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The Vissannapeta eucrite

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Abstract–A wholly encrusted single stone that fell in Vissannapeta, Andhra Pradesh, India has been identified as a cumulate eucrite based on its primary texture and mineral composition: anorthite($An_{92.4-94.6}$), orthopyroxene($En_{49.1-51.8}Fs_{44.2-49.7}Wo_{1.2-4.0}$), and clinopyroxene ($En_{38.8-46.8}Fs_{14.8-33.6}Wo_{19.6-46.4}$). The stone is pyramidal in shape, and the crust shows rib-like flow features indicating that it had an oriented passage through the atmosphere towards the terminal stage of its flight. Conditions of its fall, mineralogical characteristics, and results of measurements of cosmogenic radioactivity (^{26}Al, ^{22}Na, and ^{54}Mn) and track density are described. Aluminum-26 and ^{22}Na in Vissannapeta are ~75% of the expected values and also lower by a similar factor compared to the activities measured in Piplia Kalan, another eucrite, which fell ~18 months before Vissannapeta. Because higher activity of ^{22}Na and ^{54}Mn would be expected from solar cycle modulation of galactic cosmic rays, these results, as well as the track density gradient, indicate that Vissannapeta was a small body (≤120 kg) in the interplanetary space wherein the nuclear cascade due to galactic cosmic rays did not develop fully. Tracks, surface morphology, and crustal features indicate at least two fragmentation events in the atmosphere.

DESCRIPTION OF FALL

The Vissannapeta meteorite fell on 1997 December 13 ~ 03:00 h in Vissannapeta village (16°55' N, 80°45' E), Nuzivid Mandal, Krishna district, Andhra Pradesh, India. A single stone weighing 1303.80 g, accompanied by long streaks of bright light in the northern dark sky and zooming sound, fell with a thud on the thatched hut of Sri K. Ramulu. He was lying on his cot when he looked towards the roof and, to his surprise, saw an unknown object hanging enveloped in a gunny bag that he had previously spread on his hut to protect himself from the rain. The villagers collected and examined the stone. Eventually, through the help of local police officials, the Geological Survey of India (GSI) obtained the piece on 1998 November 16. It is presently located in the Calcutta museum.

MORPHOLOGY

The single mass of Vissannapeta meteorite is shaped like a rounded pyramid (Fig. 1), having dimensions of 13 × 10 × 7 cm. It is nearly fully covered with fusion crust. The nature and thickness of the fusion crust varies from face to face. The fusion crust of the convex face is black, ~0.5 mm thick, with numerous glossy streaks of non-overlapping flow ribs appearing to radiate outward in all directions from a central point defining the apex of the pyramid (Fig. 1). In this respect, it resembles the martian meteorite Lafayette (Meyer, 1996) and the eucrite Moama (Lovering, 1975). These features indicate that this was the leading face with the pyramid's apex in front and the basal part at the rear during the meteorite's passage through the atmosphere. At least towards the terminal stage of its flight, the meteorite had an oriented entry without spinning. The fusion crust of the subvertical face is granular, brownish black, and relatively thin. It shows a distinct rim zone defined by termination of all flow lines across the curved edge (Fig. 1). Fusion crust of the basal surface is blackish brown, very thin (0.25 mm), varies from glossy to dull, and exhibits a scoriaceous texture. This face was the rear face during the terminal stage of the meteorite's flight through the atmosphere. All along the edges of this face, the fusion crust terminates abruptly. On the basis of the morphology of

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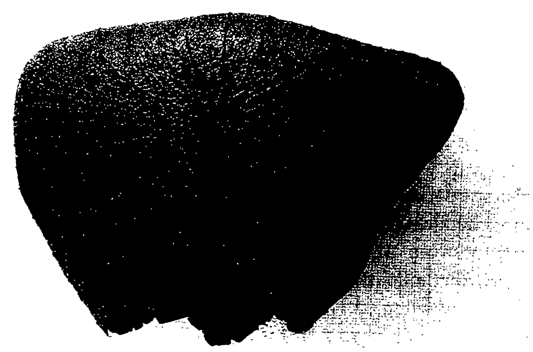

