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AN EMPLACEMENT MODEL TO EXPLAIN CONTRASTING MINERAL ASSEMBLAGES IN ADJACENT KIMBERLITE PIPES[1]

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ABSTRACT

Many closely spaced kimberlite diatremes are characterized by major differences in mineral composition of their assemblages (both kimberlite and inclusions). Although some of this variation clearly is a function of local differences of host rock through which the upward moving magma passed during emplacement of the respective pipes, variations in type and intensity of alteration are probably more significant to an understanding of emplacement history. The Sloan 1 and 2 pipes in the northern Colorado-southern Wyoming kimberlitic diatreme field are approximately 150 m apart and contain substantially different assemblages especially of nodular material. These pipes are evaluated in terms of emplacement related alteration processes. Intensity and type of secondary reaction may be a function of time, magnitude, and/or level of intrusive activity. Pipes that fail to penetrate uppermost crustal levels would approximate "roofed" dikes of similar composition in which fresh upper mantle and lower crustal materials are preserved, although carbonated and fenitized nodules may be present. Diatremes that break through to the surface are characterized by variably altered constituents (serpentinized, fenitized and carbonated), the intensity of alteration increasing with magnitude and duration of intrusion. If magma intrudes upward along essentially parallel, closely spaced paths, penetration generally will be more effective along conduits of maximum volume or minimum host rock resistance (e.g., intersecting faults). Pressure reduction accompanying breakthrough of a primary conduit will essentially terminate or cut off further upward migration or intrusive activity in subsidiary conduits. Applicability of the "cut off" mechanism of pipe emplacement for explaining major differences in style of intrusive activity is evaluated by comparison with an experimental laboratory model.

INTRODUCTION

Kimberlitic diatremes are renowned for the variability of their contents, yet mineral assemblages are generally somewhat uniform within closely spaced pipes or pipe clusters. The most impressive compositional difference between pipes involves the nature and concentration of included xenolithic and xenocrystic material. Many pipes, particularly in their uppermost regions, contain abundant blocks of wall-rock units, thus composition of penetrated host will control variations in mineralogy and chemistry of pipe fillings. For example, the Ferris diatreme in the Front Range of southern Wyoming (Chronic et al. 1969) is choked with large blocks of Lower Paleozoic sedimentary rocks and little kimberlite is exposed, whereas a few kilometers to the south in northern Colorado, kimberlite predominates in the Sloan, Nix, and Schaffer diatremes, and sedimentary rocks occur sporadically as generally small inclusions (McCallum and Eggler 1971; McCallum et al. 1975). Similar relationships are common in diatremes of the Colorado Plateau region (e.g., the Mule Ear and Garnet Ridge diatremes contain abundant sedimentary blocks whereas Buell Park and Green Knobs pipes are relatively deficient in sedimentary xenoliths; Stuart-Alexander et al. 1972; Watson 1967; Balk and Sun 1954). Relative concentration of near-surface wall rock blocks and fragments is probably primarily a function of pipe depth of present exposures (amount of erosional stripping) as such xenoliths normally would increase in number at shallower depths.

Nodules from deep seated sources may be quite varied from pipe to pipe in both number and type, and have been objects of intense investigation throughout the world to provide information on the nature and composition of the lower crust and upper mantle. Such nodules are rare or

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absent in many diatremes, although some pipes have brought up large volumes of deep seated material (e.g., Jagersfontein and Bultfontein pipes, South Africa—Wagner 1914; Carswell and Dawson 1970; Johnston 1973; Whitefield 1973: Green Knobs, New Mexico—O'Hara and Mercy 1966). A few diatremes are noted for their high content of a particular nodule type such as eclogite which is extremely abundant at the well known Roberts Victor pipe in South Africa (Wagner 1914; MacGregor and Carter 1970; Whitefield 1973). These variations in nodule type most likely reflect differences in the host rock through which the "kimberlite magma" passed on its way up towards the surface. However, in many pipes, major compositional differences appear to be chiefly a function of alteration processes rather than significant "primary" variation of the materials that were emplaced. Mineralogy may vary dramatically within a given pipe as well as between pipes. The most notable variation is degree of serpentinization and/or carbonation of pipe constituents. Some kimberlite is relatively unserpentinized and contains abundant fresh olivine and orthopyroxene crystals (e.g. Bultfontein and Wesselton pipes, South Africa—Wagner 1914; Whitefield 1973; J. B. Hawthorne 1973, personal commun.: Buell Park diatreme, Arizona—Watson 1967: Nix 2 diatreme, northern Colorado—McCallum et al. 1975), whereas kimberlite from other pipes is typically intensely serpentinized (e.g. Koffyfontein pipe, South Africa—Wagner 1914; J. B. Hawthorne 1973, personal commun.: Sekameng pipe, Lesotho—Dempster and Tucker 1973: Garnet Ridge pipe, Arizona and Moses Rock dike, Utah—Watson 1967; McGetchin 1968 and McGetchin and Silver 1970: Stockdale pipe, Kansas—Rosa and Brookins 1966; Brookins 1967: Nix 1, Sloan 1, and Schaffer pipes, northern Colorado—McCallum et al. 1975). Interpretations regarding the serpentinization process are varied; however, most workers are in agreement that alteration probably occurred either during or closely following emplacement (e.g. Wagner 1914; Dawson 1962, 1967; McGetchin 1968). Serpentinization has been so intense in some pipes that virtually all olivine and orthopyroxene is altered in the kimberlite groundmass, xenocrysts, and ultramafic rock nodules. Carbonation apparently accompanied or followed serpentinization in some cases and ultramafic nodules have been almost entirely replaced by secondary minerals. Such nodules are commonly rimmed with thin layers of radiating fibrous calcite and cores may consist of serpentine, chlorite, vermiculite, quartz, and brucite (?) arranged in a microscopic box-work of calcite; unaltered grains of relict garnet, chromium diopside, and spinel may be present scattered throughout individual nodules (e.g. carbonated ultramafic nodules in the Sekameng pipe, Lesotho—Dempster and Tucker 1973; Nixon and Boyd 1973). Somewhat similar nodules have been collected by the writer from a few pipes in northern Colorado and southern Wyoming, although they generally are not rimmed by calcite and are more silicified than those described from African sites.

