Roddy, D. J., Pepin, R. O., and Merrill, R. B., editors.
(1977) *Impact and Explosion Cratering*, Pergamon Press (New York), p. 425–448.
Printed in the United States of America

Shallow drilling in the "Bunte Breccia" impact deposits, Ries Crater, Germany

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Abstract—This is a field report concerning a shallow core drilling program in the "Bunte* Breccia" deposits, which constitute ≈90% of all impact breccias beyond the outer rim of the Ries (Germany), an ≈26 km diameter impact crater. A total of 11 locations having radial ranges between 16.5 and 35 km from the crater center were drilled and ≈480 m of core were recovered.

The cores consist of breccias whose components are derived from both the terrain outside the crater ("local") and the crater cavity itself ("crater"). The local components completely dominate the breccias at the larger ranges and possibly constitute >90% of the breccia volume at the greatest distances examined. Clast sizes, frequency, and lithologies as well as matrix character are extremely variable. Breccia matrices vary between, as well as within, specific localities indicating that thorough mixing is omnipresent but variable in intensity. There are various stages of mixing at different locations and/or times prior to final emplacement because "breccias within breccias" are common. The overall texture of the matrix is "massive"; the clast orientation is highly irregular and many twisted and swirly deformation structures are observed, indicating that the mixing and emplacement process was predominantly turbulent. The Bunte Breccia is surprisingly deep (e.g., 84 m at 27 km range). This great depth of Bunte Breccia, together with the preponderance of local components necessitate an emplacement mechanism that ploughed up and mixed the crater surroundings to depths greater than 50 m.

These new studies as well as previous observations are strong evidence for a ballistic emplacement mechanism of the Bunte Breccia deposits at distances greater than 5 km from the Ries rim.

INTRODUCTION

"EJECTA" BLANKETS associated with impact craters of all sizes attest to the importance of the cratering process in redistributing planetary materials. Depending on size and depth of any given crater, such impact deposits may

*Bunt = multicolored.

originate from the uppermost surface or from crustal depths measured in kilometers, if not tens of kilometers. Detailed understanding of these deposits which dominate cratered, planetary surfaces may only come forward, after quantitative assessment of the nature and emplacement mechanism(s) of the ejecta. Of particular interest are relatively large craters because their deposits may contain deep seated, possibly crustal materials.

Many current and fundamental problems in lunar surface evolution depend on a better understanding of large scale ejecta distribution: the source area(s) of the Apollo 14 and 16 rocks (Oberbeck *et al.*, 1973, 1974, 1975; Head, 1974; Chao *et al.*, 1973; Moore *et al.*, 1974; Morrison and Oberbeck, 1975), the assessment of the enrichment of siderophile elements indicative of meteoritic contamination (Ganapathy *et al.*, 1973), and the absolute formation ages of major basins (Schaeffer and Husain, 1974) are some examples requiring an understanding of the mechanics of ejecta emplacement.

Knowledge concerning the ejecta of relatively small laboratory experiments is fairly detailed (e.g., Gault *et al.*, 1968; Oberbeck, 1971, 1975; Stöffler *et al.*, 1975) and is also available for Meteor Crater, Arizona (Shoemaker, 1963; Roddy *et al.*, 1975) and explosive or nuclear craters (e.g., Andrews, 1976; Wisotski, 1976; Carlson and Roberts, 1963). Our understanding of large scale crater ejecta, however, is based on an extrapolation of these relatively small scale events and detailed photogeologic studies.

Present hypotheses based on such extrapolations and especially photogeologic studies which focus on the interpretation of a variety of geomorphic land forms are, however, controversial. A ballistic ejection mechanism leading to significant incorporation of local materials and final emplacement of the deposits via a debris surge of the combined crater—and locally derived materials has been proposed by Oberbeck *et al.* (1973, 1974, 1975), Oberbeck (1975), Morrison and Oberbeck (1975), and others. In contrast, Chao *et al.* (1974), Chao (1976a,b), and Moore *et al.* (1974) propose one massive, groundhugging, flow regime emanating from the crater; they consider ballistic transport and associated secondary cratering of minor importance for continuous deposits. Implications of these hypotheses are best illustrated in interpreting the potential source area(s) of the Apollo 14 and 16 samples. While Oberbeck *et al.* (1975), Morrison and Oberbeck (1975), Head (1974) and Head and Hawke (1975) postulate a largely local derivation of these samples, Moore *et al.* (1974) and Chao *et al.* (1974) suggest derivation from the Mare Imbrium if not Mare Orientale basins. Chao (1974) specifically challenged the prediction of the ballistic hypothesis that significant amounts of local materials are incorporated into continuous deposits.

The Ries Crater (Germany) is the largest terrestrial crater with significant parts of the breccia deposits beyond the outer crater rim still preserved (see Pohl *et al.*, 1977). Thus the Ries offers the opportunity to examine directly the continuous deposits and thereby to evaluate the emplacement mechanism(s) of large scale crater deposits. A shallow drilling program was therefore pursued in August–October, 1976. The following is a brief description of some field observations.

The Ries Crater

Pohl *et al.* (1977) present a detailed summary of the entire structure including target stratigraphy, lithologies, target morphology prior to impact and the various, principal breccia deposits. The following report addresses exclusively the so called "Bunte Breccia", i.e., those deposits derived predominantly from the upper stratigraphic units of the Ries target, mainly comprising sedimentary rocks (see Pohl *et al.*, 1977). Because these deposits constitute approximately 90% of all breccias beyond the outermost crater rim they are considered a valuable analogue for continuous deposits observed around large scale, planetary impact craters (Fig. 1).

The Ries not only offers the opportunity to study such deposits in general, but it also is ideally suited—owing to a fortunate geological circumstance—to discriminate between ballistic and nonballistic ejecta deposition modes: A cliff line striking approximately east-west (Gall, 1974a) occurs to the south of the crater rim as illustrated in Fig. 1. This cliff line marks the northernmost extent of widespread shallow marine sediments (middle Miocene; "Obere Meeres-

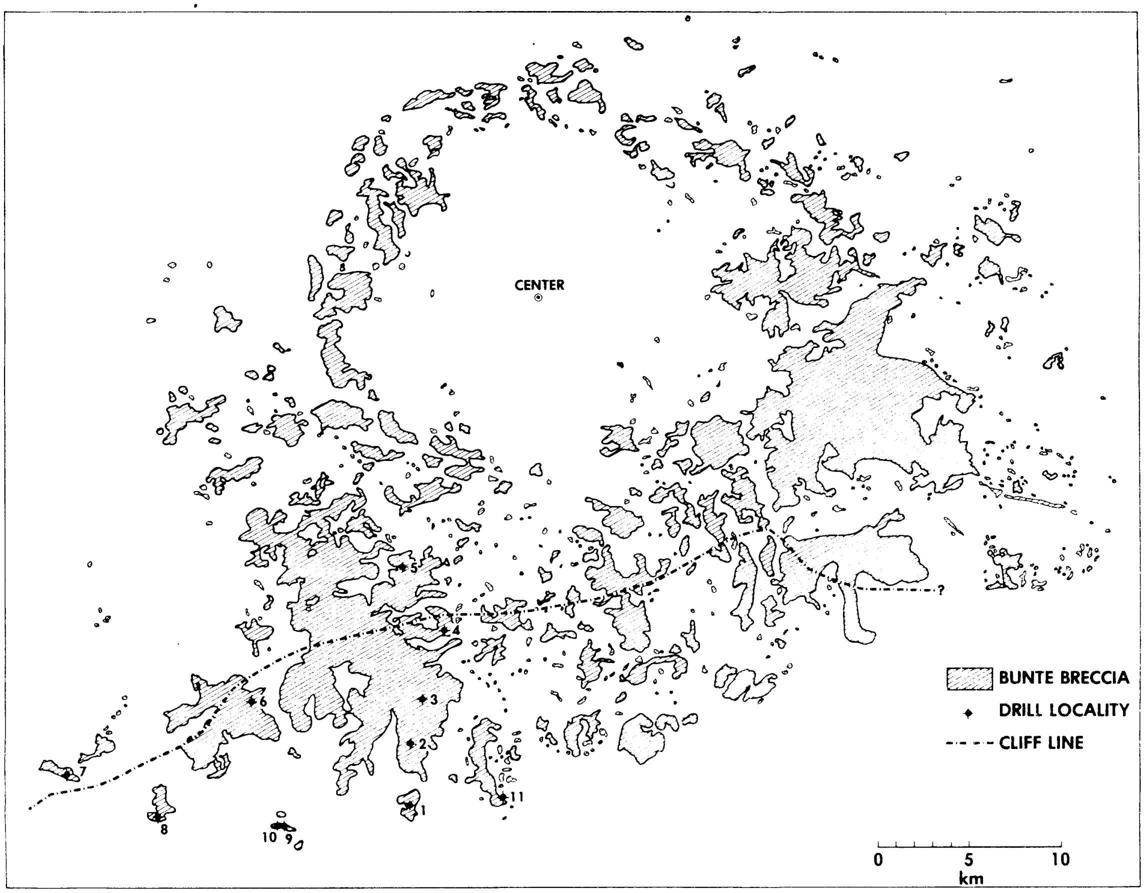

Fig. 1. Distribution of "Bunte Breccia" around the Ries Crater, Germany. Drilling locations are indicated as well as position of Miocene cliff line marking the northernmost invasion of marine OMM sediments.

