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TITLE: ^{10}Be Profiles in Lunar Surface Rock 68815

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^{10}Be PROFILES IN LUNAR SURFACE ROCK 68815

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ABSTRACT

Cosmic ray produced ^{10}Be ($t_{1/2}$ = 1.6 x 10^6 years) activities have been measured in fourteen carefully ground samples of lunar surface rock 68815. The ^{10}Be profiles from 0 to 4 mm are nearly flat for all three surface angles measured and show a very slight increase with depth from the surface to a depth of 1.5 cm. These depth profiles are in contrast to the SCR (solar cosmic ray) produced ^{26}Al and ^{53}Mn profiles measured from these same samples. There is no sign of SCR produced ^{10}Be in this rock. The discrepancy between the data and the Reedy-Arnold theoretical calculation (about 2 dpm ^{10}Be/kg at the surface) can be explained in two ways: (1) The low energy proton induced cross sections for ^{10}Be production from oxygen are really lower than those used in the calculations or, (2) compared to the reported fits for ^{26}Al and ^{53}Mn, the solar proton spectral shape is actually softer (exponential rigidity parameter Ro less than 100 MV), the omnidirectional flux above 10 MeV is higher (more than 70 protons/cm^2 s), and the erosion rate is higher (greater than 1.3 mm/My). ^{10}Be, as a high energy product, is a very useful nuclide for helping to obtain the SCR spectral shape in the past.

INTRODUCTION

The variations in the flux and spectrum of solar cosmic ray (SCR) particles are related to the variations of solar activity. Knowledge of the history of solar activity is extremely important not only to understand solar physics but also quite possibly the climatic history of the earth (for example the glaciation cycle). Although direct SCR measurements by satellites have been performed only for the last few decades, we do have a good way to study the past record. Cosmic rays produce radio- and stable nuclides during interactions with lunar surface materials and meteorites. The concentrations of these cosmogenic nuclides are directly related to the average cosmic ray intensity in the past. The nuclides of interest are produced not only by SCR but also by galactic cosmic rays (GCR). The GCR do not have a solar origin although their spectrum and flux are modulated to some extent by solar activity. In fact, the much lower energy (but higher flux) of the SCR means that their effects can only been seen in the top few milimeters of lunar materials. GCR produced nuclides dominate below that depth. Since the outer layers of meteorites are ablated during their passage through the earth atmosphere, the record of SCR effects is erased in meteorites except for a few cases (Nishiizumi et al., 1986; Evans et al., 1987). Details of these two types of cosmic rays and their interactions are given in several articles (e.g. Reedy and Arnold, 1972; Reedy, 1980; Reedy et al., 1983).

Previously, we have studied the depth profiles of SCR produced radionuclides in the upper 2 cm of lunar rocks and determined the average SCR parameters, flux and spectrum, over a time scale from a few months to 10 million years. The comparison of $^{26}Al(t_{1/2} = 7.05x10^5$ years) and $^{53}Mn(t_{1/2} = 3.7x10^6$ years) depth profiles in the surface of three lunar rocks, 12002 (Finkel et al., 1971), 14321 (Wahlen et al., 1972), and 68815 (Kohl et al., 1978), with the theoretical SCR production profiles (Reedy and Arnold, 1972) indicates that the flux of solar protons over the past five to ten million years was similar to that during the past million years and that the average SCR spectrum and flux were characterized by a exponential rigidity with a spectral shape parameter Ro = 100 MV (cf., Reedy and Arnold, 1972) and a flux J = 70 protons/ cm^2 s (E > 10 MeV, 4 π). These calculations assume 0.5 - 2.2 mm/My erosion rate for the three rocks (Kohl et al., 1978; Russ and Emerson, 1980). It was possible to fit the data also with Ro in the range 70-150 MV, with appropriate adjustments of flux J and erosion rate. The excitation functions for producing ^{26}Al and ^{53}Mn by proton-induced reactions are quite similar (Reedy and Arnold, 1972). In this present work, we measured ^{10}Be ($t_{1/2} = 1.6x10^6$ years) in rock 68815 by accelerator mass spectrometry (AMS) to investigate the SCR production of this nuclide and to verify the SCR parameters. Rock 68815 is a breccia and was collected by chipping it from the top of a meter high boulder. The ^{81}Kr-Kr exposure age of this rock is 2.04 $\pm$ 0.08 My (Drozd et al., 1974); it is thought to be associated with the South Ray crater event.

EXPERIMENTAL AND RESULTS

Fourteen samples were separated from aliquant samples that we had previously used for ^{26}Al and ^{53}Mn measurements (Kohl et al., 1978). The samples measured were from three different zenith angles (A-45^o, B-37^o, and C-12^o) and four different depths (0-0.5, 0.5-1.0, 1.0-2.0, and 2.0-

4.0 mm). A 4-8 mm and a 10-15 mm layer were also obtained from near the bottom of our specimen from face A and face C. The details of the grinding procedures were described by Kohl et al. (1978). The sample sizes ranged from 0.6 to 2.9 g. About 700 μg of Be carrier was added to each sample dissolved. Be was separated from other elements and purified by anion exchange, cation exchange, and Be-acetylacetone extraction. Finally, $Be(OH)_2$ was precipitated with water containing about 2 % of ^{17}O.

The ^{10}Be measurements were carried out at the University of Tokyo's tandem Van de Graaff accelerator. The apparatus and method used for the accelerator mass spectrometry were essentially those described previously (Imamura et al., 1984). We selected a 3.5 MV terminal voltage for the ^{10}Be measurements. We measured $^{10}Be/9Be$ ratios in the range 1-5 x 10^{-10} with experimental errors of 3-9 %. The $^{10}Be/^{9}Be$ measured values were normalized to ICN-UCSD ^{10}Be standard. The ^{10}Be activities obtained from 68815 are given in Table 1.

DISCUSSION

The ^{10}Be activity depth profiles in the three faces A, B, and C of 68815 are shown in figure 1a. The ^{10}Be results were adjusted to saturation using the ^{81}Kr-Kr exposure age of 2.04 $\pm$ 0.08 My (Drozd et al., 1974). The saturation activities are used for all the following discussion. The ^{26}Al and ^{53}Mn depth profiles in the same samples are also shown in this figure (1b and 1c). The curves shown in 1b and 1c are the Reedy-Arnold theoretical profiles for the sum of SCR and GCR production rates for each nuclide (Reedy and Arnold, 1972). The curves are slightly modified from the previous paper (Kohl et al., 1978) by calculating the production rate on a point by point basis (Russ and Emerson, 1980). SCR parameters Ro = 100 MV and J = 70 p/ cm^2 s, a 2.0 My exposure age, and 0.0 and 1.0 mm/My erosion rates are adopted for these calculations. The ^{10}Be profiles are essentially the same for all three faces and are nearly flat. In fact they show a slight increase with increasing depth. This shape is in remarkable contrast to the ^{26}Al and ^{53}Mn profiles, which show sharp increases in activity toward the surface due to SCR production of these nuclides.