Fenitization is reflected in many nodules of wallrock material, and products of this metasomatic process also vary widely in relative concentration in different pipes. Thermally metamorphosed deep-seated crustal xenoliths have been reported by several workers (e.g. Wagner 1914; Kharkiv 1967; Dawson and Hawthorne 1970), and Ferguson et al. (1973) describe a wide variety of sialic and mafic crustal rocks that have been fenitized in kimberlite pipes in South Africa and Lesotho. Ferguson et al. (1973) noted that different styles of fenitization reflect increasing depth levels of alteration: host rocks at shallow depths are replaced primarily by carbonates and brown mica, whereas in deeper zones white mica and apatite are additional replacing phases. At shallow crustal levels, only the hydrous CO_2-rich phase of the gas charged kimberlite magma is available to react with included nodular material and to penetrate wall rocks since the volatile phase will be degassed along fractures to the surface which results in release of pressure that promotes a rapid increase in the solidus temperature and attendant crystallization. At deeper levels where volatile release is less rapid, potassium and phosphorus would be important components in the magma, and biotite and apatite become major products of the fenitization process (Ferguson et al. 1973). Similar metasomatic assemblages have been observed by the writer in many nodules of crustal rocks from kimberlites in northern Colorado and southern Wyoming. Intensity of fenitization varies considerably between diatremes, but most nodules reflect the deeper zone replacement indicated by Ferguson et al. (1973).

One of the more striking contrasts of pipe assemblages observed in the Colorado-Wyoming kimberlite field (McCallum et al. 1975) involves the adjacent Sloan 1 and Sloan 2 diatremes (fig. 1). The Sloan 1 pipe is located at the intersection of two faults—Copper King and Prairie Divide Faults (McCallum and Eggler 1971)—and the Sloan 2 pipe is about 150 m to the northwest along the Prairie Divide Fault. The Sloan 2, which is at least 30 m × 70 m, appears to be a subsidiary pipe of the much larger Sloan 1 diatreme (~ 105 m × 550 m).

SLOAN 1 AND SLOAN 2 ASSEMBLAGES

The Sloan 1 and Sloan 2 pipes contain materials of different character and abundance. Although lack of outcrops at Sloan 2 allows little opportunity to compare compositions of kimberlite matrix of the two pipes, xenolithic and xenocrystic materials are readily available (table 1). The most striking difference is the greater abundance and degree of preservation of mantle nodules in the Sloan 2 pipe. Unaltered spinel and garnet lherzolite nodules are quite common in the Sloan 2 whereas only a few intensely serpentinized equivalents have been collected from the Sloan 1. Garnet websterite, garnet clinopyroxenite, harzburgite, and dunite inclusions

