With the thermal regime established, it is pertinent to mention briefly the pressure relations involved in the formation of a pingo. The two major mechanisms (not mutually exclusive) described in the recent literature are (i) upheaval due to the hydrostatic pressure of expelled pore water (*2, 3*) and (ii) uplift due to the frost-heave process (*5*). Given the temperature conditions discussed above, the first water to freeze is the pore water just beneath the impermeable lake bottom sediments. As the frost line advances, excess pore water is expelled into the unfrozen material. This surplus water, combined with the sealing effect of the frozen lake bottom, causes a buildup of hydrostatic pressure (*6*) which is sufficient to lift the overlying layer to the heights observed. In a fine-grained soil, this migration and accumulation of pore water may be followed by the formation of ice lenses and by volume expansion (frost heave), which will produce uplift over and above that already caused by hydrostatic pressure. A load of 40 m of water, or any other load influencing equally the overburden and pore-water pressures, will not affect the frost-heave phenomenon which develops in the soil upon freezing. Uplift due to hydrostatic pressure will occur when the pressure exceeds the binding strength of the impermeable frozen layer plus the pressure of the 40-m water load, which is very small (about 4 atm) as compared with the total pressures involved (*6*).

The minimum age of a mature pingo can be estimated by determining the time required for the freezing of the permafrost depression beneath the original lake bed. The size of this depression must first be calculated by assuming that the ice core of the pingo has the shape of a cone with a radius of 200 m and a height of 20 m. If this core is pure or almost pure ice, then the volume of sediment from which the ice was derived will be equal to the volume of the cone divided by the product of the sediment porosity (30 percent) and the ratio of the volume expansion of ice to the total volume of ice ($\simeq 0.1$). If the depression is approximated by a cylinder with a radius of 400 m (the size of the original lake basin), its depth is calculated to be about 60 m. The time needed for the 0°C isotherm to reach this level depends mainly upon the thermal conductivity of the sediment, the surface temperature, and the geothermal heat flow. If we assume reasonable values for these parameters, it would take about 5000 years for the frost line to reach this depth.

In the case of submarine pingos, this reasoning implies that marine transgression must have occurred prior to 5000 years B.P. This date is supported by worldwide curves of postglacial sea level submergence (*7*), which indicate transgression at these depths (30 to 70 m) taking place well before 5000 years B.P.

Note added in proof: Additional pingos have been discovered on the floor of the Beaufort Sea near the site of the survey area of 1970 (*8*).

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Uranium Distributions in Archeologic Ceramics: Dating of Radioactive Inclusions

Abstract. *Small mineral grains (10 to 50 micrometers) of high uranium concentration (100 to 3000 parts per million) were located in polished sections of eight potsherds from Cyprus, England, Greece, and Mexico by induced fission-track mapping. Most of the grains were identified as zircons or apatites by a microprobe attachment to a scanning electron microscope. The advantages in using such radioactive grains for thermoluminescence dating and alpha-recoil track dating are discussed.*

Methods of obtaining absolute dates for archeologic ceramics by thermoluminescence measurements have been reported (*1*); these methods depend on the alpha, beta, and gamma dose rates from the radioactivity in the potsherd and the surrounding burial soil. The accurate determination of these dose rates has been limited by radon emanation and groundwater (which absorbs part of the radiation) and requires detailed knowledge of the burial circumstances. Inclusions of high uranium content are often found in potsherds (*2*). We have made a study of such inclusions in a variety of potsherds, and we propose a modification of the thermoluminescence dating method that eliminates the above complications.

Eight potsherds from England, Greece, Cyprus, and Mexico have been studied by means of techniques that were developed in this laboratory for the investigation of uranium-bearing inclusions in lunar rocks (*3*). First, the uranium distribution was mapped by the induced fission-track technique (*4*). For each potsherd, fission tracks were induced (by thermal neutron irradiation) in mica held flat against an area (1 cm^2) of the polished surface. Standard uranium glass (21 ppm) was irradiated at the same time to determine the thermal neutron flux [2×10^{15} nvt (number $\times$ velocity $\times$ time)]. Before the mica was removed, photographs were taken of it in position on the potsherd in an optical microscope at 50 times magnification. This makes it possible to relocate the mica with an

Table 1. Mineral grains of high uranium concentration identified in 1-cm^2 areas of eight potsherds.

Number of each mineral	Average diameter (μm)	Uranium concentration (ppm) Minimum	Maximum	Average
Zircon, 13	28	220	3400	1100
Apatite, 3	50	100	400	210
Baddeleyite, 1	30			520

accuracy of about 50 μm. The mica was then removed and etched for 10 minutes in 48 percent hydrofluoric acid at room temperature.