molasse" (=OMM); generally medium to fine grained sands). In addition, fresh-water deposits on top of OMM occur also *predominantly* south of this cliff line, though specific facies did extend farther to the north, i.e., into the area of the crater cavity as thin (<50 m), probably discontinuous, eroded deposits (upper Miocene; "Obere Süßwassermolasse" (OSM), fine grained sands, marls, fresh-water limes, and especially clays). These conditions, i.e., cliff line and distribution of OMM and OSM deposits existed prior to the Ries event (Bolten and Müller, 1969; see also Fig. 2.2 of Pohl *et al.*, 1977). Accordingly, *most* of the OSM and *all* of the OMM sediments long known to make up a substantial part of the Ries' continuous deposits, can be taken as diagnostic indicators of "local" materials from the terrain outside the crater cavity and yet incorporated into the breccias (Ammon, 1905; Hüttner, 1958, 1969; Gall, 1969; Schneider, 1971; Gall *et al.*, 1975, and many others). It is possible therefore to distinguish unambiguously breccia components of "local" origin versus those that were genuinely derived from the crater cavity (Jurrassic limestones, marls, clays, and sandstones; triassic clays, shales and sandstones; and a few crystalline components). The stratigraphic-lithologic control of crater derived materials on one hand and a different, equally well documented set of lithologies of the surrounding target surface on the other hand (see also Pohl *et al.*, 1977), enable therefore detailed assessment of the source area of the breccia components.

Little quantitative data exist on the absolute amount of local materials in the "Bunte Breccia" deposits. Their vertical distribution within a given profile is unknown; hardly any data exist concerning their abundance as a function of radial range (Schneider, 1971; Hüttner, 1969; Gall, 1969; Gall *et al.*, 1975). Indeed, accurate thickness determinations for the entire deposit are scarce and confined to a few drill holes (e.g., Hüttner, 1969; Birzer, 1969) and geophysical measurements (Reich and Horrix, 1955; Bader and Schmidt-Kaler, 1977); thickness estimates were traditionally based on field criteria, i.e., reconstruction of detailed target morphology (e.g., Hüttner, 1958, 1969; Gall, 1969).

Selection of Drill Localities

Though breccia deposits with "local" components are described from many localities, the drilling program focussed on the "south-Vorries", because of the above mentioned cliff line and its consequences concerning OMM sediments and because detailed, modern geologic maps are available (Hüttner, 1958; Gall, 1969). The breccias of the south-Vorries and their field relations are best known.

A radial traverse was accomplished by drill localities 1–5 (see Fig. 1 and Table 1) to obtain information about the amount of local components as a function of range from the crater center. Locations 1, 2, and 3 were selected on top of local hills for two major reasons: (a) to obtain the least eroded vertical section and, (b) to determine to what degree the Bunte Breccia is merely draping a preexisting relief as a thin veneer or whether the deposits themselves are controlling the present-day relief. Clarification of this question is paramount in volumetric estimates of the Bunte Breccia deposits and also bears on the emplacement mechanism. Drill holes number 4 and 5 are placed in areas where suevites are known to overly the "Bunte Breccia" (see e.g., Pohl *et al.*, 1977) and thus yielded demonstrably uneroded profiles of Bunte Breccia. With the exception of core number 5, all cores were obtained from south of the cliff line, for most reliable identification of local components; number 5 was just north of the cliff line and serves as a tie point for potential changes of breccia character south of the cliff line.

Locations 7–11 were chosen to assess areal variations of Bunte Breccia between ≈2 and 3 crater radii range. They explore Bunte Breccia essentially at the greatest radial range for any given azimuth. They are all located on top of modest local topographic highs, the typical mode of occurrence for Bunte Breccia at such distances.

Locality number 6, also on a local hill, served two purposes: first it is a classic locality for the discussion of ejecta thickness and its relation to preexisting relief (e.g., Hüttner, 1958) and the outcrop "Guldesmühle" in its vicinity has received recent attention for the interpretation of the emplacement mechanism of Bunte Breccia (e.g., Hüttner, 1969; Schneider, 1971; Hörz *et al.*, 1974; Chao, 1974). Second, core number 6 may be considered part of a (poorly documented) radial subtraverse in conjunction with localities 5, 7, and 8.

Drill cores were obtained using a truck-mounted drilling rig; core diameter was 101 mm; core recovery in Bunte Breccia was ≈95%; some drilling through large megaclasts (>5 m) was destructive because of rotary drilling for economic reasons. A total of 560 m was drilled and 480 m of core was recovered.

Table 1 sumarizes some first order geographic, topographic, and geologic data. The observations we report here were all obtained in the field during initial core description, aided by a hand lens. The present report contains only major findings, which we feel confident will remain valid also after laboratory analyses because they address large scale features only.

The Depth of Bunte Breccia

Thickness of the Bunte Breccia deposits is highly variable (Table 1) and the deepest deposit was penetrated at locality 11 (Lutzingen, Goldbergalm). Because the drill hole was not placed on the very top of a hill, a total depth of >100 m of Bunte Breccia may be postulated for that locality at a distance of ≈27 km from the crater center (Fig. 1). Gall (1974b) describes Bunte Breccia from Tapfheim (≈29 km) overlain by fluviatile deposits of the Danube at an elevation ≈410 m a.s.l. Together with other reported Bunte Breccia deposits at many intermediate locations, this would indicate that Bunte Breccia may have covered substantial parts of the south and southeast Vorries to depth in excess of 50 m. This is one of the most important results of the drilling program because traditional interpretations had postulated that most of the deposits were draping a preexisting relief as a relatively thin veneer, thus mimicking the preimpact relief. However, the depths obtained now are comparable to those obtained from the east/southeast Ries by Birzer (1969) and Bader and Schmidt-Kaler (1977), who

Table 1.

Drill location	Range[1] (km)	Azimuth	A.s.l. (m) Top[2]	Bottom[3]	Total thickness[4] of Bunte Breccia	Bottom of Bunte[5] Breccia a.s.l. (m)	*In situ*[6] material
1	28.5	194	495	480	>15	<480	??[7]
2	25.5	196	534	471	52	482	OMM
3	23	196	553	469	76	477	OSM
4	19	195	502	460	34	468	Upper Jurassic Lime
5	16.5	207	568	488	>80	<488	??[8]
6	27	115	558	486	47	511	OSM
7	36.5	225	492	446	17	475	Upper Jurassic Lime
8	35	216	560	528	28	532	OSM
9	32	206	506	499	>7	<499	??[9]
10	32	206	505	482	21	484	OMM
11	27	184	503	401	84	419	OSM

[1]Range: From crater center (see Pohl *et al.*, 1977).
[2]Elevation of drill point above sea level (= top of profile).
[3]Elevation of final drill depth above sea level (= bottom of profile).
[4]Total thickness of Bunte Breccia encountered.
[5]Elevation above sea level of contact between Bunte Breccia and undisturbed country rock.
[6]Undisturbed country rock in contact with Bunte Breccia; because "local" components may form "megaclasts" of considerable size (> 10 m) it was necessary to penetrate substantially into the country rock for reliable identification of the Bunte Breccia substrate contact.
[7]Exploratory drill hole; terminated in OSM megaclast.
[8]Contact misinterpreted initially; terminated in upper Jurassic limestone megaclast.
[9]Exploratory drilling revealed Bunte Breccia >7 m; drill hole no. 10 is at same locality (≈10 m distance away) and fully cored.

report "unusual" depths of up to 200 m for deposits filling a localized depression, i.e., the preexisting Main valley (at a radial range of ≈28–30 km). Since our results were obtained during drilling of hills, our thicknesses encountered cannot be attributed to trapping of ejecta in depressions.