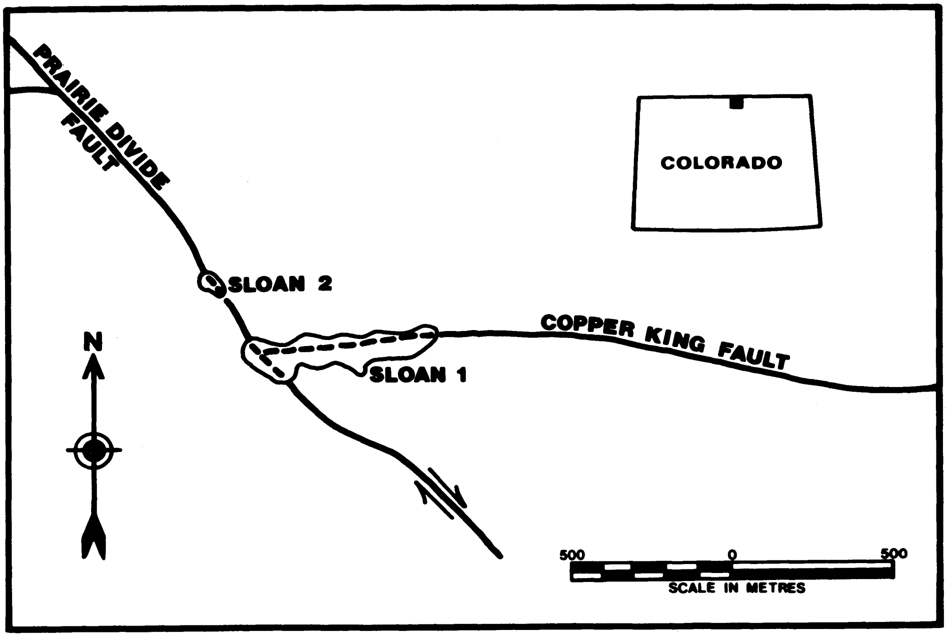


FIG. 1.—Location and structural setting of the Sloan 1 and 2 diatremes

TABLE 1

XENOLITHIC AND XENOCRYSTIC ASSEMBLAGES IN THE SLOAN 1 AND SLOAN 2 DIATREMES

Xenoliths	Sloan 1	Sloan 2
Lower Paleozoic carbonates	Very abundant (up to 3m)	Absent
Upper Crustal granitic and gneissic units	Abundant (essentially unaltered)	Abundant (essentially unaltered)
Lower Crustal granulitic and mafic units	Uncommon (intensely fenitized when present)	Very abundant (fresh and fenitized)
Carbonatite	Abundant	Present
Eclogite	2 nodules (badly altered)	Relatively common (fresh and altered)
Pyroxenite	Not recognized	Present (unaltered)
Garnet websterite	Not recognized	Relatively common (unaltered)
Garnet clinopyroxenite	Not recognized	Relatively common (unaltered)
Dunite	Not recognized	Common (unaltered)
Harzburgite	Not recognized	Common (unaltered)
Spinel lherzolite	Present (badly altered)	Common (unaltered)
Garnet lherzolite	Present (badly altered)	Common (unaltered)
Xenocrysts		
Garnet		
Cr-rich	Moderately abundant	Moderately abundant
Cr-poor subcalcic	Present	Moderately abundant
Cr-rich subcalcic	Rare	Moderately abundant
Clinopyroxene		
Cr-rich	Moderately abundant	Moderately abundant
Cr-poor subcalcic	Not recognized	Present
Orthopyroxene	All serpentinized	
Cr-rich		Moderately abundant
Cr-poor		Present
Olivine	All serpentinized	Present
Ilmenite	Abundant	Abundant

have not been recognized at Sloan 1 but are fairly common at Sloan 2, and eclogites, which are rare and badly altered in the main pipe, are fresh and relatively common in the smaller pipe. Carbonatitic nodules occur in both pipes but are most abundant in the Sloan 1, and upper crustal Precambrian granitic and gneissic units are present in nearly equal concentration in both pipes. The upper crustal rocks are characteristically unaltered to only slightly altered. Lower crustal nodules include hypersthene granulite, augite granulite, garnet kyanite granulite, charnockitic granulite, pyroxenite, and basalt (?); most show varying degrees of fenitization and carbonation. Such nodules are very abundant in the Sloan 2 pipe and many are quite fresh as opposed to the intense alteration typical of the limited numbers of lower crustal inclusions found at Sloan 1.

Mineral inclusions also show considerable range between pipes in composition, abundance and alteration. All olivine and orthopyroxene from the Sloan 1 has been completely serpentinized, whereas in the Sloan 2 both minerals are commonly unaltered (particularly orthopyroxene). Fresh emerald green Cr-rich clinopyroxene is present in both pipes, but a gray, Cr-poor, subcalcic-clinopyroxene has been recognized only in the smaller pipe. Three types of garnet inclusions (Cr-rich, Cr-rich subcalcic, and Cr-poor subcalcic) have been identified and all are moderately abundant in the Sloan 2 pipe. In the Sloan 1 pipe the Cr-rich variety is also abundant; however, both Cr-rich subcalcic and Cr-poor subcalcic varieties are considerably less common (Eggler and McCallum 1974). Ilmenite inclusions are abundant in both pipes and no significant differences in chemistry have been noted.

