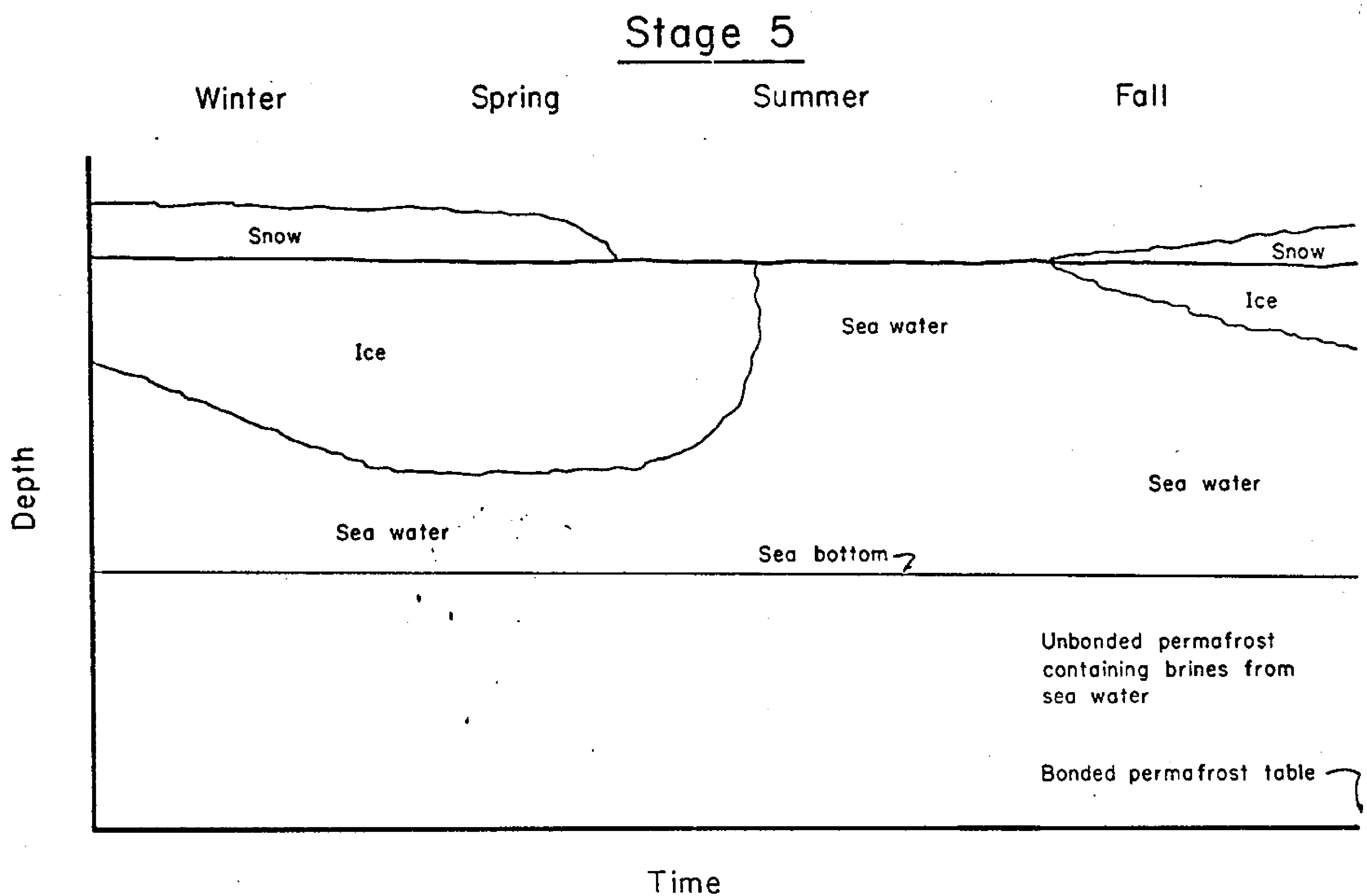

FIGURE 8. Seasonal variations in stage 5.