The deposits of Bunte Breccia encountered at our localities are mostly deeper than expected and do not mimick a preexisting relief. Indeed, where possible, i.e., where reliable geologic maps exist, the breccia depth may be qualitatively predicted by simply projecting the OSM (OMM) substrate as a horizontal datum plane (e.g., localities 2, 3, 4, 7, 8, 9, 10). Thus, the new drilling results suggest that the preexisting target morphology in the south-Vorries is not necessarily related to the present-day morphology; small scale present-day relief appears to have little in common with the morphology just prior to the Ries event. No detailed field data exist to determine whether the present relief and distribution of Bunte Breccia is a primary feature associated with the emplacement mechanism (e.g., analogous to dunes, ridges, and other morphologic landforms observed around large scale lunar craters) or whether the relief is exclusively determined by erosion since crater formation some 15×10^6 yr ago (Gentner and Wagner, 1969).

Breccia Components

The deposits to the south of the cliff line are composed of a large number of crater derived and local components (Fig. 2). Clast sizes may vary from tens of meters to <1 mm; clast size appears to be independent of source area because clasts >10 m from both local and crater sources are observed. These clasts are embedded into a relatively fine grained, clastic matrix. The vol.% of matrix is variable, generally, however, >50% of the entire volume. Because of the abundance of clays and unconsolidated sands, the entire breccia deposit is relatively unconsolidated and parts of the recovered cores disintegrate rather readily.

The following field terms apply: "matrix" is everything <1 cm in grain size. "Clasts" occur on all scales and will be qualified by size; "megaclasts" are monolithic inclusions >1 m by definition. In the following, we will describe the nature of the breccias from large to small scales, i.e., from megaclasts to matrices.

1. *Clasts*

The extreme variability in abundance of megaclasts is striking. Figure 3 attempts to illustrate this point by plotting volumes of local and crater derived megaclasts as well as the remainder of the core (= *all* materials <100 cm). Not only is the total volume of megaclasts highly variable, but also the ratio of local versus crater derived megaclasts.

We also recorded the frequency of occurrence of all clasts between 5 and 100 cm in the field, starting with drill hole number 3 (Fig. 4). The observations

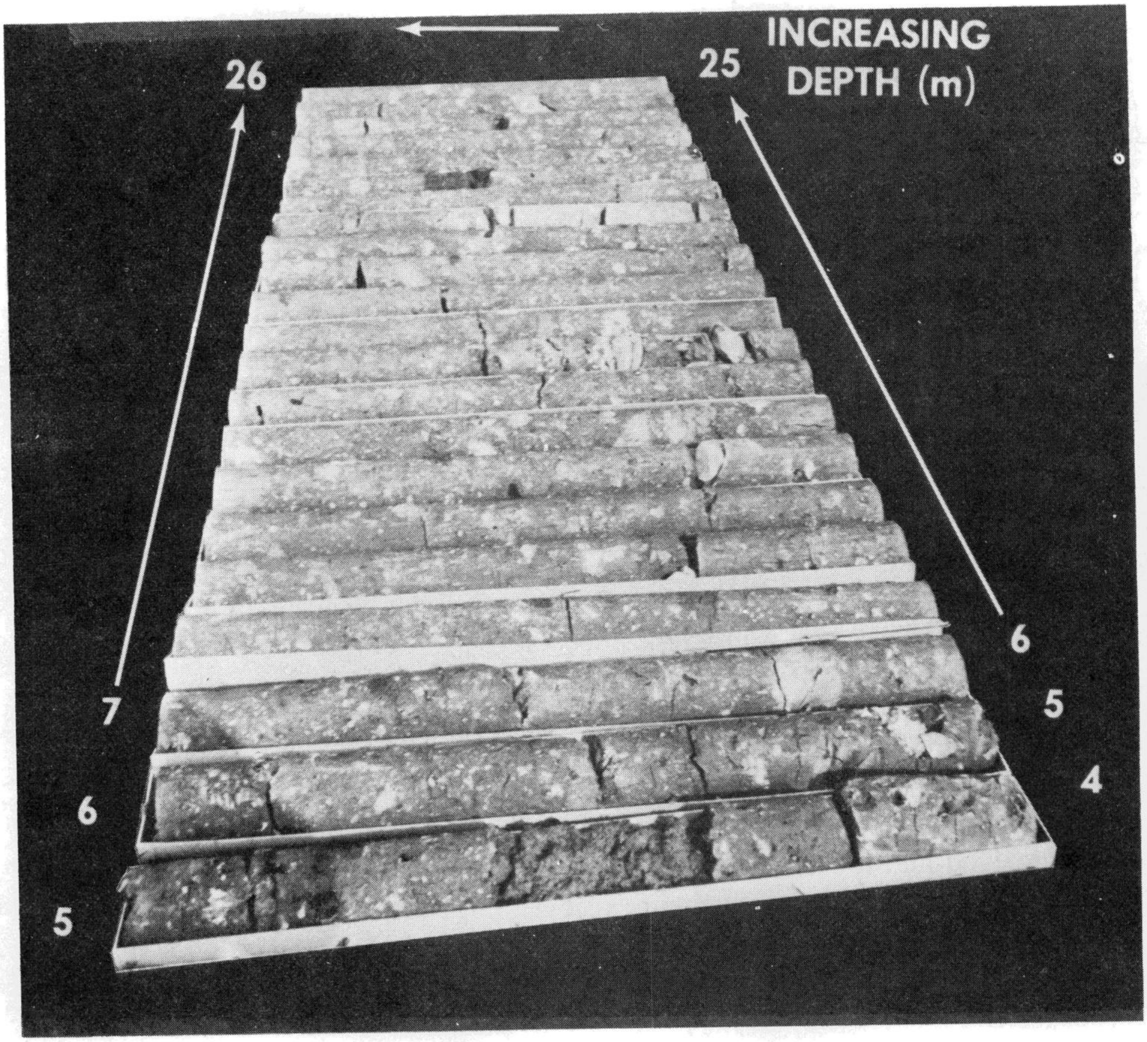

Fig. 2. General view of cores from drill hole No. 8. Note the differing clast sizes and different color shades, indicating different lithologies. Also note the relatively unstructured, massive character of the breccia matrix and the irregular orientation of clasts (length of core container: 1 m; core diameter; 101 mm).

are at present confined to only that half of the core surface which was readily accessible for inspection after the cores were placed in their respective containers. Thus the data are by necessity of a survey type nature, though valid in comparing relative frequencies of local versus crater derived clasts. No volume percentages are given because this will be possible only after a more thorough planimetric study of the cores. However, the qualitative data contained in Fig. 4 serve to illustrate two points which will certainly hold after more detailed analyses: first, the ratio of local versus crater derived clasts of 5–100 cm diameter varies in an irregular fashion with respect to radial range and second, the frequency of these clasts per running core meter (= unit surface ≈ unit volume) is also variable.

Hüttner (1969) and Gall *et al.* (1975) report decreasing mean diameters for megablocks >25 m of crater derived materials (in particular of upper Jurassic limestones) as a function of range. The data contained in Figs. 3 and 4 indicate that significant variations may exist within these trends. Referring to Fig. 3, the breccia encountered at locality 3 is much more "fine grained" than that of locality 2, despite the fact that core 3 was taken somewhat closer to the crater. In keeping with the large scale trends, cores 7, 8 and 10, however, are of a more fine grained nature, if not devoid of megaclasts (see also Fig. 2). Frequency of crater derived megaclasts appears indeed to decrease with increasing range (cores 10, 8, 7) though localities 4, 3, and 2 also contain either little or no crater material >1 m. Data of Fig. 4 show that relatively small crater clasts may occur in variable abundance in all localities; no systematic trends are obvious within the core materials, in contrast to Schneider (1971). Though not illustrated, clasts of all sizes and both of local and crater derived origin may occur along the entire profile; their distribution appears to be irregular. There are no apparent trends and concentrations of either source toward the top or bottom of the profile, again in contrast to Schneider (1971).