Russ and Emerson (1980) recalculated ^{26}Al and ^{53}Mn depth profiles in 68815 using point by point mapping of all grinding faces. Even though their detailed calculation shows that the average angles of the faces from horizontal are substantially different from those used by Kohl et al. (1978), they obtained essentially the same conclusion as Kohl et al. with regard to the SCR parameters and they found no evidence of SCR anisotropy or of differential erosion for the three surfaces.

It is necessary to subtract the GCR produced ^{10}Be from the observed ^{10}Be to see the SCR component. The expected GCR production profile using the chemical composition of 68815 was calculated based on the Reedy-Arnold model (Reedy and Arnold, 1972) and is shown in figure 2a,b. The ^{10}Be profiles for face B are essentially the same as for face A and C, but the data contain somewhat larger errors. The original model (Reedy and Arnold, 1972) and the new cross sections (Tuniz et al., 1984) were used for both GCR and SCR calculations. The Reedy-Arnold GCR profile fits the 68815 data well without any of the normalization that was required for both the ^{26}Al and ^{53}Mn GCR production profiles (Nishiizumi et al., 1983). However, the Reedy-Arnold GCR profile for ^{10}Be appears to increase with depth slower than the measured data, suggesting that the Reedy-Arnold GCR model might be slightly inaccurate for the production-rate-versus-depth profile near the surface, at least for high-energy products. As pure GCR production profiles are hard to find (almost all nuclides have significant SCR components near the surface), it is difficult to test the Reedy-Arnold model at such shallow depths. The Reedy-Arnold GCR ^{10}Be profile using the new cross sections also fits the ^{10}Be results for the Apollo 15 drill core (Nishiizumi et al., 1984).

We would expect to see SCR produced ^{10}Be only in near surface samples, if it exist. Figures 2a and 2b, however, show no sign of the presence of SCR produced ^{10}Be in this rock. The Reedy-Arnold SCR model predicts a ^{10}Be SCR production rate of about 2 atoms/min/kg in the surface layer using a SCR flux with Ro = 100 MV and J(>10 MeV) = 70 p/cm^2 s, the parameters we had obtained from ^{26}Al and ^{53}Mn profiles in this and other lunar surface rocks (Kohl et al., 1978). The observed SCR produced ^{10}Be, which was calculated by subtracting the ^{10}Be activity measured at greater depth from that of near surface depth, is less than 1 dpm/kg.

The Reedy-Arnold model is a well developed method for calculating cosmic ray interactions in various sizes of bodies for both SCR and GCR. However, the model contains some uncertainties with regard to estimating the GCR flux at near surface depths. If the calculated Reedy-Arnold GCR ^{10}Be production rates are over- estimated near the surface, we are subtracting too much from our measured values and masking a real SCR contribution to the ^{10}Be activity. SCR ^{10}Be production rates decrease drastically with increasing depth below a few g/cm^2 regardless of the

SCR parameters (see figure 3a). The observed ^{10}Be activities at a few g/cm^2 and below are almost entirely produced by GCR interactions and the measured values at these depths are an agreement with the theoretical values. This requires that the GCR production profile decrease 15 - 20 % from 1 g/cm^2 to the surface to obtain 2 dpm ^{10}Be/kg SCR production in this region. There is no theoretical or experimental support for such an abrupt change. This explanation is unlikely. The discrepancy between the model and the data can be explained in several ways as discussed below.

The ^{10}Be proton induced cross sections that are used for Reedy-Arnold SCR calculations may be too high, especially for the low energy region. Although the SCR spectrum varies from flare to flare, SCR particle intensity decreases exponentially with increasing energy (Reedy and Arnold, 1972). The low energy proton induced cross sections, especially below 100 MeV, are therefore very important for total SCR production. There are no cross section measurements below 135 MeV for protons on any target element. Reedy and Arnold (1972) estimated the ^{10}Be cross sections from nuclear systematics and comparison with the measured ^{7}Be cross section at lower energy. The original Reedy-Arnold model predicted about 4 dpm ^{10}Be/kg produced by SCR in the surface layer. The new calculation, which uses new and lower proton cross sections (Tuniz et al., 1984), predicts 2 dpm ^{10}Be/kg at the top layer of 68815, still more than we find experimentally. The target element responsible for the majority of ^{10}Be produced by SCR protons is oxygen. The elemental abundance of oxygen in 68815 is 44.8 % (Apollo 16 Preliminary Science Report, 1972; Wanke et al., 1974). ^{10}Be is also produced by proton interactions with Mg (3.85 % in 68815), Al (14.2 %), and Si (21.8 %). However, the threshold energies for these nuclear reactions are higher than those interactions of O and also the elemental abundances of Mg, Al, and Si are lower than O. The threshold energy for the ^{10}Be producing reaction with O is 34 MeV. There are only two cross sections measurements for ^{10}Be production from O available below 500 MeV proton energy. Yiou et al. (1969) reported the cross section to be 0.37 $\pm$ 0.12 mb at 135 MeV. Amin et al. (1972) also reported the cross section to be 0.59 $\pm$ 0.04 mb at 135 MeV. The result by Amin et al. (1972) was corrected by new half-life of ^{10}Be. At 135 MeV, the higher cross section was used because, as noted in Tuniz et al., (1984), the Yiou et al., (1969) cross sections are consistently lower than other measurements at 600 MeV and higher energies. There are no other cross section measurement below 500 MeV proton energy except on boron and carbon, which are not abundant elements in lunar rocks. Low energy cross sections, below 100 MeV, for ^{10}Be production from O and other elements should be measured by AMS. Lower cross sections, especially below ~100 MeV, could decrease the calculated SCR production rates by factors of 2 or more.

The second possibility is that the average SCR flux and mean rigidity over the last two million years differed from the adopted parameters Ro = 100 MV and J(>10 MeV) = 70 p/cm^2 s. The Reedy-Arnold SCR production rates of ^{10}Be, ^{26}Al, and ^{53}Mn with three different rigidities (Ro = 70, 100, and 150 MV) are shown in figure 3a-c. Although the depth profiles of both ^{26}Al and ^{53}Mn at near surface depths are very insensitive to changes in Ro, different SCR fluxes and erosion rates would be required to fit those profiles to the data. To fit the observed ^{26}Al and ^{53}Mn profiles in lunar surface rocks, different proton fluxes and rock erosion rates must be chosen for each rigidity. If we use a lower

Ro, a higher SCR flux and larger erosion rate would be required. It is known that Ro = 100 MV, J = 70 p/cm^2 s, and an erosion rate of 1.3 mm/My are not unique parameters to fit the ^{26}Al and ^{53}Mn profiles in lunar surface rocks (Russ and Emerson, 1980). For example, Ro = 70 MV, J(>10 MeV) = 150 p/cm^2 s, and an erosion rate of 3 mm/My (which was the erosion rate reported from track data for 68815 by Blanford et al., 1975) can also fit the measured ^{26}Al and ^{53}Mn activities in 68815.