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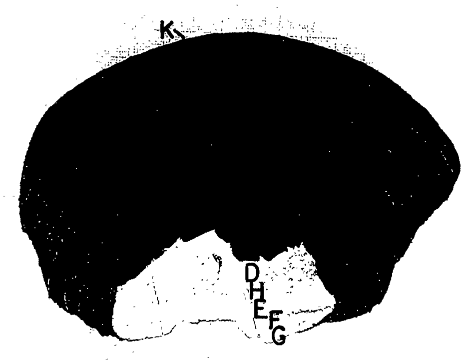

FIG. 1. Photograph of the Vissannapeta eucrite showing (a) the pyramidal shape and flow ribs on fusion crust and (b) locations of samples (D, H, E, F, and G) taken for track studies. Sample K was taken from the subvertical face. Samples A, B, and C are taken from the basal face not seen in these photographs.

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2000M&PS...35..913G

fusion crust, at least two stages of fragmentation and a short period of ablation can be visualised. Combining these observations with the degree of ablation deduced from track densities discussed later, we can partly reconstruct the meteorite's flight history.

The fractured surface as observed from the peeled-off portions is chalk white in colour (Fig. 1b). At places, tiny spots of olive green colour and greasy luster in a white matrix are indicative of the presence of pyroxene in feldspathic host. Very fine black spots, possibly chromite, are rare. No shining specks of Fe,Ni metal have been observed. Thus, an overall assemblage of plagioclase and pyroxene with a magmatic intergrowth texture implies that the meteorite belongs to the group of Ca-rich achondrites.

SAMPLING AND CHEMICAL ANALYTICAL TECHNIQUES

Three polished thick sections of Vissannapeta achondrite were studied under Orthoplan optical microscope in transmitted and reflected light for mineralogy, texture, evidence for thermal and shock metamorphism. Backscattered electron images of the essential minerals and clasts including textural features were studied under scanning electron microscope-energy dispersive spectrometer (SEM-EDX) attached to the SEM, Leica 440 to facilitate electron microprobe analysis (EPMA) carried out on a Camebax SX-51 at GSI Laboratory. In EPMA, an accelerating voltage of 15 kV and a sample current of 12 nA were used for silicates and oxide analysis and 20 kV and 20 nA current for sulfides with a beam diameter of ~1 μm. The counting time on average is 10 s for peak and 5 s for the background. The results are based on comparison with natural standards. The bulk chemical analysis was made on a 5 g representative interior piece of the meteorite. Wet chemical instrumental methods (atomic absorption spectrometry (AAS), inductively-coupled-plasma–atomic-emission-spectrometry (ICP-AES)) were used for determining the major and minor element composition that are described in detail by Dasgupta *et al.* (1978) and Shukla *et al.* (1997). Sample decomposition and separation of metallic, sulphide, and silicate phases were performed by successive treatment with ammonium mercuric chloride solution for metallics, bromine-methanol reagent for sulfides, and hydrofluoric acid–perchloric acid mixtures for silicates. The metallic phase solution was analysed for Fe, Ni, and Co by AAS without further separation. The sulfide phase solution was analysed for Fe, Ni, and Co by AAS and S by gravimetry as $BaSO_4$. The silicate phase and bulk solutions were analysed for Fe (total), Al, Mn, Cr, Ni, Co, Ca, Mg, Na, and K by AAS and ICP-AES. Fe^{2+} was determined volumetrically from a fresh sample after separation of the metallic and sulphide phases as described above. Difference between Fe (total) and Fe^{2+} is assumed to be due to Fe_2O_3. Silicon dioxide was determined by AAS after decomposition by fusion with sodium hydroxide–borax mixture. Total S was determined by Na_2O_2 fusion and gravimetry as $BaSO_4$. Difference between total S and sulphide S has been reported as SO_3 in the silicate phase. Carbon dioxide, C, H_2O, and P were determined by standard conventional techniques.