In conclusion the field observations of clast populations present strong

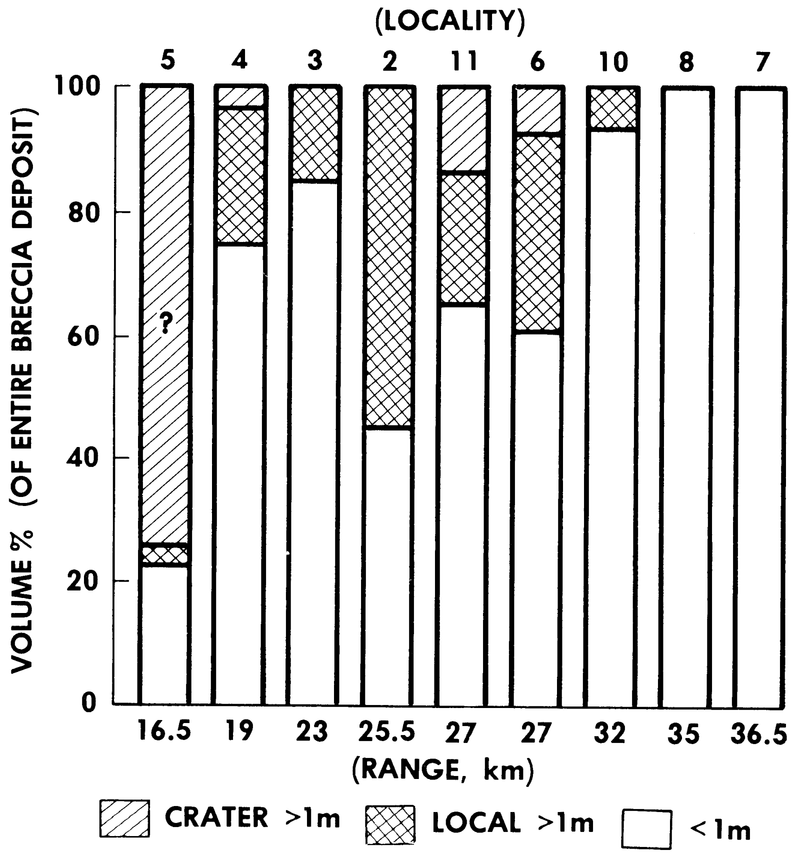

Fig. 3. Vol.% of local and crater derived "megaclasts" (>1 mm) and cumulative volume of all other components including genuine matrix (<1 m) as a function of radial range from the crater center. The source area of all megaclasts encountered in No. 5 is difficult to evaluate, because of its position north of the cliff line. The radius of the Ries Crater is ≈13 km.

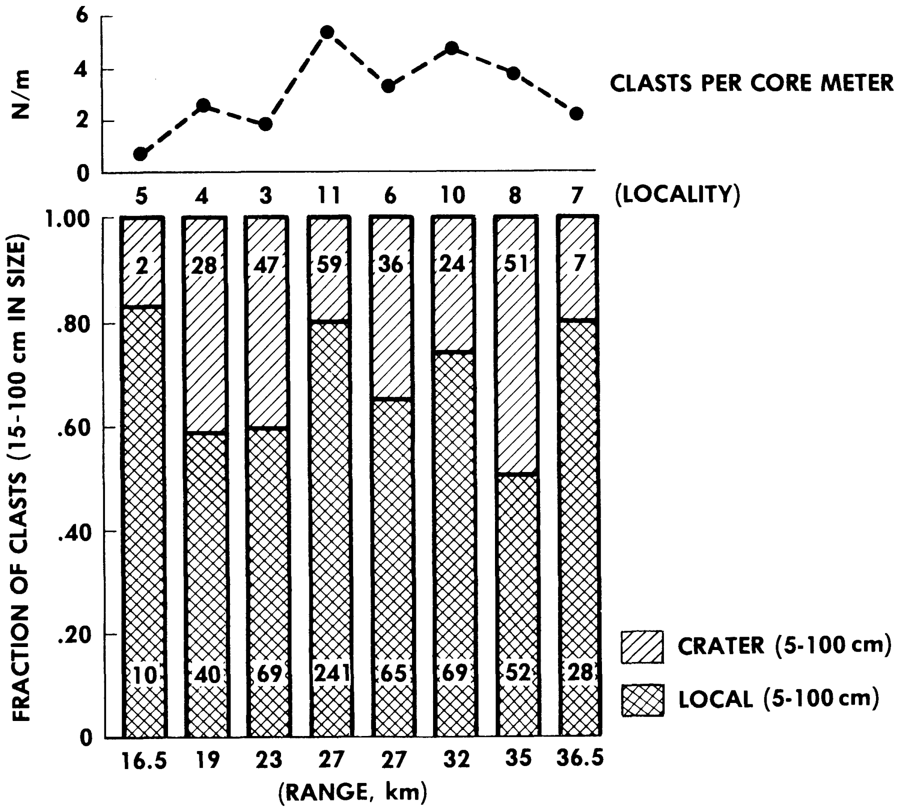

Fig. 4. Population studies of local and crater derived clasts 5–100 cm in diameter as a function of range. "Fraction" simply refers to numbers of clasts with observed absolute numbers inserted in each column. N/m refers to total number of clasts 5–100 cm in size per running core meter of matrix.

evidence that the emplacement mechanism of the Bunte Breccia produced highly variable clast sizes, incorporated large, though variable amounts of local clasts and mixed both crater and locally derived components rather thoroughly. Significant variations in clast populations may be encountered over distances measured in a few kilometers, i.e., the spacings of e.g., holes 5, 4, 3, and 2, along a radial traverse, though natural or man made outcrops in the Vorries suggest that such variations occur over still smaller distances.

2. *The Matrix*

The matrix is extremely complex and detailed description is not possible in the field. However, a few field observations referring especially to the *variability* of the matrix are described below:

First, the total amount of matrix differs from locality to locality. It may range from approximately 20% (locality 4) to >80% (localities 8 and 7). The amount present at each locality is roughly approximated by the <1 m category in Fig. 3, because the total volume occupied by clasts from 5–100 cm diameter is generally <20% of the entire core.

Second, the matrix encountered in different localities is not uniform as evidenced by different color shades, variable grain size, different proportions of clay and sand components, and various populations of discrete clasts between .1 and 1 cm in diameter. To the naked eye—aided by a hand lens—the matrix is largely made up of locally derived materials (see also Schneider, 1971), i.e., soft clays and unconsolidated sands of OMM or OSM, which are intimately mixed on centimeter and smaller scales, though frequently either one of them may dominate if not—on occasion—constitute the entire matrix.

Third, the variations in matrix character described above do even occur within one profile, though generally on a more subtle scale (Fig. 5). Within a given profile the various types of matrices may have dimensions on the order of a few meters, though variations on smaller and larger scales are also observed. The transition from one matrix type to the other may either be gradual, typically measured in decimeters or it may be rather abrupt (<1 cm) (Fig. 5). Most frequently, different types of matrices are sandwiched in between megaclasts, with the character of the matrix remaining fairly homogeneous *between* clasts, but different on either side of the clasts.

Fourth, the .1 and <1 cm clasts, considered part of the matrix, are also variable both with respect to frequency and lithological character; especially frequency and component lithologies of crater derived sources appear to be independent of the <.1 cm ground mass comprising the bulk of the matrix.

The above field observations concerning the matrix and its variability lead to the following conclusions: the matrix is to a large degree locally derived. It is extremely well mixed on centimeter scales, though pronounced heterogeneities measured on decimeter and meter scales exist within any locality. The frequent change in matrix character on either side of megaclasts and the occasionally observed, knife edge sharp contacts between two neighboring matrix types (Fig. 5) suggest that a large proportion of the matrix may be deposited as discrete, extremely polymict "megaclasts". The variable lithologies and thoroughly mixed nature of these matrix clasts seems to indicate that various matrix types were formed initially at distinctly differing locations and subsequently transported to a common, final resting place. It is unknown at present how far such breccia clasts were transported and how far apart their respective source areas were. However, all are derived from south of the cliff line (excepting cores 5 and 7), which limits both distances to less than ≈2 km for at least locality 4; similar distances may be postulated for locality 8 also. Hüttner (1958) and Gall (1974a) reported on limestone clasts in the Bunte Breccia which are characterized by pholade bore-holes and which, therefore, were dislodged from the Miocene cliff line. Such limestones were found as far as 10 km to the south of their closest source area, indicating significant lateral transport of local components.

Textural Observations

All core materials were inspected for preferred orientation of clasts, lineations in the matrix, style of deformation of soft clays, and noncohesive sands,