On the other hand, the SCR ^{10}Be depth profile is very different from both the ^{26}Al and ^{53}Mn profiles. As shown in figure 3-a, the ^{10}Be production rates change from 1 to 4 dpm/kg at near surface depths depending on the rigidity used. The production rate for ^{10}Be in the top of rock 68815 using Ro = 70 MV and J(> 10 MeV) = 150 p/cm^2 s is 1.0, only 60 % of that calculated for the other set of spectral and flux parameters. Even though the SCR production rate of ^{10}Be is lower than the GCR production, the amount of ^{10}Be activity produced by SCR is very sensitive to changes in Ro. The very low SCR production of ^{10}Be observed in 68815 could indicate that the mean SCR rigidity over the last two million years was lower than the 100 MV that was suggested by Kohl et al. (1978). A higher Ro, such as 150 MV, is most unlikely unless the ^{10}Be cross sections are more than factor of 5 smaller than the values adopted by Reedy and Arnold (1972) for their calculations. However, lowering the Ro conflicts with the argument by Bhandari et al. (1976). They proposed a higher rigidity (Ro = 150 MV) and a higher flux (J(> 10 MeV) = 140 p/cm^2 s) based on their non-destructive ^{26}Al measurements in Apollo 16 rocks. Their SCR parameters don't fit the observed ^{10}Be depth profiles in 68815 nor the ^{26}Al and ^{53}Mn profiles in 68815 and the other lunar surface rocks. It should be noted that measurements of

^{26}Al in five pieces from the top 4.4 cm of lunar rock 74275 by Fruchter et al., (1982) gave results in good agreement with those reported in Kohl et al., (1978) and not with those of Bhandari et al., (1976). Reedy (1980), using ^{81}Kr data in 12002 (Yaniv et al., 1980), found a somewhat higher Ro for the period 3 x 10^5 years, but this is not necessarily a contradiction because the main reactions producing ^{81}Kr have threshold energies above 60 MeV and the chemical abundances of the target elements were not well measured in the sample. Also ^{81}Kr, because of its half-life of 2.1 x 10^5 years, integrated solar protons for a much shorter period than the other radionuclides. Unpublished ^{81}Kr measurements (K. Marti, personal communication) in 68815 also support a lower Ro. SCR production rates of high energy products such as ^{10}Be and ^{36}Cl are very useful for obtaining the SCR spectrum. ^{10}Be has a distinct advantage over ^{36}Cl since ^{36}Cl is produced in both high energy and low energy reactions.

The comparison of ^{53}Mn and ^{26}Al profiles made by Kohl et al. (1978) is very good for detecting time variations, since the half-lives differ by a factor of ~5 while the excitation functions are similar. Since both are lower energy products and their profiles are steep near the surface, they are also sensitive to the erosion rate. The comparison of these two nuclides with ^{10}Be is useful in a complementary way. Because the excitation functions are quite different, only a narrow range of Ro values can satisfy the constraints imposed by the three profiles, even though the ^{10}Be production by SCR can only be given as an upper limit. If we accept the published proton cross sections as representative, this fixes Ro close to 70 MV. New cross section data would be most desirable, but unless they are lowered by a factor of 2 or more this conclusion will remain valid.

Previous ^{10}Be measurements, which used decay counting techniques (Finkel et al., 1971; Wahlen et al., 1972) to study lunar surface rocks 12002, 14310, and 14321, give results that are in good agreement with the ^{10}Be activity found in 68815 by AMS measurements. The ^{10}Be activities in the above rocks also show no increase of ^{10}Be at the surface and therefore no evidence of SCR production. Since substantially all the ^{10}Be in these rocks was produced by GCR and since they have different exposure ages, we conclude that no significant changes in the GCR flux were observed during the last few million years.

SUMMARY

Cosmogenic ^{10}Be activities were measured in lunar surface rock 68815. Four different depths were sampled for three different angles. The ^{10}Be profiles are flat or increase slightly with depth for all three faces and show no sign of SCR produced ^{10}Be. The extremely low SCR production of ^{10}Be compared to the calculations of the Reedy-Arnold model suggests that either (1) low energy proton induced cross sections for ^{10}Be production are lower than expected or (2) the SCR rigidity Ro is lower than 100 MV averaged over the last few million years.

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FIGURE CAPTIONS

Figure 1. ^{10}Be (a), ^{26}Al (b) and ^{53}Mn (c) activity depth profiles in the three faces of 68815 indicates the average depth interval sampled as determined from the maps made during grinding. The ^{10}Be results were adjusted to saturation using the ^{81}Kr-Kr exposure age of 2.04±0.08 My (Drozd et al., 1974). The ^{26}Al and ^{53}Mn values plotted are those measured. The curves shown for ^{26}Al and ^{53}Mn are the theoretical profiles of the SCR plus GCR production calculated by Russ and Emerson (1980) on a point by point basis for 68815 using a 2 My exposure age and Reedy-Arnold model.