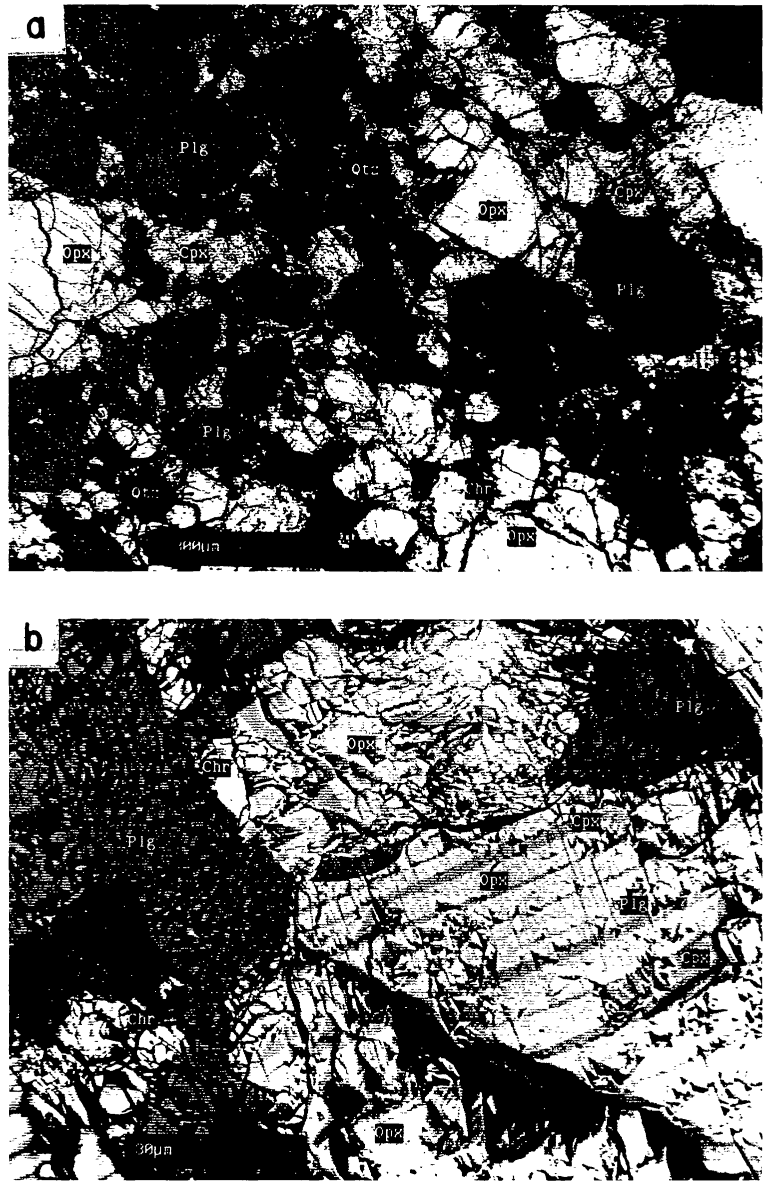

FIG. 2. (above and right) Photomicrographs of Vissannapeta eucrite: (a) breccia structure showing relic primary gabbroid texture, (b) exsolution texture showing lamellae of clinopyroxenes in the host orthopyroxene that is inverted from original pigeonite, and (c) relic cumulus texture.

PETROGRAPHY AND MINERAL CHEMISTRY

Vissannapeta achondrite is essentially composed of low Ca-pyroxene, calcic plagioclase, minor chromite, SiO_2 polymorphs, and accessory troilite. Texturally, it is a brecciated variety of cumulate eucrite in which lithic and mineral clasts are set in a relatively fine-grained fragmental matrix (Fig. 2a). Lithic clasts are generally medium- to coarse-grained equigranular aggregates of plagioclase and orthopyroxene. Number of clasts enriched in the orthopyroxene component is relatively more than those enriched in the plagioclase component. Larger mineral clasts of plagioclase (up to 1000 × 700 μm) and orthopyroxene (up to 1200 × 600 μm) and smaller clasts (up to a maximum size of 30 μm across) of mainly pigeonite, chromite, and SiO_2 polymorphs are present. Larger lithic as well as mineral clasts are both invariably encircled with a relatively fine-