Inclusions of Lower Paleozoic carbonate units are quite common in the Sloan 1 diatreme. These consist of small subrounded fragments to large angular blocks (up to 3 m across) of limestone, dolomite and dolomite breccia of Ordovician and Silurian age that represent formations that were stripped away be erosion subsequent to kimberlite emplacement (McCallum and Eggler 1971). No inclusions of sedimentary rocks have been recognized at the Sloan 2 pipe, which might indicate that this diatreme failed to penetrate as high a crustal level as did the Sloan 1 pipe that clearly cut up into the Lower Paleozoic sequence and probably broke through to the surface. Although time of diatreme emplacement is still uncertain, a very late Silurian or Early Devonian age has been postulated (McCallum and Eggler 1971).

EMPLACEMENT HISTORY

Differences in the mineralogy of materials included in the two Sloan diatremes imply significant differences in emplacement history. The absence of sedimentary rock inclusions in the Sloan 2 pipe supports the contention that this diatreme failed to penetrate as high a crustal level as did the Sloan 1; however, near surface sedimentary rocks also would be absent in a pipe if intrusive activity had ceased during the early breakthrough stage when all material was on the way up and no downward circulation had begun. It has been suggested by McGetchin (1976, personal commun.) that the same pipe characteristics could reflect a much more mature evolutionary stage in a pipe system with flow velocities sufficiently high to sustain the total upward passage of blocks. Violent eruption would accompany high flow velocities in such systems and lead to "reamed out" pipes characterized by "absence of downward transported blocks, and greater abundance of large lower crustal and possible upper mantle fragments" (McGetchin 1976, personal commun.). Although the elements of McGetchin's eruption model are appealing, I question its applicability to the Sloan diatreme system. Considering the close proximity of the Sloan 1 and 2 pipes, it seems unlikely that late stage high velocity eruptions would be confined to the smaller Sloan 2 pipe while lower velocity activity with accompanying circulation (or no activity) occurred in the Sloan 1 pipe.

Although attainment of a lower intrusion level or a "frozen" early stage breakthrough stage without downward circulation can readily account for the absence of sedimentary inclusions, it does not explain the other major differences in xenolith and alteration assemblages, especially the variable degree of alteration and concentration of deep-seated nodules. Alteration and relative concentration of inclusions may be in part a function of duration of the intrusive event or of the number and nature of multiple intrusions of kimberlite magma. A long and/or complex intrusive history could result in more effective comminution of host rock fragments, thus reducing the number and size of inclusions. Time and complexity of intrusion might also enhance the effectiveness of hydration, carbonation and/or fenitization processes. Pipes with repeated eruptive activity have longer life and greater availability of volatiles and fluids that promote serpentinization. Kimberlite dikes generally are products of a single intrusive event and commonly are not intensely serpentinized. It might be expected, therefore, that blind pipes (those that fail to breach the surface) and "frozen" early stage breakthrough pipes which apparently reflect minimal intrusive activity might also show less intense serpentinization. The Sloan 2 pipe may represent one of these two systems.

Carbonation and fenitization processes

were apparently both significant during the emplacement of the two Sloan diatremes, even though products thereof are now more abundant in the Sloan 2 pipe. In both pipes, carbonated and fenitized nodules are almost exclusively derived from the lower crust (chiefly granulites), whereas upper crust and mantle inclusions only rarely show metasomatic effects. It is suggested that carbonate and alkalic metasomatism of the included lower crustal rocks occurred very early during the emplacement of kimberlite magma. Upward movement of the gas charged magma was apparently arrested, perhaps only briefly, upon entering the lower crust, and enrichment of gases at the top of the "magma column" caused extensive metasomatism of adjacent and locally stoped rocks. Eventually, due to continual increase in gas pressure and/or subsequent intrusion of additional magma from below, the kimberlite magma moved upward through the crust stoping fresh upper crustal rocks and transporting unaltered mantle rock nodules in addition to inclusions of intensely altered lower crustal material. A somewhat similar mechanism was suggested by Nixon and Boyd (1973) to explain the unique carbonation of ultrabasic nodules in kimberlite from the Sekameng diatreme in Lesotho.

Some differences in mineral assemblages of fenitized inclusions may be related to depth of source of those inclusions. Fenitized granitic inclusions of apparent upper crustal granitic rocks occur in some of the diatremes in the northern Colorado-southern Wyoming kimberlite field. Replacement products are primarily carbonates, chlorite, biotite, magnetite, clinozoisite, and locally muscovite. Fenitized lower crustal granulite inclusions are replaced by carbonates, abundant biotite, muscovite, apatite, serpentine, amorphous silica, and fine grained aggregates and films of sphene-leucoxene-calcite. Depth and associated volatile content of magma were apparently important factors in these mineralogical differences in addition to bulk composition; however, relative intensity of metasomatism and alteration of nodules were probably also a function of the amount of time these materials were in contact with the kimberlite magma. Prolonged or multiple intrusion would likely favor maximum replacement. Such a relationship is inferred in the Sloan 1 pipe where virtually all lower crustal nodules have been intensely fenitized or carbonated. The Sloan 2 pipe, however, contains many unaltered nodules of lower crustal rocks, and those xenoliths that have been metasomatized are less intensely altered than similar nodules in the Sloan 1 pipe. This striking difference in fenitization of nodules found in adjacent pipes, coupled with similar differences in degree of carbonation and serpentinization, probably reflects an early cut-off or cessation of intrusive activity in the Sloan 2 conduit, as opposed to long term activity of intrusive and fluidization processes in the Sloan 1 pipe.