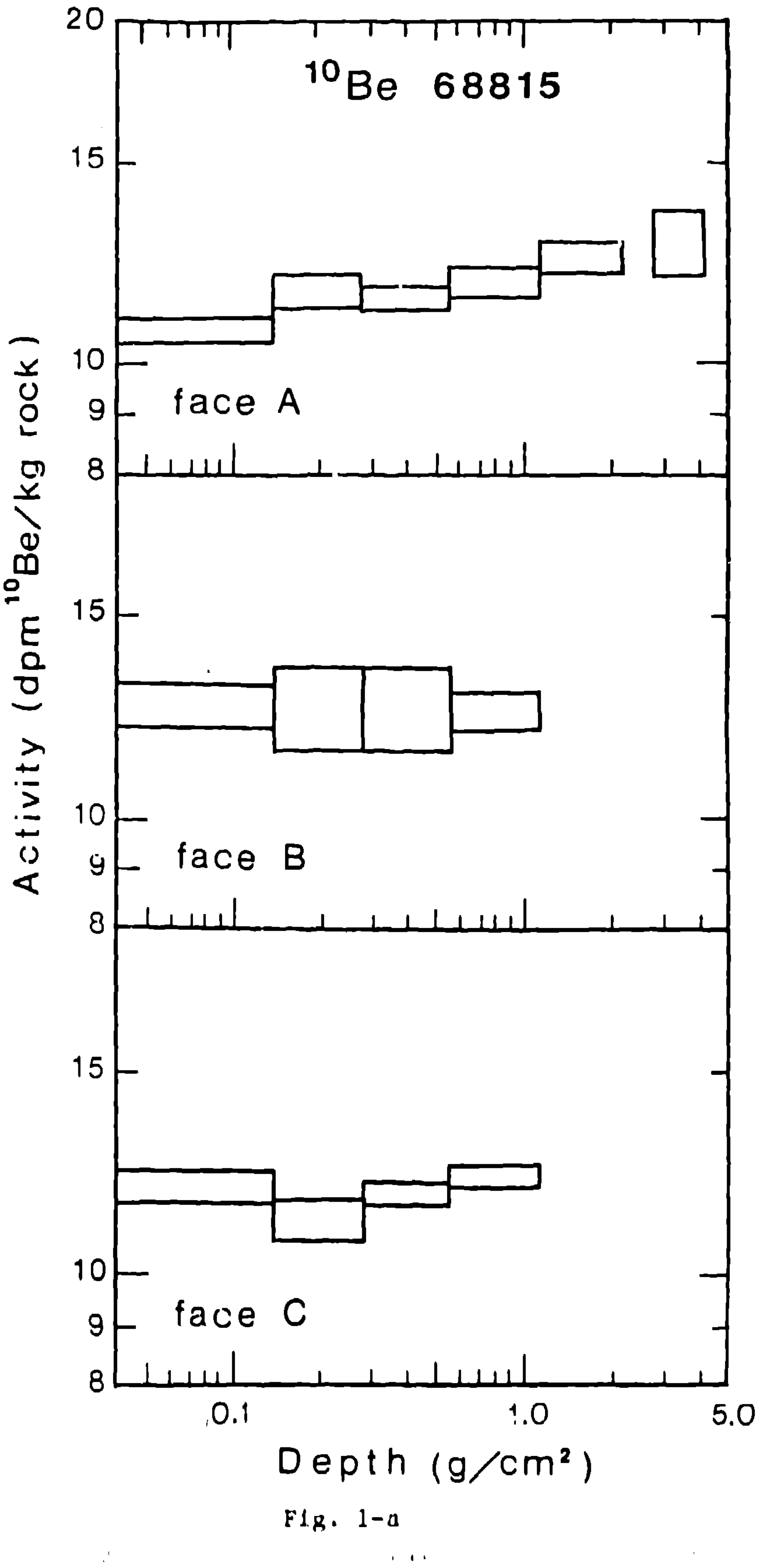
Figure 2. ^{10}Be activity depth profiles in face A (a) and face C (b) of 68815 plotted values have been adjusted to saturation using the ^{81}Kr-Kr exposure age of 2.04±0.08 My (Drozd et al., 1974). The curves are the unnormalized GCR production profiles calculated using the Reedy-Arnold model (Reedy and Arnold, 1972) and the new cross sections (Tuniz et al., 1984).

Figure 3. Calculated SCR production profiles for ^{10}Be (a), ^{26}Al (b) and ^{53}Mn (c) in 68815. The depth profiles were calculated using the Reedy-Arnold model (Reedy and Arnold, 1972) and the cross sections of Tuniz et al., (1984) for ^{10}Be. They show expected saturation levels for each nuclide for three sets of SCR parameters (R_o = 150 MV, J = 45 p/cm^2 sec, R_o = 100, J = 70 and R_o = 70, J = 100). Erosion was assumed to be 0 for these calculations.

Table 1. ^{10}Be in 68815

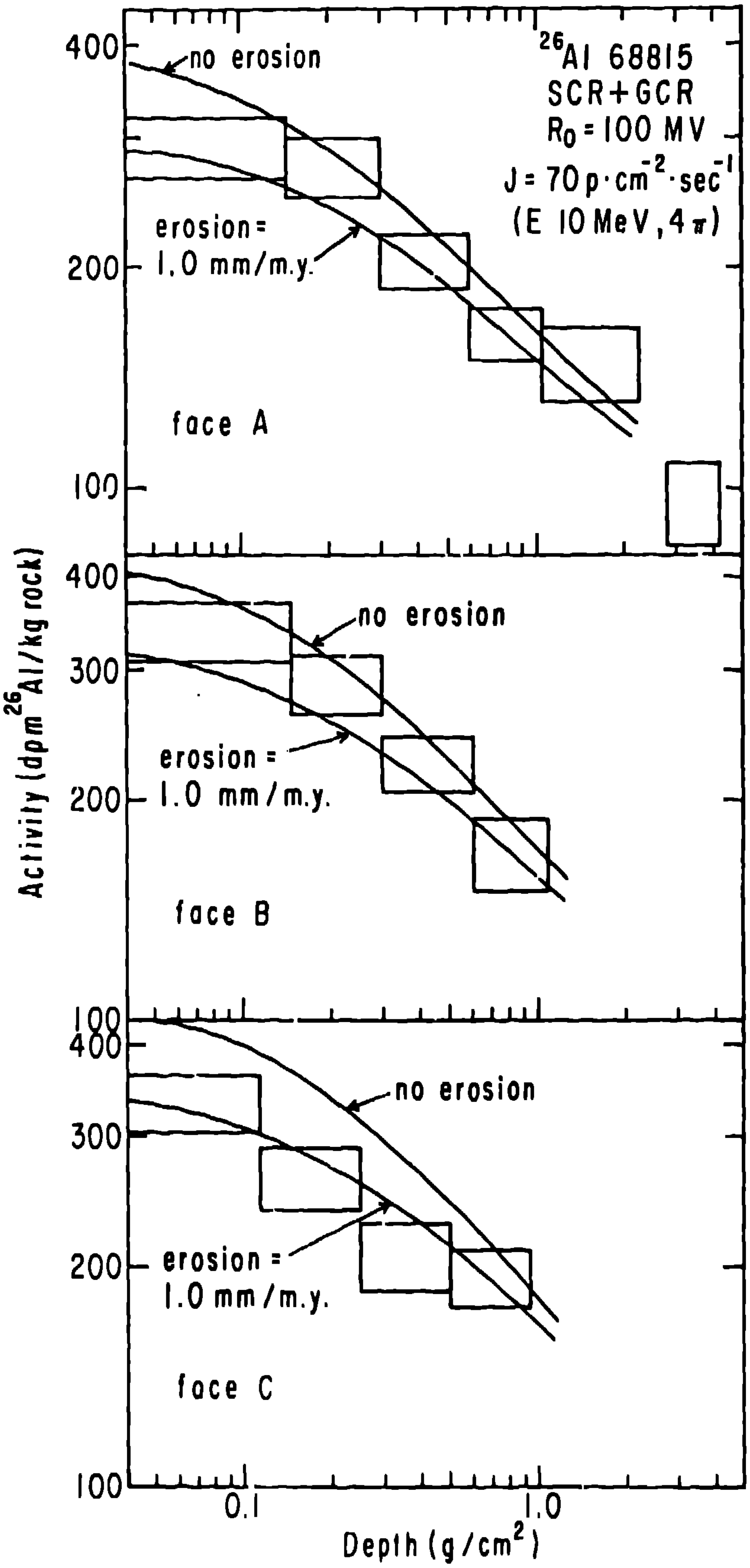
Depth (g/cm^2)*	FACE A	FACE B (dpm ^{10}Be/kg)	FACE C
0 - 0.14	6.19 ± 0.21	7.28 ± 0.37	6.92 ± 0.24
0.14 - 0.28	6.75 ± 0.23	7.22 ± 0.65	6.47 ± 0.30
0.28 - 0.56	6.61 ± 0.18	7.24 ± 0.66	6.81 ± 0.20
0.56 - 1.12	6.81 ± 0.21	7.21 ± 0.32	7.07 ± 0.29
1.12 - 2.24	7.22 ± 0.21		
2.8 - 4.2	7.43 ± 0.53		