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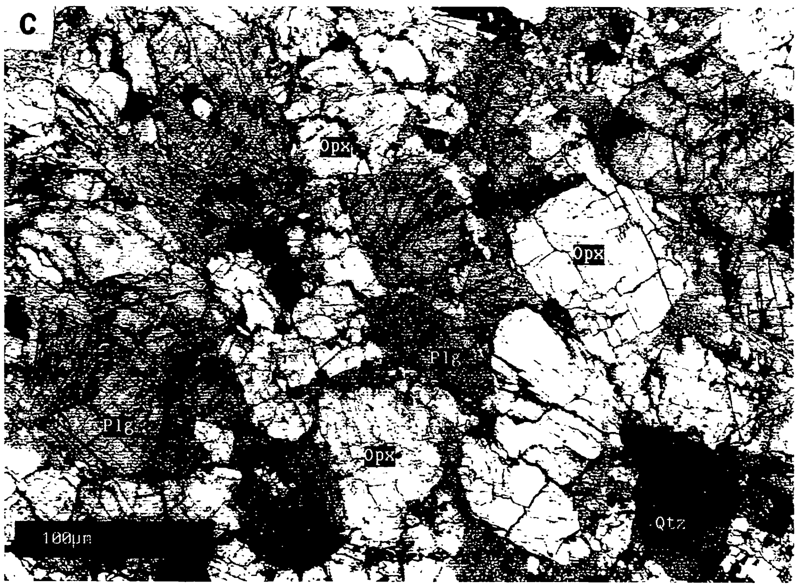

TABLE 1. Modal mineralogical abundance of Vissannapeta eucrite.

Minerals	Vol%
Orthopyroxene	49.0
Plagioclase	45.0
High-Ca pyroxene	3.0
Low-Ca pyroxene	1.0
SiO_2-polymorphs	1.2
Chromite and troilite	0.8
Total	100.0

grained fragmental matrix of similar mineralogy without any distinct modality. Overall clast–matrix ratio is 7:3. Modal abundance of the eucritic components based on auto-mode EPMA is given in Table 1.

The mineral chemistry shows the following range of composition: Feldspar (19), $An_{92.4-94.6}$; orthopyroxene (20), $Fs_{44.2-49.7}$; relic pigeonites (6), $En_{49.2-50.1}Fs_{38.9-44.2}Wo_{5.6-11.7}$; and clinopyroxenes (16), $En_{38.8-46.8}Fs_{14.8-33.6}Wo_{19.6-46.4}$. Representative analyses of the mineral phases are presented in Table 2. We discuss some mineralogical details below.

Pyroxene

Pyroxene is identified to be dominantly orthopyroxene and almost all these grains have exsolved lamellae of augite. A few relics of low Ca-pigeonite (10 to 20 μm across) exist in close association with the exsolved hypersthene clasts, but the pigeonites do not show any exsolved lamellae. Original compositional zoning from core to rim was noticed in the relic pigeonite. Although no regularity in compositional variation could be observed from the fractured components, pigeonite near its margin and in proximity to orthopyroxene is Fe-rich and Ca-poor.

Orthopyroxene clasts vary in size from submicron to 200 × 600 μm, and these show no compositional variation from core to rim. Hypersthene grains do not show any cloudiness except for sporadic occurrence of a few inclusions of SiO_2 polymorphs (average size ~150 μm) and troilite (~5 μm). Intense fracturing in the pyroxene seems to be related to mild shock events in the eucrite parent body.

Clinopyroxene as discrete grains have not been observed and is present only as exsolved lamellae within the orthopyroxene host (Fig. 2b). The exsolved lamellae of augite within the orthopyroxene varies in width from <1 to 4 μm, but each individual lamellae of augite is uniform in width, continuous, and has separation of 1 to 10 μm. In some lamellae, gradual pinching of width from 2 to <1 μm is observed in a few grains. The frequency of lamellae varies from grain to grain but the exsolved lamellae in some of the hypersthene grains are too numerous, indistinct, and very thin (<1 μm). Such host orthopyroxenes are likely to be the intermediate stage of inversion from pigeonite to hypersthene. Compositional variation of exsolved lamellae within the clast is relatively more than that between the clasts. A maximum variation of 5 mol% in Wo content and 3 mol% in Fs content is observed within an individual clast. Though a few clinopyroxene lamellae show subcalcic nature ($Wo_{19.6-32.5}$), it is verified by the electron beam technique that they do not contain subsequent generation of the exsolved phase. The observations suggest that the original igneous pyroxene of Vissannapeta eucrite was low Ca-pigeonite (with ~4% CaO) that got inverted to hypersthene with development of exsolved augite lamellae during the subsolidus cooling history.