Experimental Studies.—A possibly analogous sequence of pipe development has been observed in recent experimental studies of diatreme emplacement at Colorado State University (Woolsey 1973; Woolsey, McCallum and Schumm 1975). Small scale models utilizing fluidization techniques were employed to simulate the development of diatremes and related structures. Containers of several geometric configurations were used, but parallel plate models with plexiglass walls were most informative. The parallel plate container shown in the experimental series in figure 2 is 100 cm wide, 35 cm high, and 4 cm thick. The container was filled to a depth of 19 cm with particulate materials ranging from powdered clay-sized kaolinite to 0.125–1.0 mm sand arranged in horizontal layers (fig. 2A). Gas was passed up through the sediment column from a screened, 2 cm diameter orifice at the base. Gas used in the experiment was compressed air from a large volume source piped to the model through a pressure regulator and float-type flow meter at a flow rate of approximately 0.3 m^3/min.

Initial injection of gas generated dual fluidized conduits leading upward to a single void space beneath the uparched surface layers without major breakthrough to the surface (figs. 2B and C) although gas was escaping to the surface by diffuse intergranular flow. The apparent increase in thickness of the uppermost white bed that contains the "void" is, in addition to the presence of the void, a function of bed expansion resulting from the introduction of abundant gas into pore spaces in sand beneath the void. Continued gas flow led to enlargement of the left conduit (primary) accompanied by decreasing activity in the right conduit (now subsidiary) (fig. 2D). Eventually the primary conduit was enlarged substantially and broke through to the surface, diminishing internal pressure, and activity in the subsidiary conduit was terminated, preventing its penetration to the surface (fig. 2E). Breakthrough was accompanied by subsidence of surface layers into the fluidized conduit and development of pronounced inward dips of near-surface wall sediments (3E and F) similar to those described at many pipe localities (e.g. Fife, Scotland—Francis 1962; southwest Germany—Lorenz 1971; Montana, USA—Hearn 1968). All subsequent fluidization activity was confined to the primary conduit which was additionally enlarged, and foundered blocks of wall sediments (fig. 2F) were progressively broken down and "comminuted" to small particle sizes. Continued fluidization further enlarged the primary conduit and was accompanied by the development of a ring of bedded airfall ejecta (fig. 2G). Surface layers have been dragged down and smeared out along the margins of the conduit and crude, inward-dipping, saucer-shaped bedding has developed in air-fall ejecta descended into the conduit. The inactive subsidiary conduit is nearly engulfed by the widened primary conduit (fig. 2G).

Emplacement Model for the Sloan Diatremes.—Based upon field evidence that suggests that the Sloan 2 pipe may have failed to penetrate to the surface, and experimental studies that support a non-breakthrough mechanism for subsidiary fluidized conduits, a fluidization emplacement model has been developed to explain the compositional differences between the Sloan 1 and 2 diatremes in northern Colorado. Charting a fluidization emplacement path somewhat analogous to that presented above and shown in the experimental series of figure 2 and diagrammatic series of figure 3, the following sequence of events is postulated:

1. Crystal mush kimberlitic magma was intruded slowly along deep-seated fractures from its source area in the mantle (200+ km depth).
2. Stoping of upper mantle wall rocks accompanied upward migration of magma and abundant nodules of peridotite, eclogite, and discrete minerals (xenocrysts) were incorporated.
3. Intrusion of the magma was arrested, perhaps only briefly, upon entering the lower crust (approximately 50 km depth) (fig. 3A) and enrichment of volatiles at the top of the magma column was accompanied by carbonation and fenitization of wall rock and locally stoped inclusions of mostly granulitic composition.
4. Increased gas pressure and/or intrusion of additional magma from below, containing fresh nodules of mantle material, initiated renewed upward movement and inclusions of upper crustal granitic rocks were added to the intruding kimberlite. Fenitization of wall rock and nodular material in shallow crustal regions, where increasing proportions of the magma's volatile phase could be degassed, would be characterized by decreasing concentrations of K-bearing and P-bearing alteration products.
5. At some unknown upper crustal level, the magma "entered" the Prairie Divide fault zone and subsequent upward migration was controlled by this structural discontinuity.