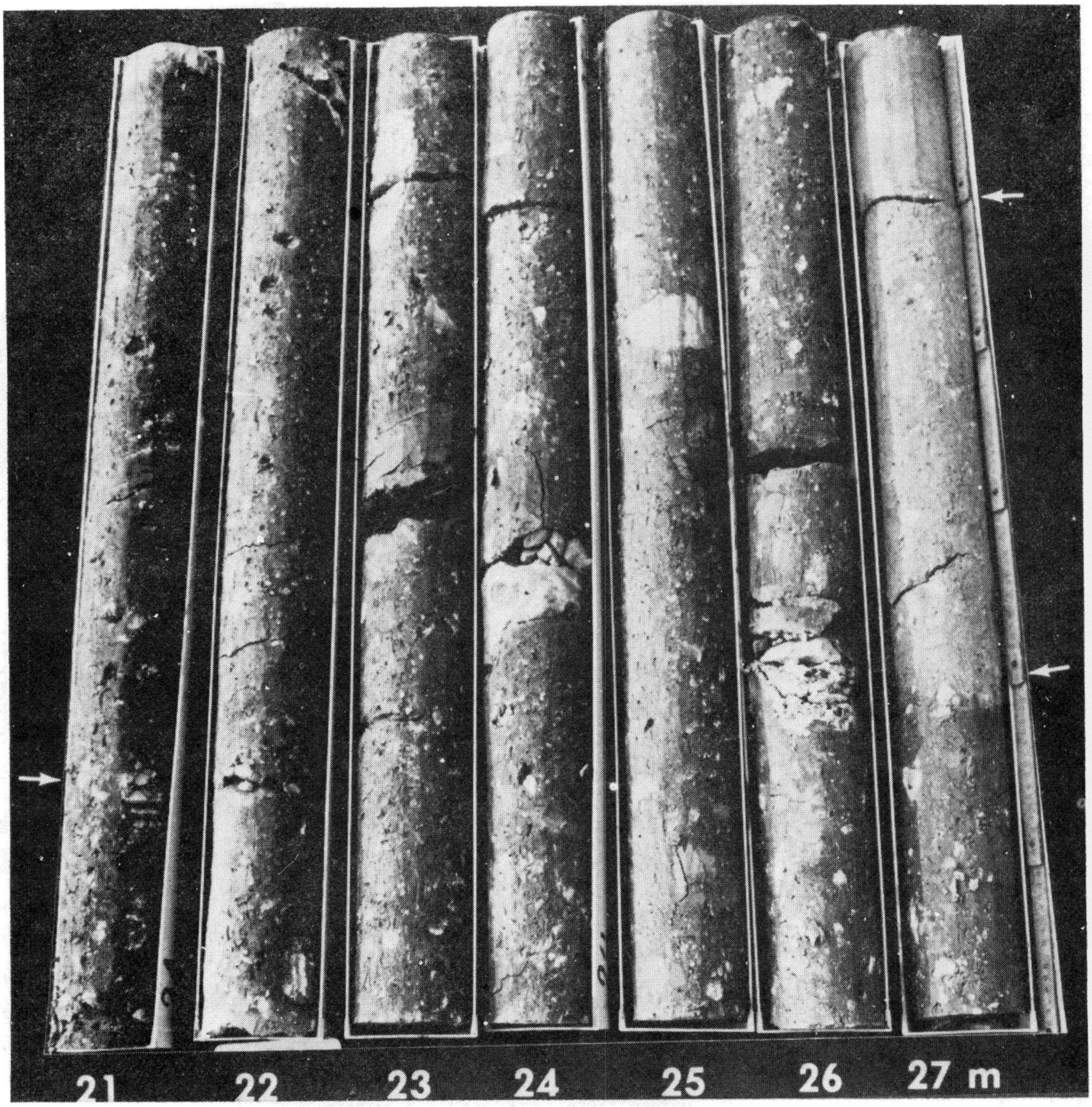

Fig. 5. Cores from locality No. 8 illustrating various matrix characters: Note distinct change of matrix character at ≈21.30 and at 27.35 m. Though more difficult to observe, the character of the matrix between 21.30 and 27.30 m also changes *gradually* from a more clay-rich (OSM), darker matrix to a lighter, more sandy (OSM/OMM) matrix. Note also irregular distribution and orientation of clasts and the equant shapes of many clay clasts in contrast to some deformed inclusions. Furthermore light colored, monomict, cataclastic limestones are readily identified. At 27.80 m, a *sharp contact to the in situ OSM substrate* (= fine grained sands) occurs.

etc., in an attempt to determine whether the depositional environment was largely turbulent or laminar. For the first we expect a rather random orientation of linear textural elements, while the latter should result in more or less lineated textures. The observations were performed on the cylindrical core surfaces occasionally aided by orthogonally cut samples.

1. *Orientation of monolithic clasts* <50 *cm*

These observations generally refer to clasts up to 50 cm in size, with the bulk of the observations, however, based on 1–10 cm clasts. The majority of all clasts appears to be oriented irregularly as illustrated in Fig. 5. The field evidence argues strongly for a random orientation of clasts. These observations apply not only to the orientation of a clast's longest axis, but also to primary sedimentary textures such as rare bedding planes in some sand clasts, foliation of shales and primary layering in clay clasts. On occasion, however, sections of matrix were encountered, which did contain some uniformly oriented clasts, distributed over 10–50 cm of core length. Such occurrences are rare and they are confined to individual matrix clasts, i.e., do not transgress into an adjoining matrix type. Common dip angles of such oriented clast groups are variable from group to group, i.e., matrix type to matrix type, thus strengthening our observations that discrete breccia matrices are deposited as megaclasts.

2. *Lineations in the matrix*

Two types of "lineations" were searched for: one among the abundant .1–1 cm clasts embedded in the matrix and a second among the fine grained sands and clays in the groundmass proper. In general, no preferred orientation of .1–1 cm clasts is observed; their orientations are highly irregular, if not random both with respect to longest axis and primary sedimentary textures. In general, the fine grained sandy and clayey groundmass also displays no lineations. Thus the overall appearance of the matrix is that of a thoroughly mixed, rather "massive" deposit, devoid of linear structural and textural elements (Fig. 6).

Though the above "massive" character is by far the most abundant, there are also matrix sections which display irregular swirls and other highly contorted configurations of alternating and interfingering sandy and clayey matrix components as well as individual sand and clay clasts. Such textures are indicative of turbulent forces during ejecta emplacement.

In contrast to these "massive" and "swirly" matrix types there are however, rare instances where good and even extremely well developed matrix lineations occur. In these sections the clay and sand clasts are extremely deformed, elongated and smeared out, quite frequently >5 cm in length and <.5 cm in width. Such matrix lineations are preferably horizontally oriented though other orientations occur; furthermore they are particularly abundant in locality 2 and extremely rare to nonexistent in the other localities.

3. *Deformation structures of clasts* >1 cm

Two types of deformation may be observed: "external" deformation referring to overall shape of the easily deformed clay and sand clasts and "internal" deformation as evidenced by primary, sedimentary features.

Many examples exist for external deformation, especially well displayed by

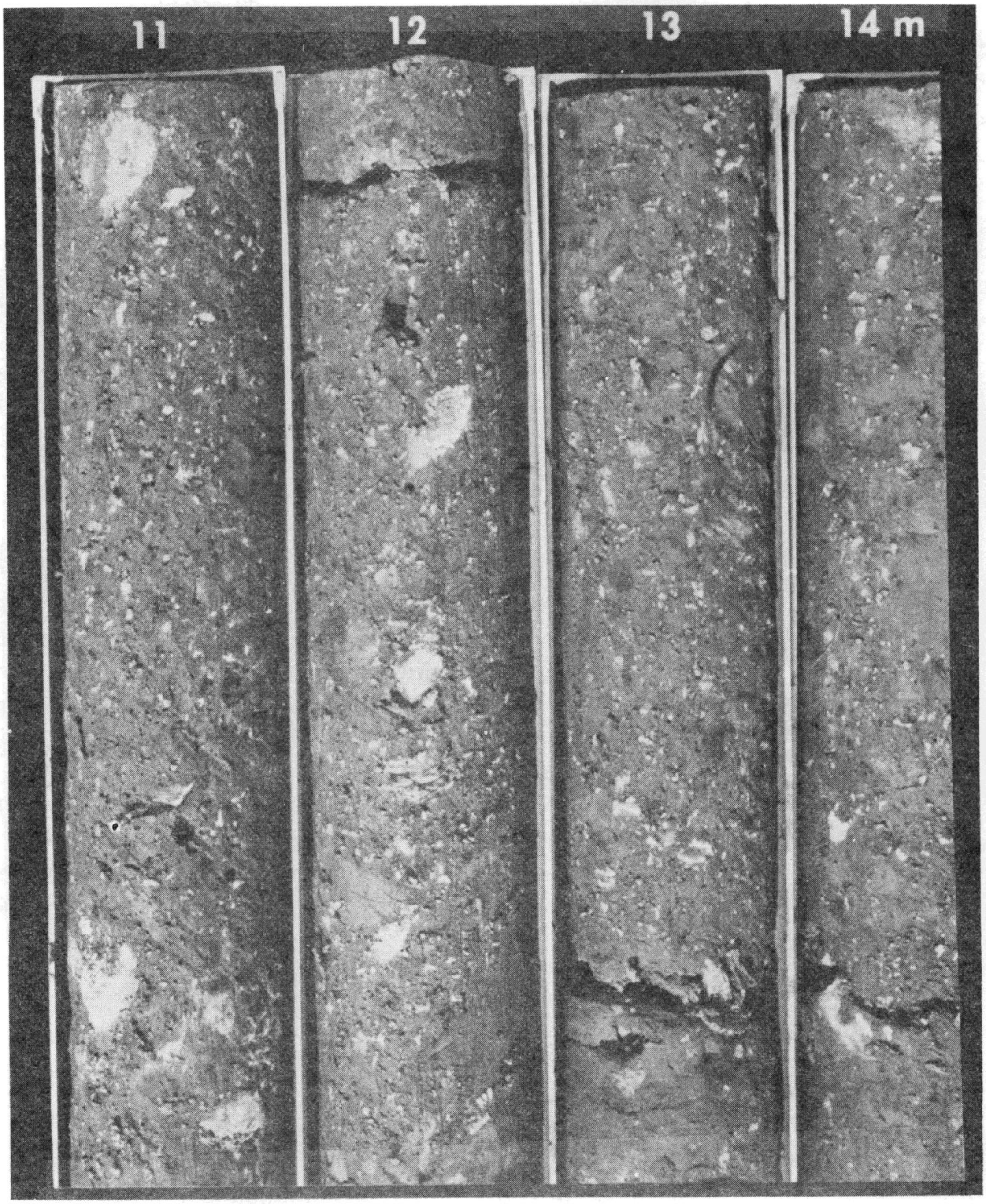

Fig. 6. Closeup of Bunte Breccia (locality 8). Note irregular orientation of clasts and "massive" character of matrix.