* density of 68815 was taken to be 2.8 g/cm^3



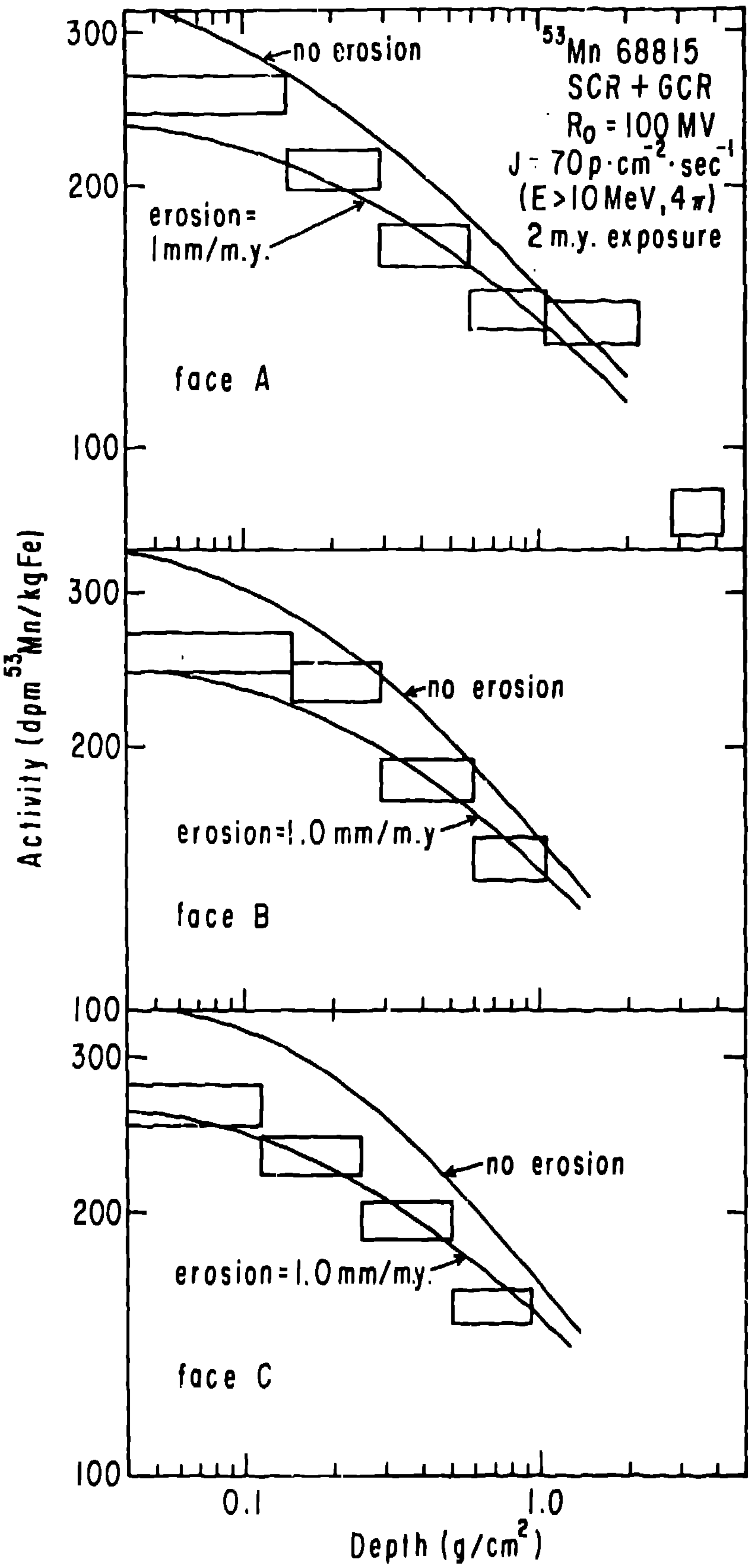
^{10}Be 68815
Activity (dpm ^{10}Be/kg rock)
20
15
10
9
8
face A
face B
face C
0.1
1.0
5.0
Depth (g/cm^2)