Feldspar

Clasts of feldspar vary in size from submicron level to 1000 × 700 μm. It is extremely calcic in composition with a very small range of anorthite ($An_{92.4-94.6}$). Content of K_2O is also extremely low (≤0.01%). There is no compositional zoning even in the largest clast but inclusion of tridymite within plagioclase is common. In one instance, a plagioclase clast shows SiO_2 polymorphs as inclusions at least up to 10% of its volume. These SiO_2 polymorphs are mostly euhedral, although a few are rounded anhedral in shape. Besides SiO_2 polymorphs, plagioclase occasionally include a few submicron-sized troilite droplets.

TABLE 2. Typical mineral composition of Vissannapeta eucrite.

	Pigeonite	Plagioclase	Ortho-pyroxene	Clino-pyroxene	Chromite	Quartz/tridymite
SiO_2	50.83	44.78	50.51	51.6	0.09	98.42
TiO_2	0.03	0.00	0.08	0.01	0.48	0.06
Al_2O_3	0.54	35.03	0.37	1.07	9.62	0.20
FeO	26.69	0.19	29.08	12.57	32.26	0.18
MnO	1.12	0.00	1.11	0.59	0.65	0.00
CaO	4.08	18.39	0.53	18.58	0.10	0.06
MgO	16.48	0.00	17.36	14.18	0.83	0.03
Na_2O	0.03	0.71	0.00	0.05	0.02	0.00
K_2O	0.00	0.01	0.01	0.01	0.00	0.08
P_2O_5	0.11	0.00	0.06	0.03	0.00	0.00
Cr_2O_3	0.17	0.06	0.35	0.80	54.85	0.04
Total	100.07	99.16	99.46	99.51	98.93	99.13
Composition	$En_{49.3}$ $Fs_{41.9}$ $Wo_{8.8}$	$An_{93.4}$	$En_{52.2}$ $Fs_{46.7}$ $Wo_{1.1}$	$En_{41.5}$ $Fs_{19.3}$ $Wo_{39.1}$		

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Chromite, Metal, and Troilite

Chromite occurs as discrete grains at the interface between orthopyroxene and plagioclase. It is low-TiO_2 bearing but with Al_2O_3 up to 9.62%. It is nearly uniform in composition, and in general there is no striking variation in Cr_2O_3 (52.14–54.85 wt%) and TiO_2 (0.44–0.48 wt%). No ilmenite was observed either as exsolved lamellae within chromite or as discrete grain. No Fe,Ni metal grain is detected at the micron level, but troilite is present as accessory phase in sizes up to tens of microns.

SiO_2 Polymorphs

It is a common accessory mineral noticed mostly as inclusions within the plagioclase and rarely within orthopyroxene. In addition, it occurs in the interstices between plagioclase and pyroxene.

On the basis of petrography and mineral chemistry, Vissannapeta is classified as a cumulate eucrite having the following characteristic features: (1) a relic primary medium to coarse-grained equigranular cumulus texture enriched in pyroxene component (Fig. 2c); (2) a dominant breccia texture; (3) relic pigeonite as the original igneous pyroxene; (4) ferrohypersthene as the dominant pyroxene; (5) an ubiquitous feature of exsolved lamellae of clinopyroxene within orthopyroxene host; (6) extremely calcic plagioclase; (7) presence of free SiO_2 polymorphs as inclusions mainly within the plagioclase; and (8) absence of ilmenite, normally unexpected in cumulate eucrites. This classification is consistent with the bulk chemical composition discussed later. The subsolidus exsolution temperature and the inversion temperature from pigeonite to hypersthene can be estimated using the orthopyroxene (host) – clinopyroxene (lamellae) pairs based on pyroxene thermometry developed by Lindsley and Anderson (1983) to be 1009 and 845 °C, respectively.

BULK CHEMISTRY

The major and minor element concentrations of Vissannapeta eucrite are given in Table 3. The CIPW normative mineralogy estimated from the bulk chemistry compares well with the estimated auto-mode EPMA data. Low TiO_2 (0.03 wt%), *mg#* (50.96), Fe/Mn ratio (30.1), and molar Ca/Al ratio (0.62) are the characteristics of this eucrite that distinguish Vissannapeta as a pyroxene-rich cumulate eucrite. However, the TiO_2 content is lower than generally found in the cumulate eucrites because the data lie below the field of cumulate eucrites on a TiO_2 *vs.* *mg#* diagram (BVSP, 1981; Warren and Jerde, 1987).