highly contorted, twisted, and elongated clay clasts (Fig. 7). Very commonly, however, one may also observe clay, and in particular, sand clasts that are relatively equant and undeformed, as also illustrated in Fig. 7. Notice the close spatial association of deformed and undeformed clasts in Fig. 7. Clasts >5 cm

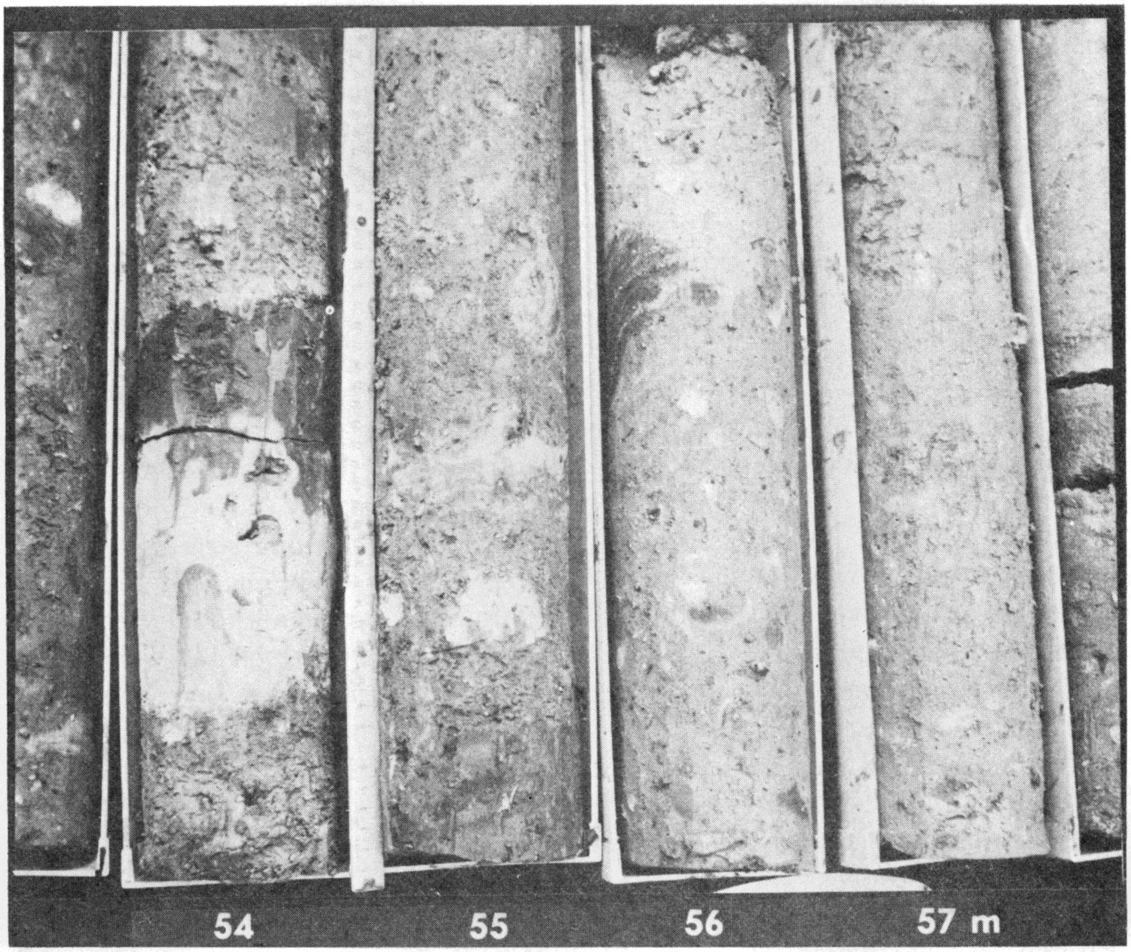

Fig. 7. Unusual concentrations of relatively large clay clasts (locality 11). Note various degrees of deformation of relatively soft clay clasts and irregular direction of deformation force vector. Note also "mixed clast" at 54.09–54.31, representing "breccia within breccia", and the relatively sharp contacts with surrounding breccia matrix.

appear to be more severely and more frequently deformed than those <5 cm, where relatively equant shapes seem to dominate (Fig. 7).

Primary sedimentary structures of clay, shale, and sand clasts are commonly deformed, ranging from modestly wavy, possibly folded textures to extremely complex, contorted, and twisted configurations. Again, however, undeformed clasts are commonly observed, though not as frequently as the deformed ones and furthermore predominantly in the size range <5 cm (Fig. 7).

The "local" megaclasts (>1 m) are generally only modestly deformed, if at all. Complexly contorted, twisted, and swirly textures are extremely rare in the megaclasts. In many cases original sedimentary textures are so well preserved and so consistent along the entire megaclast that dip angles of the entire inclusion may be readily obtained; these dip angles are highly variable.

We thus conclude from these textural observations that the depositional environment of the Bunte Breccia was dominated by turbulent forces. Furthermore, utterly deformed, contorted and twisted clasts may be in close spatial association with completely undeformed inclusions of the same lithology, indicating highly variable energy distributions during breccia formation. Laminar flow is evidenced by lineated matrix types but appears to be of subordinate importance.

EVIDENCE FOR EXTENSIVE MIXING

General

As already partly described and illustrated in Figs. 5–7, the core materials are extensively mixed on all scales. Clasts ranging from meter to probably submicroscopic sizes may occur anywhere along the core profiles. Though variable, the preponderance of mixing on centimeter and millimeter scales in essentially all matrix sections is truly extraordinary. Local and crater derived materials participate equally well in this mixing process and may be encountered on all scales of naked eye and hand lens inspection. Component populations with respect to size frequency and lithology of clasts are variable, however, any particular component may never be excluded *a priori*, though any specific component may very well be absent in some cases. The intensity of the mixing process must have been such that the above described matrix differences only represent variations of an extremely efficient, omnipresent and thorough mixing process operating south of the cliff line.

This mixing process was not only thorough but also extremely energetic. The energetic nature of the mixing process is illustrated by small limestone clasts (<1 mm in size) which occur in the center of decimeter sized sand or clay inclusions (Fig. 8). Even more startling are similar, small inclusions of clays within clays or sands; almost incomprehensible are discrete sand inclusions lodged inside pure clay clasts. These inclusions have no obvious connection to neighboring sand clasts. The relatively unconsolidated sands must have penetrated the very viscous clays while maintaining their integrity and without significantly deforming the host material either. These phenomena are truly startling, but attest to very high relative velocities between clast and host materials during the mixing process.

Qualitatively similar arguments can be made for some core sections which have matrices of predominantly one lithology, e.g., almost pure OSM clays or OMM sands. The clastic components in these sections are evently distributed and display a large variety of lithologies and/or clast sizes. However, the primary sedimentary textures in such "matrices" do not indicate large scale deformation, much less wholesale auto brecciation and mixing of the host material. Again it appears that penetration was accomplished rather nondestructively by *all* clast components, irrespective of local or crater derived origin. Particular emphasis is placed on such observations which involve exclusively locally derived host and clast materials because they demonstrate collisions at relatively high velocities of local components only.