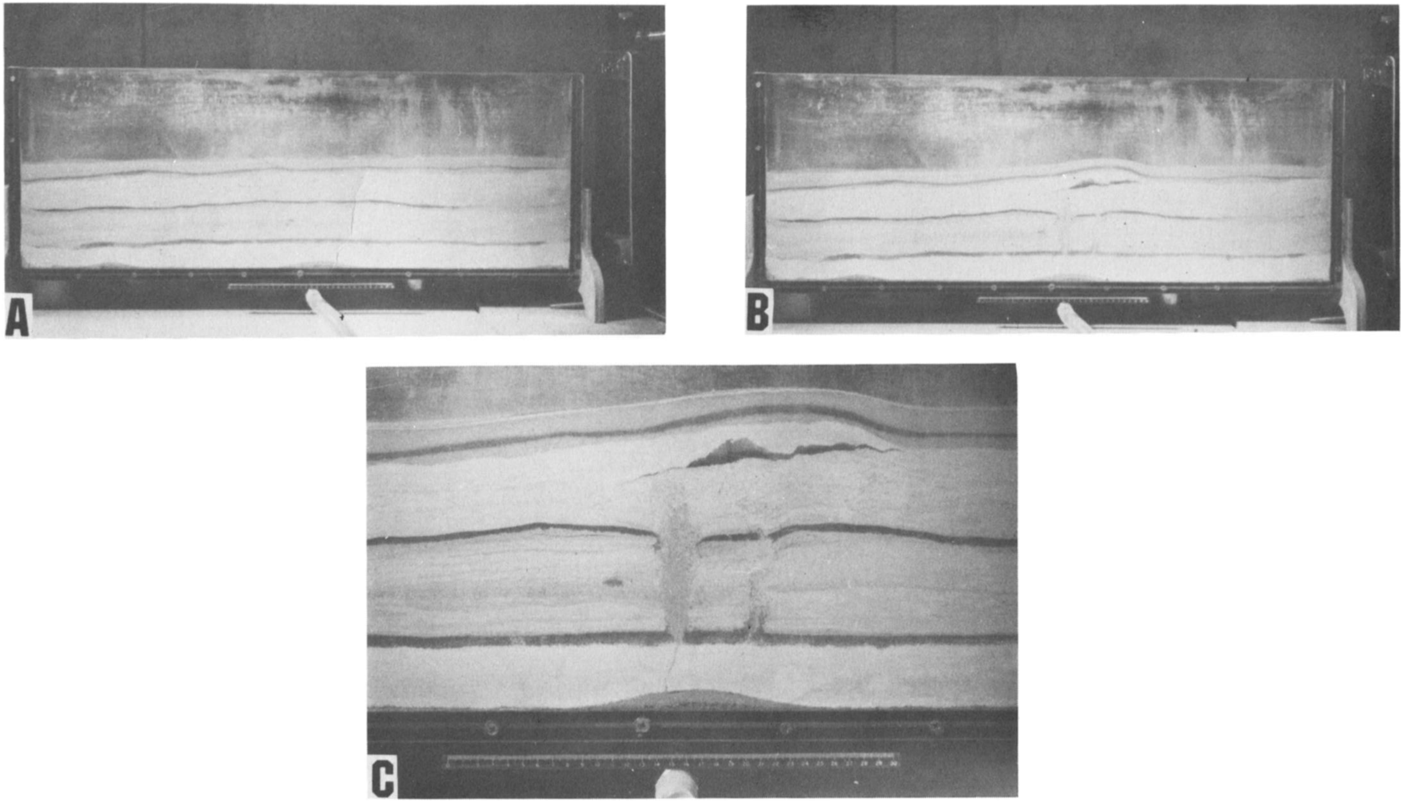
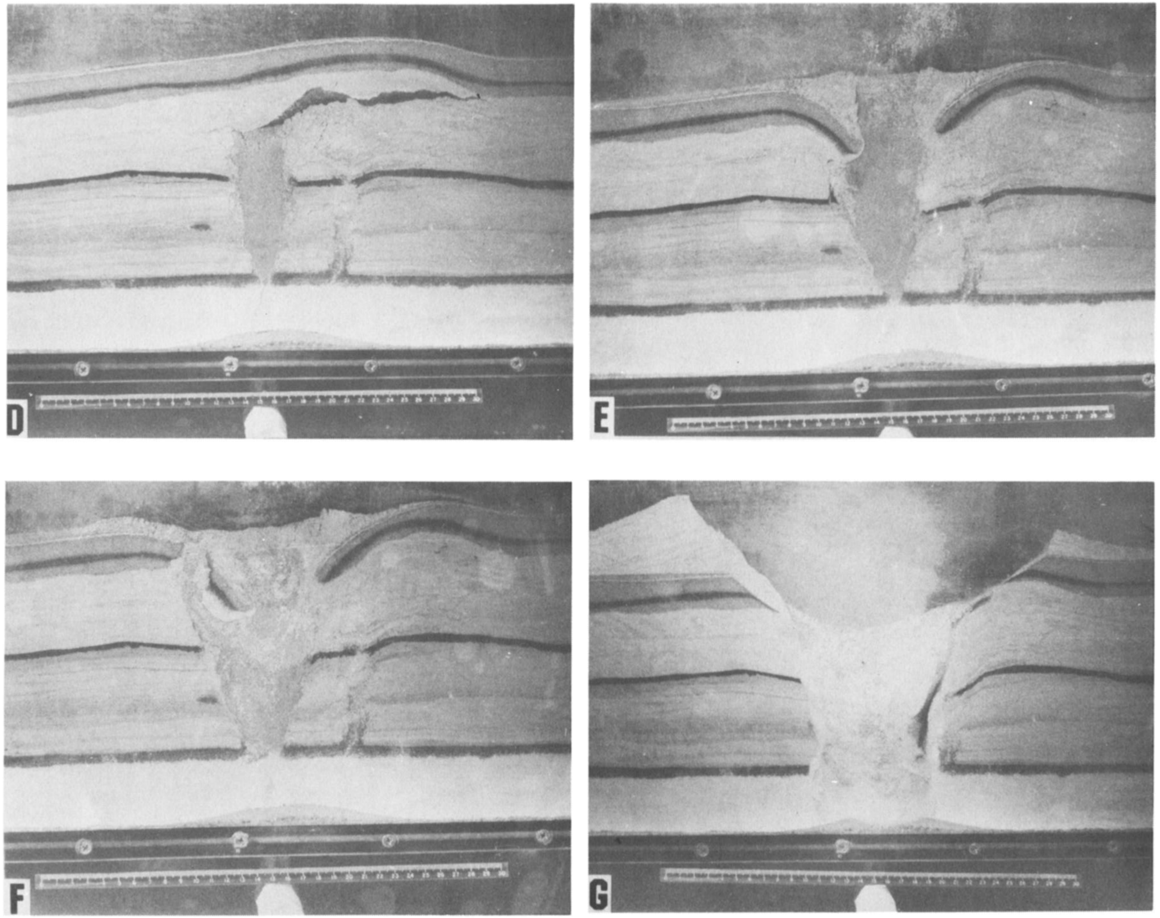