Absence of any distinguishable ilmenite phase either as discrete grains or as exsolved phase within chromite is responsible for very low TiO_2. Cumulate eucrites so far reported show a wide range of *mg#* values from ~44 for Yamato 791195 to ~65 for Binda. In this context, overall chemistry of Vissannapeta is comparable to the Moama eucrite (Lovering, 1975), and it can be considered as a normal cumulate eucrite for its *mg#* (50.96). The Fe/Mn ratio for Vissannapeta (30.1) lies well within the eucritic range (29–31).

Potassium was also estimated by γ-ray spectrometry of two samples (28.5 and 1265 g), yielding 117 and 134.5 ppm, respectively. This is close to but slightly higher than the value of 98.5 ppm determined in a 5 g piece by AAS. However, aliquots of smaller samples (<1 g) yield values of 304 and 316 ppm. From these results, we infer that K is not homogeneously distributed within the meteorite, and the average concentration for the bulk can be taken as 117 ppm.

TABLE 3. Bulk chemical composition and CIPW normative mineralogy of Vissannapeta eucrite.

Chemical composition	Wt%	CIPW norm	Wt%
Metallic phase		Quartz	1.32
Fe	0.03	Hypersthene	47.5
Ni	<0.01	Diopside	8.10
Co	0.01	Orthoclase	–
Sulphide phase		Albite	2.10
Fe	0.05	Anorthite	37.81
Ni	<0.01	Ilmenite	–
Co	<0.001	Apatite	0.34
S	0.025	Chromite	0.45
Silicate and oxide phase		Metal (Fe-Ni)	0.03
SiO_2	48.0	Troilite	0.07
TiO_2	0.03		
Al_2O_3	14.25	Total	97.72
Cr_2O_3	0.34		
Fe_2O_3	Trace		
FeO	15.95	**Selected parameters**	
MnO	0.53	Fe/Mn	30.1
CaO	9.75	Mg#	50.96
MgO	9.3	Ca/Al	0.62
Na_2O	0.24	Norm. An	91.9
K_2O	0.014		
P_2O_5	0.08		
Total	98.48		

COSMOGENIC EFFECTS

Cosmic ray tracks and radioactivity were measured in this meteorite. Track density was measured along the vertical transact (D, H, E, F, and G) as shown in Fig. 1b and in a few spot samples (A, B, C, and K) taken from the basal and subvertical faces (Table 4). Tracks were measured after appropriate etching of plagioclase (boiling 12.5 molar NaOH for 30 min) and pyroxenes (22.5 molar NaOH for 30 and 120 min for clino- and orthopyroxenes, respectively). The track density varies between $5.8 \times 10^6/cm^2$ to $1.3 \times 10^7/cm^2$ and shows a gradient by a factor of 2 over a distance of ~2 cm (Fig. 3).

The results indicate that the base (containing spots A, B, and C) is more ablated compared to the pyramidal face with the flow ribs and, therefore, must have remained the leading face for most of the meteorite's flight through the atmosphere. On the other hand, presence of flow ribs would indicate that the pyramidal face was the leading face towards the terminal stage of the flight, when the meteorite had a nonrotating oriented passage at low velocity through the atmosphere. Thus, the track data, surface features of the crust,

TABLE 4. Track density in pyroxenes.

Sample code	Depth from crustal face (cm)	Number of tracks	Track density (tracks/cm²)
D (cut section)	0.5	1917	1.27×10^7
H (cut section)	0.7	2213	1.13×10^7
E (cut section)	1.0	1163	9.85×10^6
F (cut section)	1.5	1774	9.66×10^6
G (cut section)	2.0	1718	8.6×10^6
A (basal face)	–	2750	1.38×10^7
B (basal face)	–	364	5.8×10^6
C (basal face)	–	2007	1.03×10^7
K (subvertical face)	–	2040	1.64×10^7