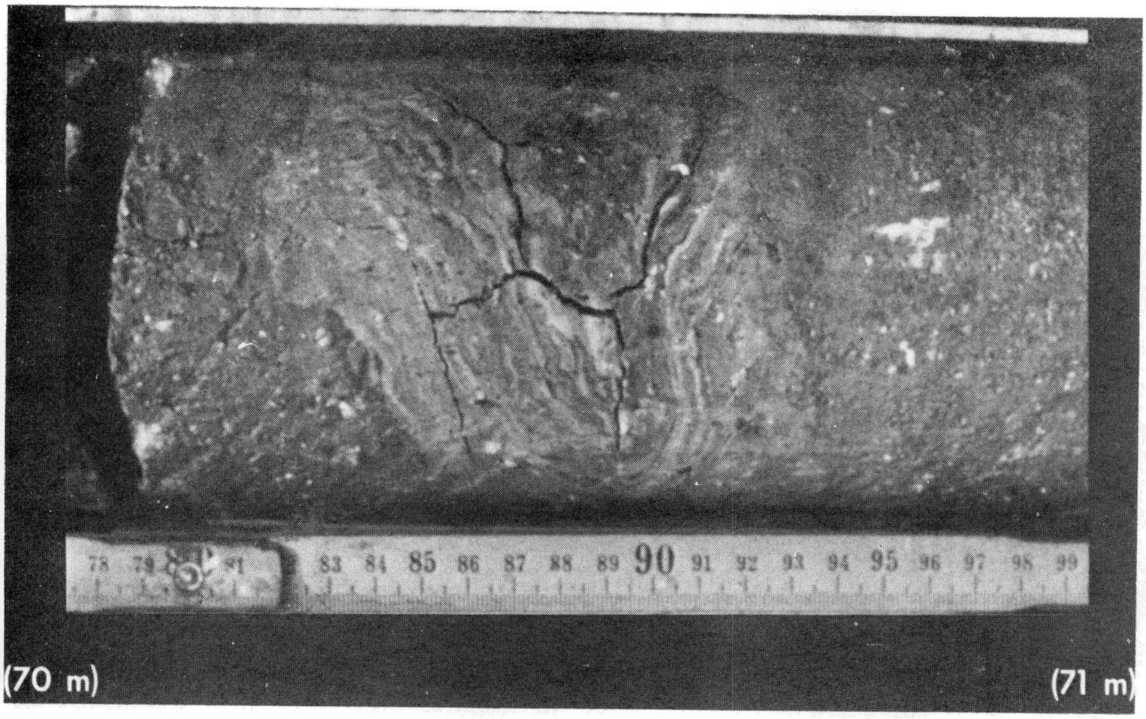

Fig. 8. Closeup of Bunte Breccia (locality 5, ≈70.90 m deep). One of the best examples of deformed, i.e., folded clay clast. Close inspection will reveal some clastic, brecciated material within this clast, thus illustrating three "breccia within breccia" generations.

In contrast to this relatively energetic and violent mixing, there is, however, evidence for less energetic conditions in close spatial association: many clasts are undeformed and must have been embedded rather gently into the polymict matrix. Furthermore, the contacts between megaclasts and matrix or contacts between various matrix types may be exceedingly sharp without evidence of mixing. Clasts <10 cm of noncohesive sands and soft clays more often display knife sharp contacts than evidence of mixing with the surrounding, polymict breccia (Figs. 5–8). These observations imply that some, if not most, of the clastic material was embedded into the polymict matrix relatively gently.

In conclusion, the mixing process operating south of the cliff line was extremely efficient, thorough, and omnipresent. The intensity of mixing may range from extremely energetic, requiring high relative velocities, to rather gentle forces. Evidence for both violent and relatively gentle forces is so abundant and in such close spatial association that one must postulate a mixing process of dramatically different energy levels in close spatial and temporal proximity.

Breccias within breccias. The above described clastic materials within monolithic host materials that are embedded in some matrix can be viewed as "breccia within breccia". The same applies to relatively small sections (<1 m) of one matrix type breccia bounded by some other matrix type(s) (e.g., Fig. 5). Frequently one observes also distorted, yet distinct "clasts" composed of two (or more) intimately mixed and smeared out lithologies (Fig. 7); again they can be viewed as breccias within breccias. Thus breccias within breccias are common on a large variety of scales and up to four "generations" of breccias within breccias were encountered, e.g., a specific matrix type (breccia 4) containing a mixed clast composed of two lithologies (breccia 3), one of them containing clastic material (breccia 2) if not even brecciated (breccia 1) components (Fig. 8). While the term "generation" may be valid for one specific set of observations, such relative "timing" is not applicable to others. We envision the formation of such breccias within breccias as individual stages of a continuous mixing and recycling process; neither the number of "generations" nor their order of formation may be of general significance, as they represent minor and unpredictable excursions of a more general mixing process. They do indicate, however, that individual constituents of the Bunte Breccia and thereby the entire deposit have a complex history of mixing with discrete mixing events separated in space and time and occurring on a variety of scales (see also Hüttner, 1969).

The Contact Bunte Breccia/Country Rock

Previous studies of the Guldesmühle outcrop (Hüttner, 1969), suggested a generalized "transition zone" enriched in local components at the contact of Bunte Breccia and its substrate. At Guldesmühle, Bunte Breccia rests on relatively unconsolidated OMM sands which are also observed in decreasing abundance over a vertical distance of 3 to 4 meters above the relatively sharp contact. Thus Guldesmühle served as a classical site to study the incorporation of local materials (e.g., Hüttner, 1968, 1969; Oberbeck *et al.*, 1975; Chao, 1974). Such "transition" zones are not observed in any of the new core materials. With the exception of locality 8, all cores displayed extremely sharp contacts measured over <5 cm; most are indeed knife edge sharp (Fig. 9). The contact at locality 8 may have a transition zone of 50 cm width (see Fig. 5). Such sharp contacts are surprising because in many cases the substrate is formed by unconsolidated OSM or OMM sands (see Table 1), i.e., by exactly those materials that in turn make up a large fraction of the matrix and clasts. Thus the outcrop Guldesmühle needs re-evaluation and cannot be generalized to the entire Bunte Breccia deposit.

The substrate itself lacks any deformation features (except at locality 4). At distances measured in less than decimeters the primary sedimentary textures, e.g., bedding planes, etc., are not only horizontal, but also completely undisturbed. At locality 4, the substrate is formed by upper Jurassic limestones which are thoroughly fractured and shattered over a distance of ≈90 cm; there is a distinct gradient of decreasing deformation with increasing depth along this 90 cm zone.

Furthermore, none of the contacts observed represents the old land surface prior to impact, because they lack any pre-Ries weathering horizon. Such weathering horizons are found as discrete clasts in the Bunte Breccia deposit, however. The lack of any weathering products at the present contacts implies complete stripping of the old land surface to depths of ≫5 m; the present contact