Fig. 1-a



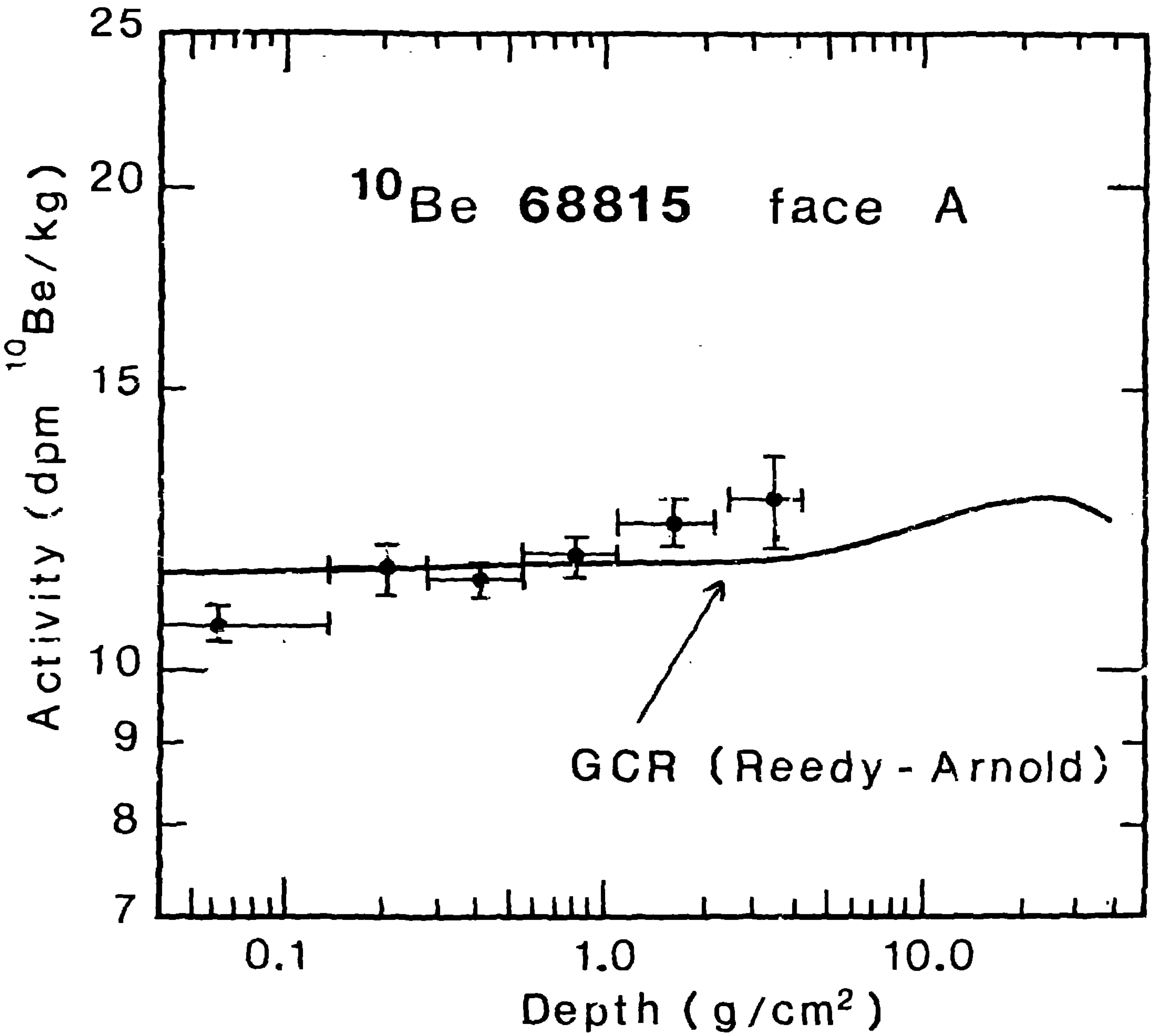
no erosion
^{26}Al 68815
SCR+GCR
R_0 = 100 MV
J = 70 p·cm^{-2}·sec^{-1}
(E 10 MeV, 4π)
erosion =
1.0 mm/m.y.
face A
face B
face C
400
300
200
100
Activity (dpm ^{26}Al/kg rock)
0.1
1.0
Depth (g/cm^2)

Fig i-b.



53Mn 68815
SCR + GCR
R0 = 100 MV
J = 70 p·cm-2·sec-1
(E>10 MeV, 4π)
2 m.y. exposure
no erosion
erosion = 1mm/m.y.
face A
no erosion
erosion=1.0 mm/m.y
face B
no erosion
erosion=1.0 mm/m.y.
face C
300
200
100
0.1
1.0
Activity (dpm 53Mn/kgFe)
Depth (g/cm2)

Fig 1-c.



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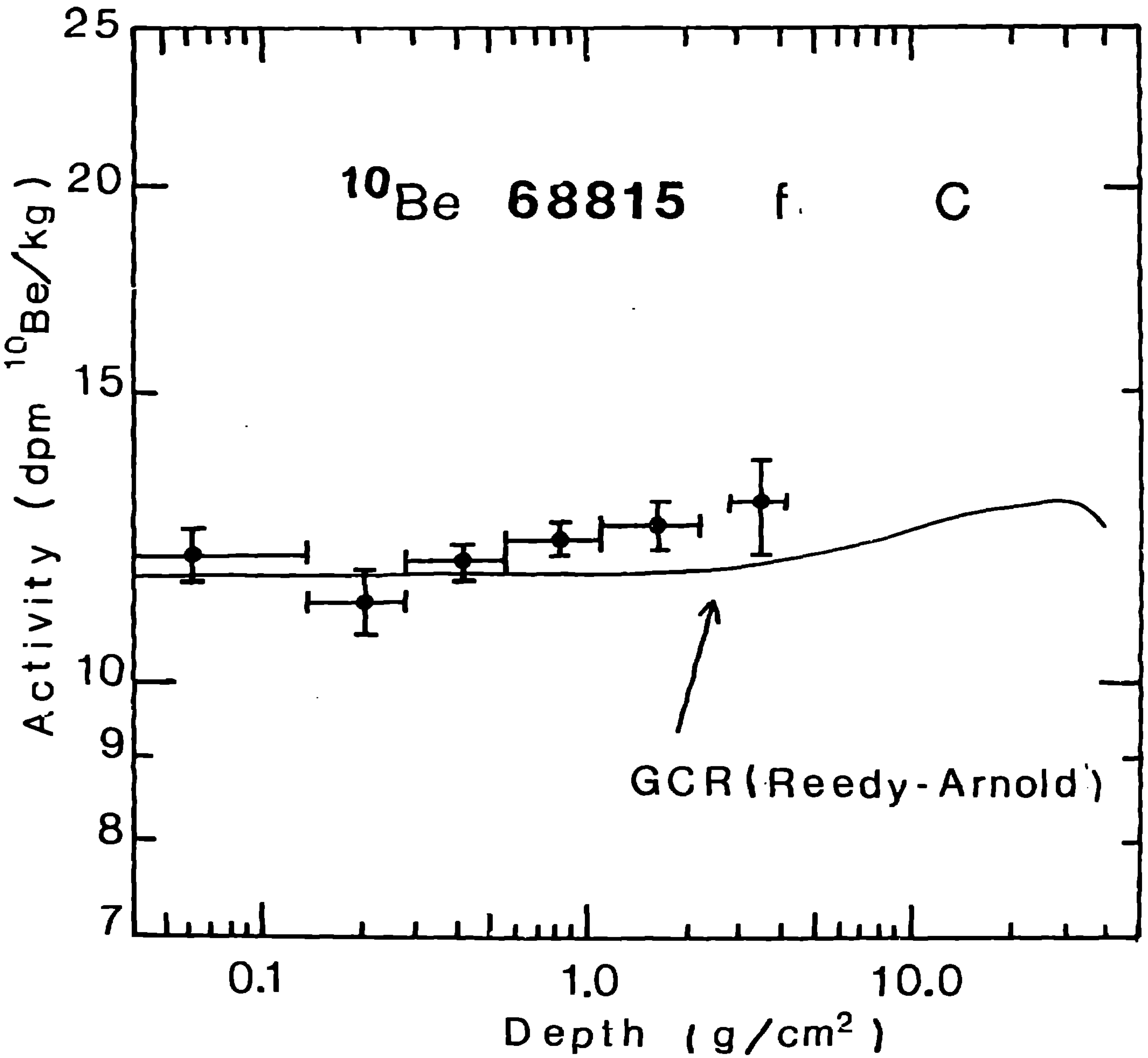
8
7
Activity (dpm ^{10}Be/kg)
^{10}Be 68815 face A
GCR (Reedy - Arnold)
0.1
1.0
10.0
Depth (g/cm^2)

Fig 2-a.