Fig. 2.—Experimental series showing the development of dual fluidization conduits in a gas-solids (particulate matter) system. Parallel plate model used in experiments is 100 cm wide. Scale is in cms. (After Woolsey, 1973, p. 76–78.)

A. Interbedded sand and marble dust with dark silt marker horizons. Bottom layer is kaolinite powder.

B and C. Development of dual fluidized conduits with a single void space above both. Surface layers are up-arched but no breakthrough has occurred.



D. Conduit on left (primary conduit) has become enlarged as the subsidiary right conduit becomes progressively less active.

E. Continued enlargement of primary conduit accompanied by surface breakthrough and subsidence of surface material into enlarged fluidized zone. Surface and near surface wall sediments are downwarped adjacent to conduit by downward movement of material in fluidized zone. Subsidiary conduit has become inactive.

F. Further enlargement of primary conduit accompanied by detachment and subsidence of surface and near surface sediments.

G. Further enlargement of primary conduit and development of ring of bedded air-fall ejecta. Smeared portion of surface layer has descended along right margin and crude, inward-dipping, saucer-shaped bedding has developed in pipe. Inactive subsidiary conduit is nearly engulfed by widened fluidized zone of primary conduit.

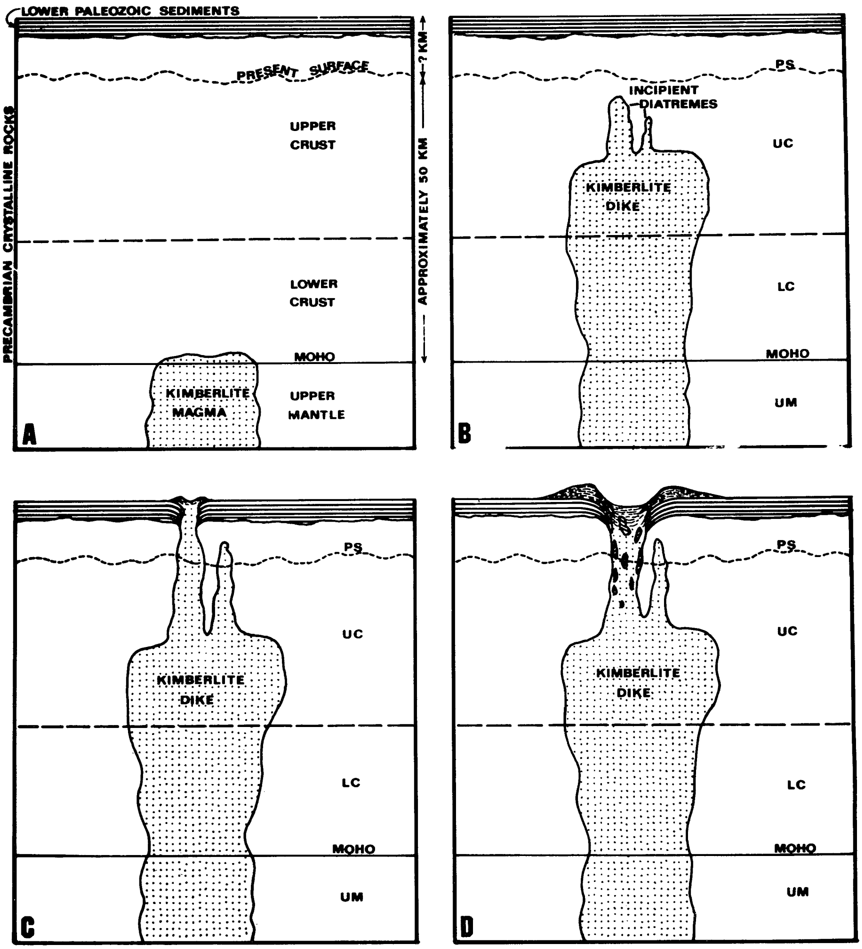


FIG. 3.—Diagrammatic representation of the emplacement history of the Sloan 1 and 2 pipe system. Cross section drawn parallel to the Prairie Divide Fault and parallels the main "feeder" kimberlite dike at depth. Both vertical and horizontal scales are greatly exaggerated.

A. Initial intrusion of kimberlite "magma" into the lower crust.

B. Emplacement of kimberlite "magma" into upper crustal zones, probably as a dike system, and development of pipes at uppermost levels. Deep portions of dike system probably controlled by major zone of crustal weakness, uppermost levels of dike and pipe emplacement controlled by near surface structural trend (Prairie Divide and Copper King faults for Sloan pipes).

C. Enlargement of the primary pipe (Sloan 1) with upward penetration into surface Paleozoic sediments and eventual breakthrough. Subsidiary pipe (Sloan 2) becomes inactive.

D. Continued intrusive activity in primary pipe promotes subsidence of sedimentary units down to deeper pipe levels and favors extensive serpentinization of magnesian constituents in kimberlite and ultramafic nodules. Rings or cones of bedded kimberlite tuff may have developed by air-fall of extruded pyroclastics.

6. As load pressures decreased at progressively shallower levels of intrusion (upper few kilometers of crust), the gas-charged kimberlitic crystal mush magma probably began to fluidize and two (or more) pipe-shaped intrusive channelways evolved (as in figs. 2B and 3B).