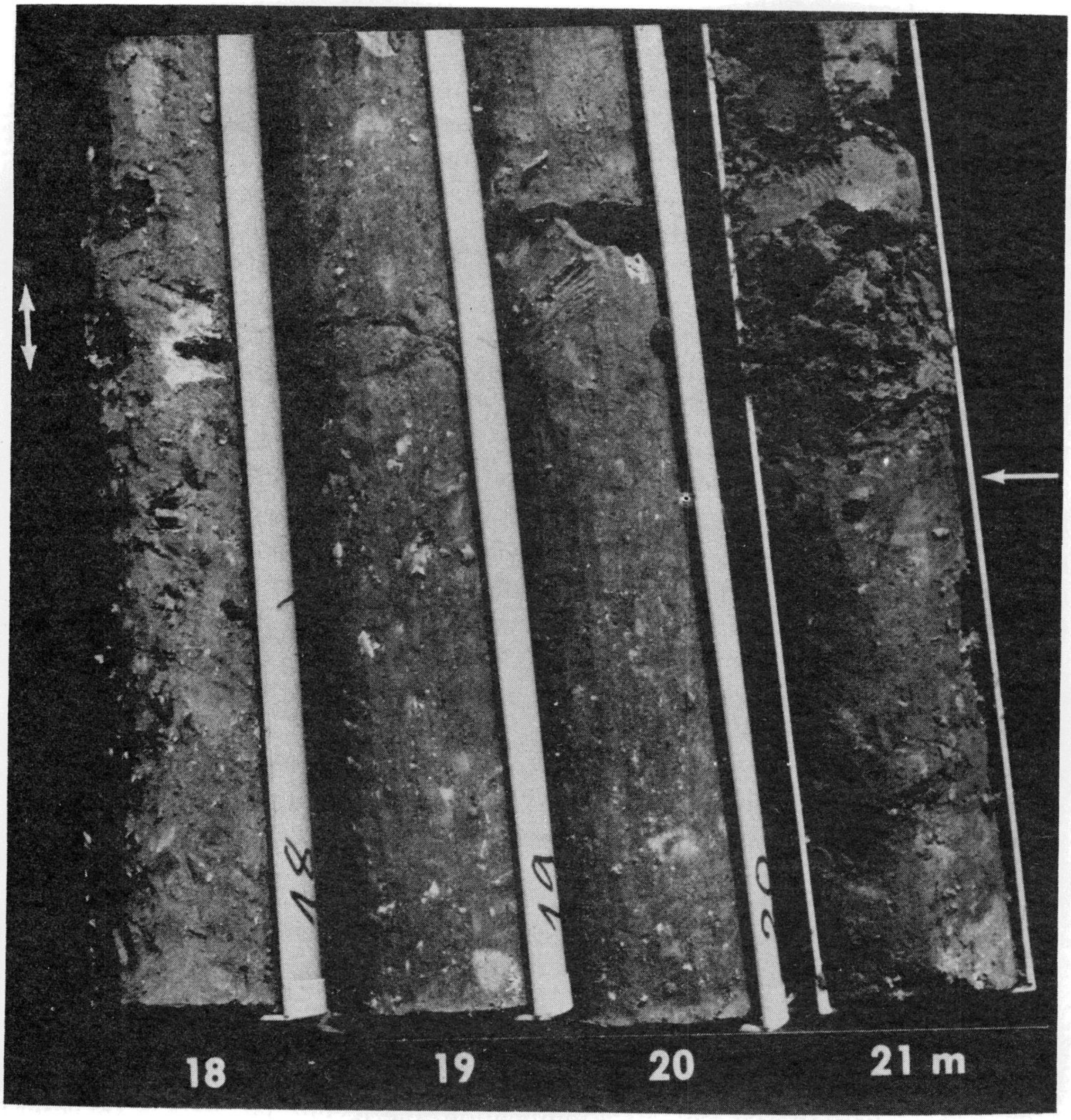

Fig. 9. Sharp contact of Bunte Breccia and underlying unconsolidated OMM sands at locality 10 and 21.35 m depth. Again note a "matrix" clast between 21.02 and 21.35 m and a gradual change in matrix character at ≈18.45 m

surface was created by the ejecta emplacement mechanism prior to final deposition of the Bunte Breccia.

We therefore conclude from the observations concerning the contact of allochthonous/authochtonous masses that most contacts are rather sharp and the old target surroundings were stripped to depths below the old weathering horizon before final deposition of the breccia layer.

PERCENTAGE OF LOCAL MATERIALS

Oberbeck *et al.* (1974) postulated that the percentage of locally derived components in large scale crater deposits increases with radial range. Therefore an attempt was made in the field to estimate the ratio of locally derived materials versus primary crater components for the Bunte Breccia. Because of the fine grained matrices that constitute as much as 80% of the core materials, accurate ratios may be obtained only after careful examination of the matrix and detailed volumetric assessment of all clasts both of which must be completed in the laboratory.

Presently available field estimates, however, indicate that local components dominate the character of Bunte Breccia south of the cliff line. Local materials may vary between 50 and 80% of the entire deposit for most cores; cores number 7 and 10 may contain >90% local components. Schneider (1971) arrived at similar observations based on the analysis of heavy mineral populations and he actually identified "breccias that do not contain components from the crater cavity". This latter finding, however, may apply only to rare matrix types and does not hold for an entire breccia profile; crater components—though subordinate—may be found essentially anywhere in our cores.

Although no precise volume fractions for the local components can be given at present, the important and fundamental prediction of the ballistic ejecta hypothesis is strengthened by present field estimates: continuous deposits around large impact craters contain local materials which may dominate the entire deposits at sufficient ranges; at the Ries, local components may constitute as much as ≈90% of the total deposits at ranges of 2–3 crater radii.

DISCUSSION

The reported field observations contain important new results for the Ries itself and by analogy, for planetary, large scale, continuous crater deposits beyond the crater rim.

Though of limited planetological implication, the newly determined thickness of Bunte Breccia is significantly deeper than previous estimates and thus of great importance to the Ries. Bunte Breccia is not a thin veneer mimicking a preexisting landscape. Thus, a variety of previous estimates of Bunte Breccia volumes need serious reconsideration as well as the reconstruction of preimpact target morphology and relief. It is unclear at present, to what degree thickness variations and present-day relief are the result of erosion or to what extent they may reflect primary features of the emplacement mechanism.

A variety of new observations concerning the incorporation of local materials and the mixing of the entire breccia unit were described. These lead to important observational insight and constraints about the formation of Bunte Breccia and—by analogy—other planetary, large scale crater deposits:

(1) Incorporation of local materials is significant and may lead to widespread

deposits that contain only subordinate amounts of crater derived materials.

(2) Judging from the total thickness of Bunte Breccia and from the percentage of local components present (>90%), the emplacement mechanism must have excavated and disturbed the surrounding crater terrain to depths in excess of 50 m.

(3) As evidenced by the sharp contacts of Bunte Breccia with the underlying substrate and by the undisturbed nature of the substrate itself it is mandatory to invoke a process that excavated and stripped the crater surroundings to significant depths prior to terminal emplacement of the breccias.

(4) Random orientation of clasts and the massive matrix character indicate a predominantly turbulent environment, rather than laminar flow.

(5) Multiple generations of breccias within breccias indicate discrete mixing and brecciation events at discrete locations and/or times, thus attesting to a complex, multi-stage mixing process.

(6) Various matrix types are generated during the intense mixing process and may be incorporated into the overall deposit as discrete clasts.

(7) Evidence for energetic mixing is present, requiring significant relative velocities of both crater and locally derived materials to penetrate each other.

(8) Evidence for "violent" and "gentle" forces is so abundant and in such close spatial association that an environment of dramatic energy variations over small distances must be postulated.

These observations lead to the following major constraints: any ejecta emplacement mechanism must be capable of excavating local terrain, incorporating and thoroughly mixing these materials with crater derived components and transporting such components laterally after having stripped or excavated the local crater surroundings.

Two rather different emplacement mechanisms are presently suggested for the Ries deposits: Oberbeck *et al.* (1974), Oberbeck, (1975), and Morrison and Oberbeck (1975) suggest a ballistic regime whereby primary crater ejecta is transported in ballistic trajectories and impacts the surrounding terrain with sufficient velocities to cause secondary cratering. As a consequence local materials are excavated, mixed with the primary ejecta and both primary and secondary ejecta combine into a terminal, ground-hugging flow. In contrast, Chao (1976a,b) argues against a ballistic transport mode and suggests a ground-hugging, roll-glide type ejecta transport, in which the ejecta leave the crater cavity essentially as one massive ground-hugging flow that must spill over tens of kilometers.

Many of the features observed are predicted by the ballistic hypothesis, most importantly the incorporation of local materials. Judging from the sizes of crater derived "megablocks" in the Vorries (see Pohl *et al.*, 1977; Hüttner, 1969; Gall, 1969) which may reach tens, if not hundreds, of meters in dimension at distances of 1–2 crater radii, excavation of the local substrate to tens of meters is perfectly plausible and expected. Indeed, Hüttner (1958) elaborates already on the possibility that such large blocks may have shattered and excavated local terrain north of the cliff line after impacting from ballistic trajectories, setting a debris surge in motion. New observations, e.g., breccias within breccias, the turbulent mixing environment, the existence of various breccia matrices formed at distinctly different locations, and, finally, the evidence of proximal "violent" and "gentle" forces are all compatible with secondary cratering followed by formation of a ground hugging debris surge for final breccia emplacement. Though velocity vectors of secondary ejecta are predominantly downrange, i.e., radially away from the primary crater, they *can* be distributed essentially over the entire 360° range, thus leading to a large array of collision—and mixing conditions over a relatively large span of time. We therefore consider all observations consistent with a ballistic ejection mechanism and resulting debris surge.

We note that the observations of Chao (1976a,b) may also be entirely consistent with ballistic transport followed by a debris surge, inasmuch as the observed striation of breccia components indicate nothing else but relative movement of particles; similarly the large striae (Schliffflächen) frequently observed in areas where the Bunte Breccia substrate is Malm limestone (Wagner, 1964) prove only relative movement. Such relative motions, however, are nonspecific for the presently competing emplacement mechanisms, because they are produced easily during secondary cratering and the subsequent ground-hugging debris surge. The observations of Chao (1976a,b) are not suitable to distinguish between a "primary" or a "secondary" debris surge.

We thus conclude that our present and previous observations are consistent with a ballistic emplacement concept. The energy expanded in excavating local materials followed by intense mixing and final emplacement via a debris surge is derived from the kinetic energy contained in ballistic ejecta. Unless other mechanisms are suggested by which up to 90% local materials are incorporated into a crater's continuous deposits, the ballistic hypothesis remains the most viable one.

Acknowledgment—It is a pleasure to thank Messrs. K. Camann, H. Arndt, L. Schuler, H. Jahn, and G. Karg of Prakla Seismos GmbH for the successful completion of the drilling program. The generous assistance of President H. Vidal and Drs. H. Schmidt-Kaler and H. Gudden are gratefully acknowledged as well as helpful discussions with Profs. D. Stöffler and W. v. Engelhardt and Drs. J. Pohl and G. Graup.

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