^{10}Be 68815 f. C
Activity (dpm ^{10}Be/kg)
25
20
15
10
9
8
7
GCR (Reedy-Arnold)
0.1
1.0
10.0
Depth (g/cm^2)

Fig 2-b.

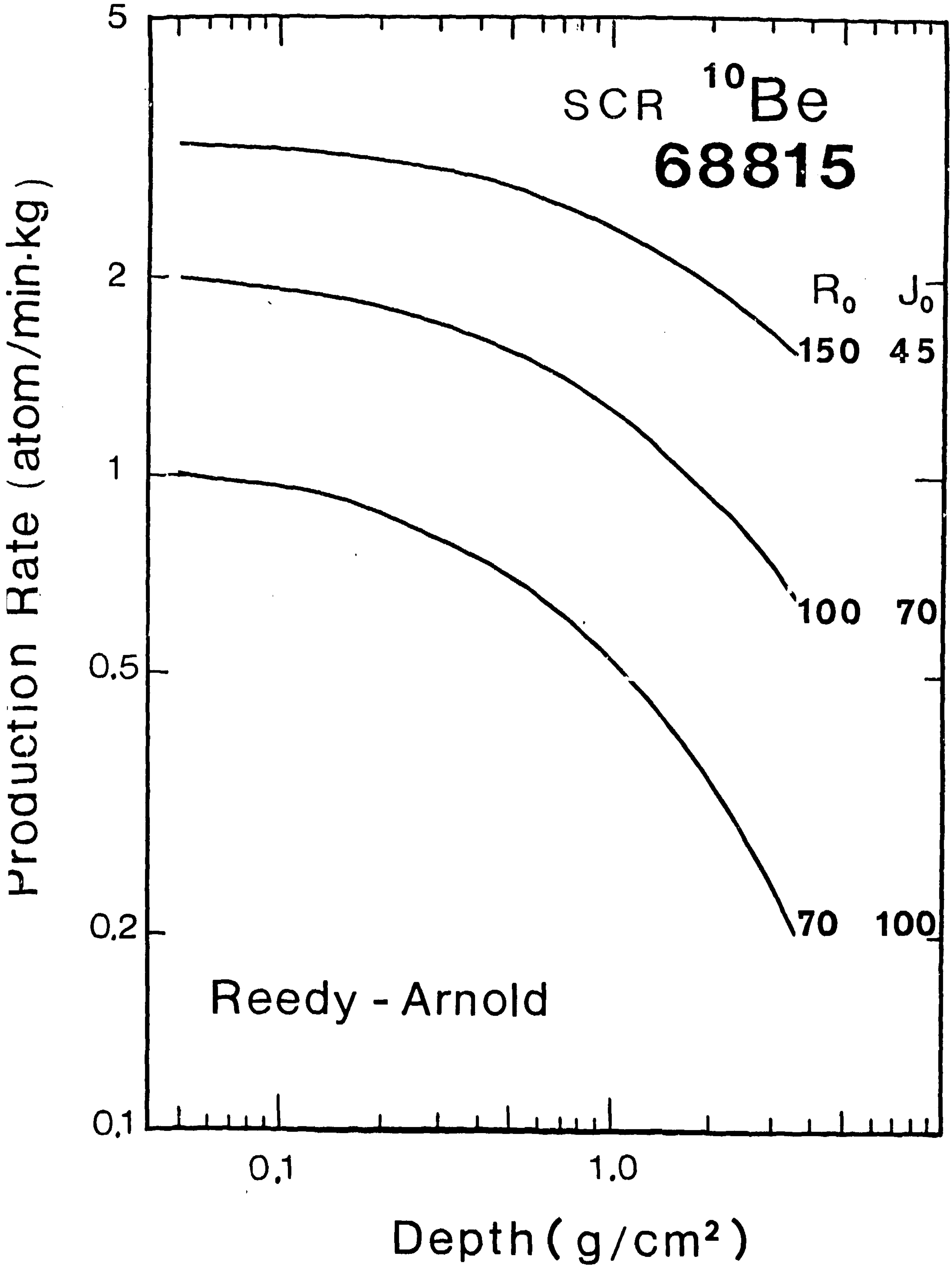

SCR ^{10}Be
68815
R_0 J_0
150 45
100 70
70 100
Reedy - Arnold
Production Rate (atom/min·kg)
Depth (g/cm²)
5
2
1
0.5
0.2
0.1
0.1
1.0

Fig 3-a.