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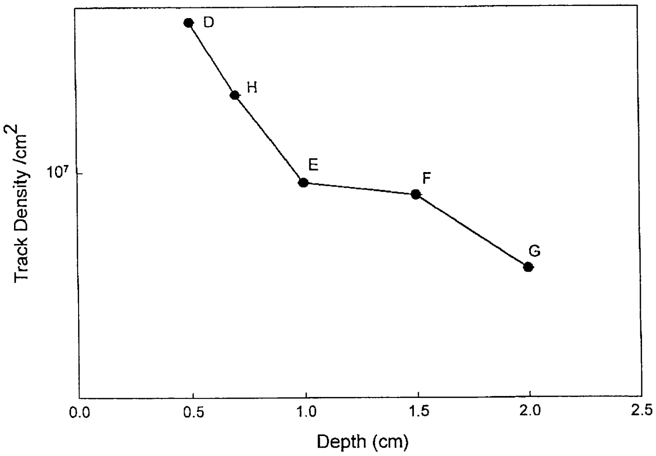

FIG. 3. Track density profile in Vissannapeta along transact D–G shown in Fig. 1b.

and shape of the meteorite suggest at least two stages of fragmentation and reorientation within the atmosphere.

Cosmogenic radionuclides ^{26}Al, ^{22}Na, and ^{54}Mn were measured in the whole meteorite as well as in a 28.5 g powder using a large volume (relative efficiency 115%), low-background, high-purity Ge gamma-ray spectrometer located within a 20 cm thick lead shield. The measured activities corrected for decay to the time of fall are ^{54}Mn (39 ± 7 dpm/kg), ^{22}Na (42 ± 4 dpm/kg), and ^{26}Al (78.1 ± 3.0 dpm/kg). Considering only ^{22}Na and ^{26}Al, for which errors of measurements are small, we find that their activities are ~25% lower than those calculated using isotope production models (Bhandari, 1981; Bhandari *et al.*, 1993). They are also lower by a similar factor compared to the activity levels in the eucrite Piplia Kalan (^{54}Mn = 51.4 ± 1.2, ^{22}Na = 53.0 ± 1.6, and ^{26}Al = 111 ± 9 dpm/kg), which fell 18 months before Vissannapeta in June 1996 (Bhandari *et al.*, 1998; Shukla *et al.*, 1997), when the sunspot activity was approaching the solar minimum of October 1996. The $^{22}Na/^{26}Al$ ratio (0.51), however, agrees with the expected value and is also similar to that found in Piplia Kalan (0.48). According to the various isotope production models (*e.g.*, Bhandari, 1981), the activity levels depend on four factors: (1) degree of saturation during the cosmic-ray exposure; (2) chemical composition; (3) modulation of galactic cosmic rays due to heliospheric magnetic field that depends on the sunspot cycle and largely affects production of short-lived radionuclides; and (4) the size of the meteoroid and the shielding depth of the sample within the meteoroid body. The rare gas exposure age is currently being measured in our laboratory; but assuming a typical value of several million years, the activity of the three radionuclides measured here must be in secular equilibrium. Higher Mg (5.5%) and Al (~8%) in Vissannapeta indicate that ^{22}Na activity should be more than that in Piplia Kalan whereas it is actually ~25% lower. The solar cycle modulation of galactic cosmic rays before the fall of Vissannapeta was lower than applicable to Piplia Kalan and hence higher activity by about 13 and 15% for ^{22}Na and ^{54}Mn, respectively, is expected based on the calculations using the climax neutron monitor data (National Oceanographic and Atmospheric Administration, 1998). The low levels of activities in Vissannapeta therefore are not due to differences in chemical composition nor are they due to different degrees of solar modulation of galactic cosmic rays before its fall (Bhandari *et al.*, 1989). The underproduction can not also be explained by a complex exposure history and multiple fragmentation events in the interplanetary space. Having eliminated the first three causes listed above, we conclude that the Vissannapeta was a small body in space (radius <20 cm, mass <120 kg) in which the nuclear cascade due to galactic cosmic rays did not develop fully. This inference is also consistent with the observed track density gradient in this meteorite (Fig. 3).

SUMMARY

The Vissannapeta meteorite belongs to the cumulate group of eucrites on the basis of its chemical as well as textural and mineralogical characteristics discussed above. The track density gradient and low levels of cosmogenic radionuclides indicate that Vissannapeta was a small body (<120 kg) in the interplanetary space wherein the nuclear cascade due to galactic cosmic rays did not develop fully. Tracks and surface morphology and crustal features indicate at least two fragmentation events in the atmosphere.

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