duce rocks with most of the features that are distinctive of achondrites. Thus the gross differences between the two classes of stony meteorites can be related to segregation of a crudely layered body with clots, or perhaps a core, of nickel-iron, a mantle of achondritic composition, and a thick chondritic crust. The chondrites, by this reasoning, are close to the original bulk composition of the terrestrial planets before they formed a core and acquired their present structures and evolved compositions.

This is not to say that all meteorites have come from a primitive planet close to the earth in size and position in the solar system. Apart from specimens recently discovered in Antarctica and shown to have come from the Moon, most are thought to be from the asteroidal belt between Mars and Jupiter. Being farther from the Sun, these bodies must have differed, at least in minor ways, from the inner planets. Nor could they have been as large as Earth, because the mineral assemblages of meteorites show no evidence of ever having formed under pressures even approaching that of Earth's mantle. Some of the common minerals in stony meteorites, most notably plagioclase, are stable only at shallow depths; no high-pressure forms, such as garnet or spinel, have been found to indicate that the mineral assemblages crystallized in the deep interior of a large body.

Though chondritic meteorites differ somewhat in their bulk compositions, proportions of chondrules, and oxidation states, their differences are not random. They can be related to various degrees of heating and metamorphism at differing depths within the outer layer of their parental bodies. Carbon, sulfur, and water contents, for example, vary inversely with the inferred original temperatures and relative depths of burial deduced from the textures and mineral assemblages of individual chondrites. The average composition of chondrites (Table 1-1, no. 1) is not far from that of the non-volatile parts of the inner solar system as a whole. Apart from certain deficiencies of the volatile elements, which may be due to the conditions under which the parental bodies of meteorites accreted, the individual elements have proportions not unlike those of the earth. The abundances of heat-producing radioactive elements, for example, are almost exactly those that would produce the observed surface heat-flow of the earth if they were distributed in the same proportions as they are thought to have in the earth's core, mantle, and crust. It is these remarkable consistencies that lead us to conclude that the initial bulk composition of the earth resembled that of chondritic meteorites and that the present abundances of elements in different parts of the earth resulted from their redistribution during formation of the core, mantle, and crust.

Formation of the earth's core and mantle

It is uncertain whether the earth's core formed during the initial process of accretion or at a slightly later stage after the temperature of the earth had been raised by meteoritic impact and decay of radioactive elements in its interior; the latter seems more likely. At some early stage, as the temperature of the earth rose during a period of intense heating, the melting temperature of nickel-iron and iron sulfides was exceeded, and molten metal began to gravitate toward the interior.

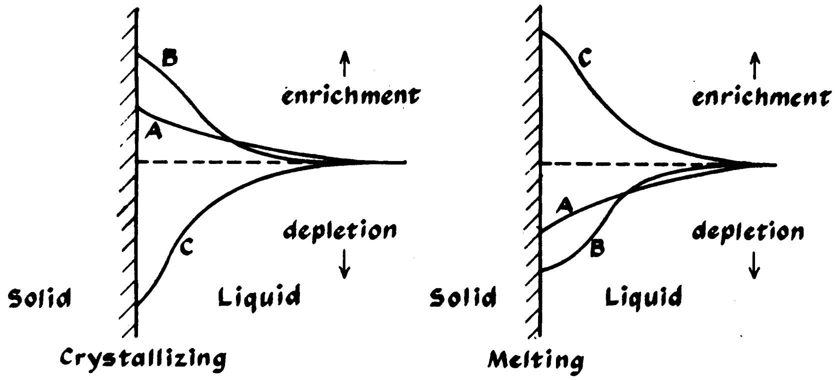

Figure 5–28 Schematic traces of compositional gradients for crystallization and melting in the three-component system in Figure 5–27.

10^{-8} cm^2 sec^{-1} or more, and crystal sizes of less than 5 cm, the effective distribution coefficient does not differ greatly from the equilibrium value, but for elements with large values of K the problem is more serious and can result in an effective value that is only 30 percent or so of the equilibrium one. Thus excluded trace elements can be modeled with reasonable accuracy, especially in slowly cooled magmas, but included elements of low diffusivities may deviate widely in their partitioning from the patterns predicted by equilibrium models.

In summary, then, we see that the effect of diffusion can be to change the effective distribution coefficents, especially for included elements. In systems in which individual components have differing diffusivities, the variations of concentration during crystallization or melting may result in paths of evolution of the differentiated liquid that are functions, not just of their distribution coefficients, but of their rates of crystallization and diffusivities as well.

In the next chapter we examine a number of well-studied examples of differentiated magmas and see how these effects are reflected in the compositions of igneous rocks.

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THE BUSHVELD COMPLEX

Any discussion of layered intrusions must begin with the Precambrian Bushveld Complex of South Africa. Not only is it the largest intrusion known, but, in many ways, it is one of the most remarkable bodies of igneous rock on Earth. Apart from its geological interest, it has great economic importance as a rich repository of platinum, chromium, vanadium, and other valuable metals. Thanks to extensive mapping, undergound mining, and exploratory drilling, a wealth of data is available on the intrusion, but, owing to its enormous size and complexity, much still remains to be learned.

The intrusion was emplaced as a nearly flat tabular mass of gabbroic magma that spread laterally from at least two separate feeders beneath a thin cover of sediments and volcanic rocks. The present area of outcrop (Fig. 6-12) measures about 270 km north-south by 450 km east-west, and its original thickness must have exceeded eight kilometers. The time required to crystallize this huge mass is thought to have been on the order of 200,000 years.