7. Upward migration and stoping of the two adjacent conduits continued in a parallel fashion, although one (Sloan 1)

apparently was larger and more active than the other (Sloan 2) (fig. 3C). The primary conduit (Sloan 1) was developed at the intersection of the Copper King fault with the Prairie Divide fault (fig. 1), and granulation and comminution of solid constituents probably was more effective in this conduit than in the subsidiary Sloan 2 pipe.

8. The primary conduit (Sloan 1) penetrated the uppermost granitic rocks of the crust (Precambrian) and punched up through a thin sequence of Lower Paleozoic rocks before breaking through to the surface.

9. Surface breakthrough of the primary conduit (Sloan 1) (fig. 3C) was accompanied by diminished internal pressure and all intrusive activity in the subsidiary conduit (Sloan 2) ceased before the level of surface and near surface sedimentary rocks was reached (or shortly after breakthrough before any subsidence of surface sedimentary rocks). Breakthrough of the Sloan 1 pipe was accompanied by subsidence of sedimentary blocks, many of which are still preserved even though the entire in situ sedimentary sequence has been completely stripped by post-emplacement erosion (note level of present surface indicated in figure 3.)

10. Repeated intrusive activity in the Sloan 1 pipe provided increased availability of volatiles and fluids that promoted serpentinization of olivine and orthopyroxene both in nodules and kimberlite matrix. The short term intrusive activity in the subsidiary conduit (Sloan 2) did not favor the repeated or continued presence of volatiles and fluids thus the serpentinization process was relatively ineffective, particularly in respect to nodular material.

11. All subsequent intrusive activity was confined to the primary conduit (Sloan 1 pipe), and the subsidiary conduit (Sloan 2) was essentially "cut off" (fig. 3D). A tuff cone or tuff ring may have developed at the surface of the Sloan 1 pipe (similar to that developed experimentally and shown in figures 2E, F, and G and postulated in fig. 3D), but extensive erosion has destroyed all evidence for the existence of any such features.

12. Continued or repeated intrusive activity in the primary conduit (Sloan 1) facilitated enlargement of the pipe (fig. 3F), which was accompanied by increased comminution and alteration of pipe materials.

13. Subsequent erosional processes stripped off all sedimentary rocks and an undetermined amount of the Precambrian crystalline sequence exposing the two pipes at their present levels (note present surface indicated in fig. 3D).

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