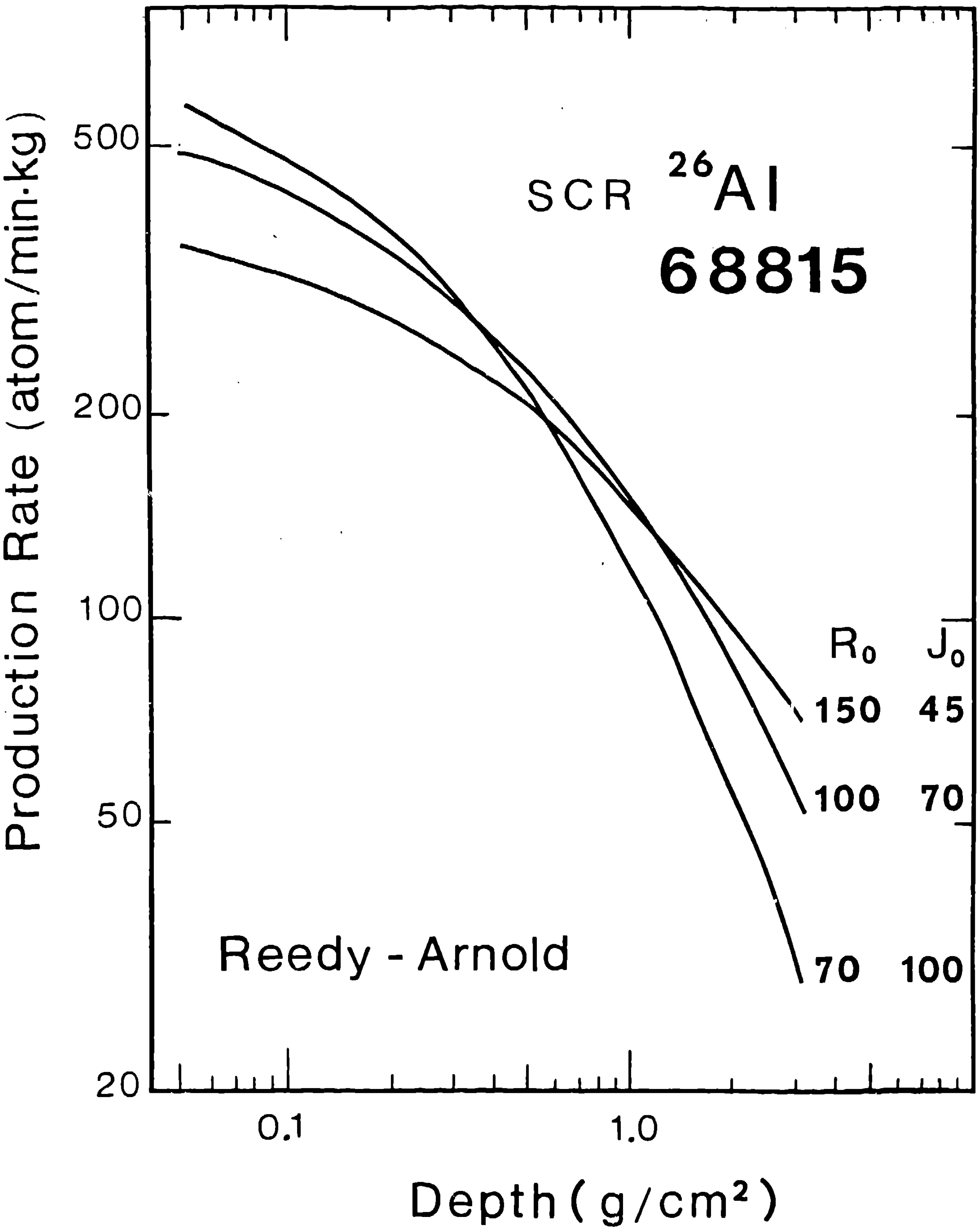

SCR ^{26}Al
68815
Production Rate (atom/min·kg)
500
200
100
50
20
R$_0$ J$_0$
150 45
100 70
70 100
Reedy - Arnold
0.1
1.0
Depth (g/cm^2)

Fig 3-b.

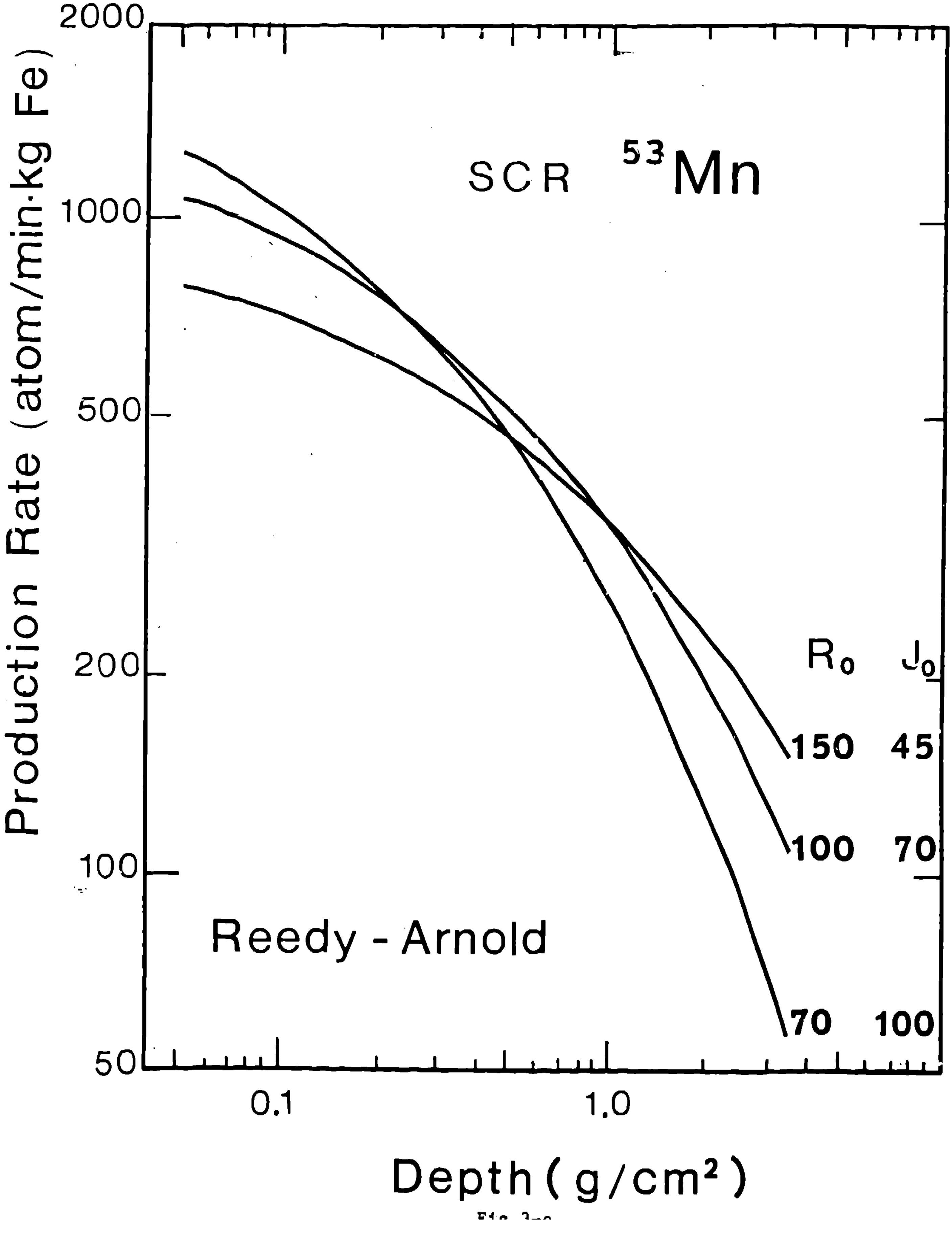

SCR ^{53}Mn
Production Rate (atom/min·kg Fe)
2000
1000
500
200
100
50
Reedy - Arnold
R_0 J_0
150 45
100 70
70 100
0.1
1.0
Depth (g/cm²)

Fig. 3-[illegible]