Much of the roof of the intrusion is made up of metamorphosed and partly fused sediments and felsic volcanic rocks of the Rooiberg Series. The latter are only slightly older than the intrusion and may have been related to the same magmatic episode. The central part of the Bushveld is occupied by a composite granitic pluton emplaced 50 to 100 million years after the gabbroic magma had crystallized.

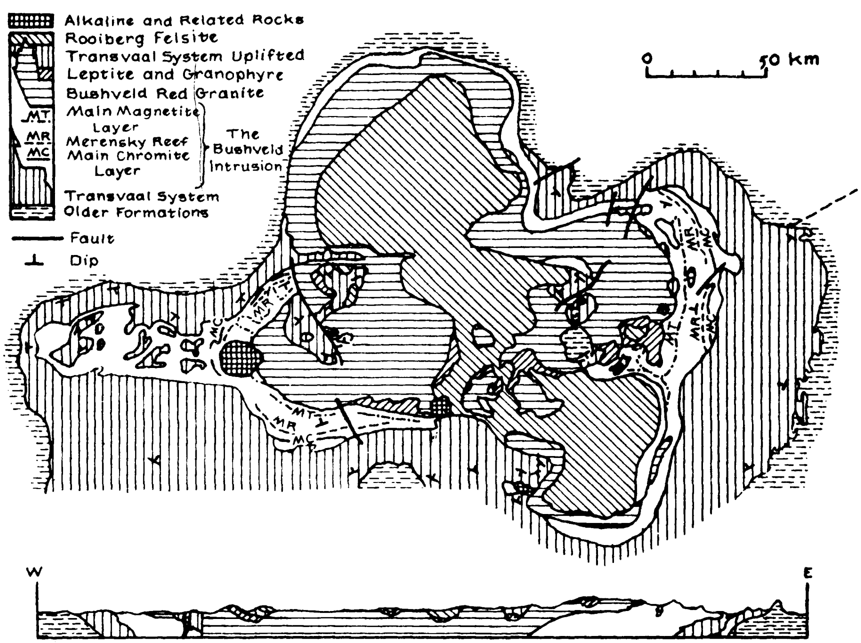

Figure 6–12 Simplified map and cross section of the Bushveld intrusion of South Africa. (Based mainly on a compilation by J. Willemse.)

THE MUSKOX INTRUSION

Most of the basal horizons that crystallized during the earliest stages of cooling of the Bushveld magma are buried deep below the present level of erosion. If they could be seen, they might resemble the root zones of more deeply eroded bodies, such as the Muskox intrusion in northern Canada. This long, trough-shaped body has an exposed length of 120 km, and geophysical surveys indicate that it has at least that much additional length beneath its roof rocks. It has been tilted slightly toward its upper end, so that the exposed section is equivalent to an original vertical dimension of over 6 km (Fig. 6–14). A thin feeder-dike of olivine-rich gabbro can be seen passing upward into a prism-shaped body of more differentiated rocks.

The main part of the intrusion is made up of numerous cyclical sequences that follow a regular order of crystallization before reverting to a more primitive composition. The cyclic units consist, from their base upward, of dunite, olivine clinopyroxenite, and olivine gabbro, so that the order of appearance of crystallizing minerals was first olivine, then clinopyroxene, followed by plagioclase. Orthopyroxene appears late in the lower units, but, higher in the section, it enters at an earlier stage of the cycle of crystallization. The nearly monomineralic character of the dunites testifies to efficient segregation of olivine crystals with only small amounts of interstitial pyroxene or plagioclase. Overlying layers of olivine clinopyroxenite become increasingly rich in clinopyroxene upward, then end abruptly with the appearance of plagioclase. From that level upward the gabbroic rocks become proportionately richer in plagioclase.

The cyclical series may have resulted from new injections of fresh magma that reset the bulk composition and gave rise to repeated sequences of crystallization. The effects of these influxes are clearly shown by the nickel content of the rocks, which have a remarkably regular sawtooth pattern (Fig. 6–15). The order of crystallization of minerals was slightly different in later cycles, possibly because the new liquid differed in composition from the earlier one or, more likely, the magma became contaminated with greater amounts of siliceous roof rocks.

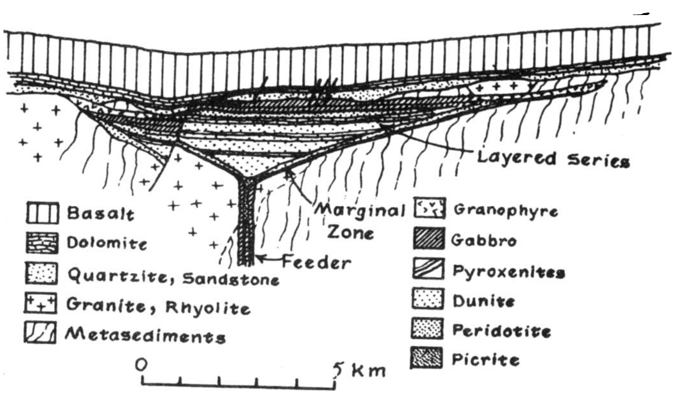

Figure 6–14 Simplified cross section of the Muskox intrusion of Canada. (After T. N. Irvine and C. H. Smith, 1967, in *Ultramafic and Related Rocks*, P. J. Wyllie, ed., John Wiley & Sons.)