Most of the fission tracks seen in an optical microscope were in an apparently random distribution over the area of the mica and were induced by uranium in the clay matrix. The density of these tracks, about 2×10^5 cm^{-2}, gave an average uranium content of about 3 ppm for the potsherds. There also appeared several small areas (less than 100 μm) of much higher track density (more than 5×10^6 cm^{-2}) that represented inclusions high in uranium (Fig. 1A). In some areas, the tracks radiated from a central point ("star") and were evidently produced by a high uranium inclusion about 10 μm or less in diameter. For larger grains, the tracks were random in direction near the center and radial at the edges. The potsherds showed an average of three high track density areas, 30 μm or more in diameter per square centimeter, as well as many smaller ones. One potsherd, a fine-grained Greek ware, showed no high track density areas greater than 30 μm in diameter.

We attempted to identify the mineral grains responsible for the 25 largest areas of high track density. By means of the photographs of the mica above the potsherds the region of each inclusion was located in the optical microscope, and a photograph was taken at 200 times magnification (Fig. 1B). The mineral grain could be seen in 18 of the 25 cases. (The mineral grain cannot be found in every case as some grains are buried.) The same region was located in a scanning electron microscope and the chemical composition of the grain determined with an x-ray microprobe attachment. Fourteen of the mineral grains showed Zr + Si (zircon), one showed Zr only (baddeleyite), and three showed P + Ca (apatite). The names in parentheses were assigned on the basis of elemental constitution and have not been confirmed by mineral identification. Zircon and apatite are high uranium minerals commonly found in terrestrial rocks (*5*). Table 1 is a summary of the results for the eight potsherds. The uranium concentrations (Table 1) were obtained from the number of fission tracks produced by the inclusions and the sizes of the inclusions (estimated from the photographs and the fission track distributions).

The common presence of radioactive inclusions in potsherds offers excellent possibilities for dating. The internal alpha dose rate for such inclusions far exceeds the beta and gamma dose rates from the rest of the sherd and the burial soil. The alpha particles may be only 10 percent as efficient as beta or gamma particles in inducing thermoluminescence (*2*). Nevertheless, for a 50-μm grain of 500 ppm of uranium in a sherd and soil of typical radioactivity, over 98 percent of the thermoluminescence is induced by the internal alpha dose. If only the high radioactivity grains are used for thermoluminescence dating, the determination of the dose rate is much simpler than in present methods. The concentrations of uranium and thorium in a radioactive grain can be found by the induced fission-track method with the use of thermal neutrons and 30-Mev alpha particles (*6*); the alpha-particle dose rate can then be calculated. Complications in the present dating methods (*2*) are then eliminated as follows: (i) the gamma dose rate becomes negligible, and a knowledge of the burial circumstances is not needed; (ii) ground water is unimportant as it does not affect the internal alpha dose rate; and (iii) radon emanation is probably much less from the high radioactivity mineral grains (*7*) than from the potsherd and soil.

From the frequency of occurrence of the radioactive grains (Table 1) there should be several hundred such grains in 1 g of pottery. It should be possible to separate the grains from the potsherd by heavy liquid and magnetic techniques. Zircon and apatite are good thermoluminescent materials (*8*), and preliminary measurements indicate that there is sometimes a measurable thermoluminescence signal from a single 50-μm grain from pottery.

The fission-track method has been used for archeologic dating (*9*), but the precision has generally been worse than 10 percent because of the small number of tracks that could be counted. It appears that the same limitation will apply to the radioactive inclusions (for example, at an age of 10^3 years in an inclusion of 10^3 ppm of uranium, an area of 3×10^5 μm^2 is needed to find one fission track). Alpha-recoil tracks, on the other hand, are several thousand times more numerous than fission tracks (*10*). So if alpha-recoil tracks can be detected in the high uranium inclusions, this technique can also be applied to archeologic pottery.

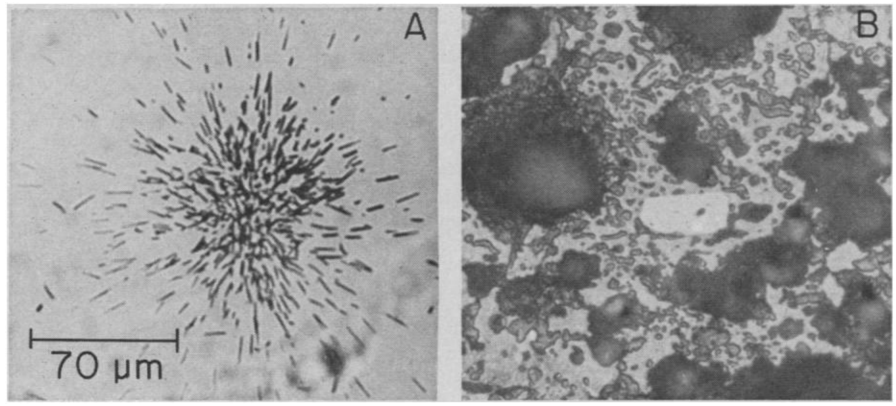

Fig. 1. (A) Transmitted light photograph of etched mica showing neutron-induced fission tracks from a radioactive inclusion in a potsherd. (B) Reflected light photograph of the potsherd showing the area adjacent to the mica in (A); the scale is the same as in (A). The dark areas are pores; the bright mineral grain associated with the large track density was identified with a microprobe as zircon.

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